System Dynamics Modelling as Policy Decision Support for Retaining and Recycling Water within the Urban Water System to Address Water Scarcity – the Case of the City of Cape Town

by

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Dissertation presented for the degree of Doctor of Philosophy in Industrial Engineering in the Faculty of Engineering at Stellenbosch University

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Abstract

System Dynamics Modelling as Policy Decision Support for Retaining and Recycling Water within the Urban Water System to Address Water Scarcity – the Case of the City of Cape Town

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Water scarcity is a worldwide phenomenon, identified as the number one global risk, that if neglected, can result in social and economic collapse. The City of Cape Town is one such urban region experiencing ongoing water shortages in conjunction with several other urban regions in South Africa. Subsequently, the need for innovative and sustainable solutions, to address the growing water deficit, has become essential to assure sustainable water resources for the future. The City is predominantly dependent on traditional water resources from the Western Cape Water Supply System that are vulnerable to climate change and rising water demands. Therefore, alternative sources of water serve to diversify the water resources for City consumption.

Using an integrated approach to alleviate water stress in the City, value can be extracted from within the water system. Retaining and reusing water in the system and reducing water consumption are interventions that align with circular economy principles to zero waste for value generation. However, legislation aimed at extracting value from the urban water system need to be tested and evaluated to ensure sustainability in the City's economic, social and environmental sectors. The urban water system is a complex system with interconnecting elements. To avoid unexpected outcomes as a result of implemented changes, a holistic approach to water management is required. Literature found system thinking to be a suitable approach for evaluating policy changes in complex water systems, providing insight and understanding to decision-makers.

To develop a decision support model that represent the real-world system behaviour, technical and census data as well as case study research was used to link causal behaviour by constructing equations and stock-and-flow diagrams. The constructed system dynamics model, once validated, allowed for the development of policy scenarios. These scenarios tested the impact of utilising rainwater harvesting, greywater reuse and decentralised wastewater treatment plants together with consumption restrictions to alleviate water supply stress in the City over the period 2001-2040.

The results found that rainwater harvesting and decentralised wastewater reuse did not significantly decrease the water supply stress in the City. However, the effective reuse of greywater lowered the water stress experienced, while combining several intervention actions simultaneously had the most success in reducing water supply stress in the City. Furthermore, the model presented expected oscillatory behaviour due to the system's reaction to constraints on water allocation. Finally, as time progress the impact of interventions declined, indicating that continuous evaluation and intervention actions are required to balance the growing demand.

Uittreksel

Beleidbesluit ter Ondersteuning van Waardeverhaling uit Afvalstrome om Waterskaarste in die Stadsgebied van die Kaapse Metropool Aan te Spreek - ’n Stelseldinamika Benadering

(“System Dynamics Modelling as Policy Decision Support for Retaining and Recycling Water within the Urban Water System to Address Water Scarcity – the Case of the City of Cape Town”)

A. van Zyl

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Watertekort is ‘n wêreldwye verskynsel. Dit sluit ook die Stad Kaapstad in wat ernstige watertekorte in die gesig staar as gevolg van verminderende reënval in die area. Die stad is ’n digbevolkte verstedelikte metropool wat oorwegend op oppervlakwater staatmaak vanuit die Wes-Kaapse Watertoevoerstelsel. Oppervlak- en grondwater is tradisionele waterbronne, maar is kwesbaar vir klimaatsverandering en stygende wateraanvraag. Om die dreigende waternood wat in die streek ondervind word aan te spreek, sal alternatiewe waterbronne dien om diversifisering van waterbronne vir die stad se behoeftes, vry te stel. Om die waternood in die stad te verlig, kan waarde uit die huidige watersisteem verhaal word deur retensie en hergebruik van water binne die sisteem sowel as deur gebruiksvermindering. Die tipe intervensie is in lyn met sirkulêre ekonomiese beginsels wat lei tot nul vermorsing om waarde te genereer.

Wetgewing wat daarop gemik is om waarde uit die stedelike watersisteem te genereer moet getoets en geëvalueer word om die volhoubaarheid van die stad se ekonomiese, sosiale en omgewingsektore te verseker. Dit moet daarop gelet word dat die stedelike watersisteem ‘n baie ingewikkelde sisteem is wat baie interverbindings bevat. Om onverwagte gevolge wat spruit uit veranderinge wat aangegaan word te vermy, is ‘n holistiese benadering ten opsigte van waterbestuur uiters noodsaaklik. Bestaande literatuur wys daarop dat sistemiese denkwyse die geskikste manier is om beleidsveranderinge ten opsigte van komplekse watersisteme te evalueer en ook om insig en begrip aan besluitnemers te verskaf.

Om ‘n besluitsondersteuningsmodel, wat werklike sisteemsgedrag weergee, te ontwikkel is tegniese- en sensusdata sowel as gevallestudie navorsing gebruik om veroorsakende gedrag te koppel deur die gebruik van vergelykings en dinamiese vloei diagramme. Die opgestelde stelsel dinamika model, sodra gevalideer, laat vir die ontwikkeling van beleidscenarios toe. Die scenarios toets die impak van die gebruik van reënwater, gryswater hergebruik, gedesentraliseerde afvalwatersuiwering asook gebruiksverminderingmeganismes op water spanning verligting en die watervoorraad vir die stad oor die tydperk 2001-2040.

Die resultate het gevind dat die gebruik van reënwater en hergebruik van gedesentraliseerde afvalwater nie 'n beduidende impak op watervoorraad spanning in die Stad het nie. Egter, die effektiewe hergebruik van gryswater verlig die watervoorraad spanning oor die tydperk, maar daar word die meeste sukses behaal as verskillende intervensies gelyktydig aangepak word. Verder het die model verwagte ossilerende gedrag openbaar wat gekoppel is aan reaksies teenoor beperkings op waterallokasies. Daar moet ook op gelet word dat soos die tyd verloop het, het die effek van intervensies afgeneem wat daarop wys dat deurlopende evaluering en ingryping aksies nodig is om die groeiende vraag na water te balanseer.

Acknowledgement

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- My husband, Rudolf, thank you for encouraging, motivating, and assisting me throughout the years to achieve my goals.
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- Thanks and appreciation to the South African Air Force and colleagues for allowing me the opportunity and assistance to continue my education and broaden my area of knowledge.
- Finally, thank you to my friends and family for being supportive and cheering me on.

“Come, let us sing for joy to the LORD; let us shout aloud to the Rock of our salvation. Let us come before him with music and song. For the LORD is the great God, the great King above all gods.” – Psalm 95:1-3

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Acronyms and Abbreviations

AGEP	Average Groundwater Exploitation Potential
AWRMS	Atlantis Water Resource Management Scheme
AWSS	Atlantis Water Supply Scheme
BAU	Business as Usual
CLD	Causal Loop Diagrams
CMA	Catchment Management Agency
CoCT	City of Cape Town
CSAG	Climate System Analysis Group
DEAT	Department of Environmental Affairs
Dmnl	Dimensionless
DPLG	Department of Provincial and Local Government
DPR	Direct Potable Reuse
DSSO	Decision Support System Optimizer
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EU	European Union
GBCSA	Green Building Council South Africa
GDP	Gross Domestic Product
GRDP	Gross Regional Domestic Product
GWM&E	Government-wide Monitoring and Evaluation
IDP	Integrated Development Plan
IPCC	Intergovernmental Panel on Climate Change
NPV	Net Present Value
IPR	Indirect Potable Reuse
IWA	International Water Association
IWRM	Integrated Water Resource Management
MAR	Mean Annual Runoff
MAR	Managed Aquifer Recharge
MCDM	Multi-Criteria Decision Making
MLD	Million Litres per Day
M&E	Monitoring and Evaluation
NERA	National Environment Management Act
NPR	Non-Potable Reuse
NPV	Net Present Value
NWA	National Water Act
NWP	National Water Policy
NWPR	National Water Policy Review
NWRS	National Water Resource Strategy

PPP	Public-Private Partnership
RDP	Reconstruction and Development Programme
SA	South Africa
SANS	South African National Standards
SD	System Dynamics
STD	Stock-and-Flow Diagram
SUWM	Sustainable Urban Water Management
SWH	Storm Water Harvesting
TMGA	Table Mountain Group Aquifer
TWD	Total Water Demand
TWS	Total Water Supply
UGEP	Utilisable Groundwater Exploitation Potential
URV	Unit Reference Values
WaSSI	Water Supply Stress Index
WB	Water Board
WC	Western Cape
WCDM	Western Cape Demand Management
WCWDM	Water Conservation and Water Demand Management
WCWSS	Western Cape Water Supply System
WD	Water Demand
WDS	Water Demand Strategy
WeCaGEM	Western Cape Green Economy Model
WfGD	Water for Growth and Development
WHO	World Health Organisation
WMA	Water Management Area
WRC	Water Research Commission
WSA	Water Service Authority
WSD	Water Sensitive Design
WSI	Water Scarcity Index
WSP	Water Service Provider
WSS	Water Supply System
WSUD	Water Sensitive Urban Design
WUA	Water User Association
WWF	World Wide Fund
WWTW	Wastewater Treatment Works
ZAR	South African Rand

Glossary

Aquifer is an underground system of permeable material which transmit or contain groundwater.

Blackwater is water waste from toilets, urinals and kitchen sinks/dishwashers.

Desalination is the process of removing salt and other minerals from water (usually seawater) to obtain fresh water suitable for industrial use or human consumption.

Direct Potable Reuse (DPR) refers to the direct injection of potable quality recycled/reclaimed water into the potable water supply reticulation system for distribution. DPR can also refer to the direct injection of recycled water into raw water supply immediately upstream from the raw water treatment facility.

Greywater is water waste from showers, basins, baths and in some cases laundry.

Groundwater is water stored underground in pores and crevices of rocks or in soil pores. The stored water moves slowly through the geologic formations, usually as a result of gravity.

Indirect Potable Reuse (IPR) refers to the use of an environmental buffer, to blend recycled water with natural water in aquifers or reservoirs that will be used as drinking water (potable) after additional treatment.

Non-potable Reuse (NPR) refers to wastewater treated for purposes other than drinking, which include irrigation, industrial uses and the replenishment of wetlands.

Non-potable Water is water not suitable for human consumption (drinking), but remain useful for other purposes.

Potable Water is water treated to quality and distributed by the municipality for human consumption.

Rainwater Harvesting is the capturing and storage of rooftop runoff during precipitation.

Reclaimed Water refers to the treatment process that transforms wastewater, by removing impurities and solids, to become suitable for other purposes. Uses may include: Irrigation and groundwater recharge.

Recycled Water see definition for *Reclaimed Water*.

Stormwater is the surface runoff from roofs, buildings and impervious surfaces during precipitation which can also include overflow from river or dam floodwaters.

Stormwater Harvesting is the capturing and storage of stormwater runoff.

Stormwater Ingress is the inflow of stormwater entering the sewer system.

Sustainability is the process of continued behaviour indefinitely, thus maintaining the change within a balanced environment.

System refers to a set of things or processes working together in an integrated network forming an unified whole.

Wastewater is water affected by human interference (by-product of domestic, agricultural or industrial activities)

Water Scarcity refers to the lack or physical shortage of fresh water sources (surface-and groundwater) to meet the water demand in a region.

Water Stress is the inability of available water resources to meet both human and ecological water demand, taking water quality and accessibility into account.

NOTE: The Department of Water and Sanitation title has changed as per Figure 1.

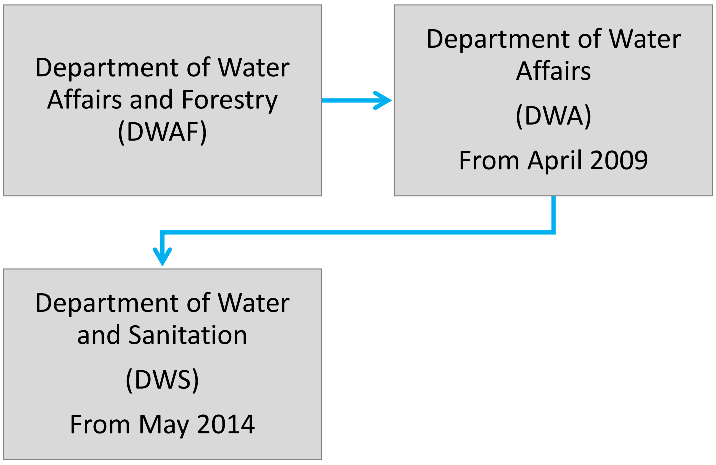


Figure 1: Title Changes for the Department of Water and Sanitation

Chapter 1

Introduction

> *"As the world charts a more sustainable future, the crucial interplay among water, food and energy is one of the most formidable challenges we face. Without water there is no dignity and no escape from poverty."* – Past UN Secretary-General Ban Ki-moon

The aim of this chapter is to give background and introduce the research study. The themes introduced in this chapter include the implications of constrained water resources in the City of Cape Town, the identification of opportunities and challenges for the improvement of the City's urban water system and the formulation of the research problem and objectives. Furthermore, the chapter provides an overview of the proposed research contributions and the dissertation design and methodology used to address the research questions. The chapter concludes with the dissertation outline, which aims to provide a roadmap for the research project.

1.1 Project Background

The scarcity of fresh water resources was identified as the largest global risk with four billion people in the world experiencing extreme water shortages, for at least one month in the year (Ganter, 2015; Mekonnen and Hoekstra, 2016). In this regard, water scarcity refers to the inability of fresh water resources to sufficiently meet the demand for water. With the current severe drought inhibiting the recharge of water supplies, the City of Cape Town has been identified as one of the first major urban cities facing the possibility of running out of water (BBC, 2018). Unfortunately the shortage of water is not an uncommon occurrence, with global fresh water demand predicted to exceed supply in 2030 by 40% (2030 Water Resource Group, 2009).

Global population growth, growing economies, impacts of climate change and urbanisation in cities are driving the rapid increase in water demand, while water supply remains constrained (Wei et al., 2016). As the water balance is the description of the inflows and outflows in the water system, the increase in water demand places stress on the water balance resulting in a rise in water stress (Brown and Matlock, 2011; Bugan, Jovanovic, and De Clercq, 2012). In context, water stress is the term used to describe the inability of meeting the demand for water, taking into account the quality, accessibility and environmental flows of the water supply (Almeida et al., 2013; Wada et al., 2011).

The City of Cape Town Metropolitan Municipality, situated on the coastal edge of the semi-arid Western Cape Region, is a major urban area accounting for the second largest economic centre in South Africa (SA) (Bugan, Jovanovic, and De Clercq, 2012, *City of Cape Town Metropolitan Municipality (CPT)* 2017). The Cape Metropolitan Area in Figure 1.1 is a densely populated area with a population of just over 4 million (2016). The City is situated in the southern peninsula of South Africa, stretching from Atlantis down to Gordon's Bay, covering an area of approximately 2474 km^2 (Provincial-Treasury, 2017).

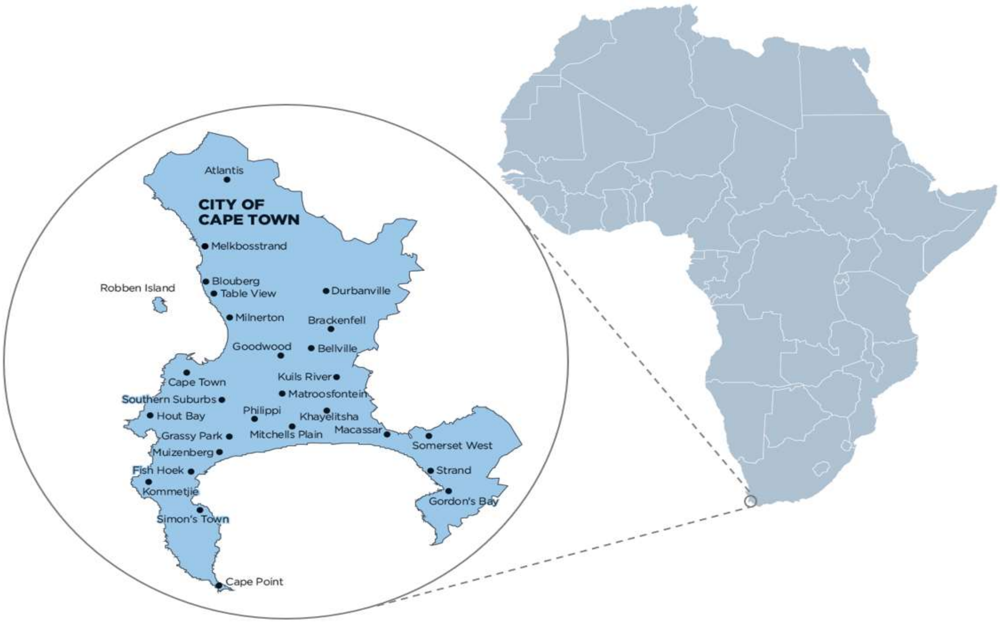


Figure 1.1: Cape Metropolitan Area (Adapted from www.municipalities.co.za)

According to the 2016 Wesgro district report 64% of the Western Cape population is housed within the City of Cape Town, which contributes 70.72% of the total Western Cape Regional Gross Domestic Product (GDP) (Wesgro, 2016). The diverse economy of the City boast a variety of contributors from the finance, property, manufacturing, retail and catering sectors (C. Wright et al., 2016). Although the agriculture sector uses the largest amount of water in South Africa for irrigation and livestock, the industrial sector is another major driver of water demand in South Africa (Colvin and Muruven, 2017). Regardless, in the City of Cape Town, urban usage amounts to the majority of water consumed within the Western Cape Water Supply System (WCWSS) (CoCT, 2017d).

There is strong link between the economy and water scarcity (Hallowes, 2019). Not only is the City of Cape Town's total revenue also dependent on water sales (approximately 10%), but ten South African companies found water scarcity to have an economical impact of R610 million in 2015 (Groenewald, 2018; Moss, n.d.). Therefore, both direct and secondary impacts may result in economic and social decline if the City neglects water shortages (Hallowes, 2019; Moss, n.d.). Reduced water sales influence the revenue generated, diminishing the budget for infrastructure upkeep and service delivery (Groenewald, 2018). Further impacts include declining agricultural production, reduced industrial production, high water costs, high energy requirements, migration and social divide (Hallowes, 2019).

In 2018 the City of Cape Town, under strict water restriction level 6b, still demanded an average of over 500 million litres of water per day, which is mainly supplied by surface water sources (98% of usage) (CoCT, 2018b). With the remaining 2% being abstracted from groundwater aquifers within the City. The City of Cape Town falls predominantly in the Berg-Olifants Water Management Area (WMA), where 99,6% of the City's surface water supply is provided by six major dams (Bredell, 2012). Low average rainfall and severe drought, brought on by climate variability, has placed further strain on the region's water supply resources, resulting in surface water storage levels reaching extreme lows with slow recharge rates (DWS, 2017).

Historically the supply side of the water value chain would be addressed through augmentation projects or the construction of new dams to address water shortages (C. Chen et al., 2017). However, all available sites for new surface water constructions in the Western Cape have been developed and augmentation of current dams are limited and require extensive capital investment (Basson et al., 2010). This limits the extension of water supply sources in a region where the demand for water resources are continuously rising, resulting in an increase in water scarcity.

Water scarcity refers to the physical water shortage in a region and therefore, has a significant impact on the economic, political, environmental and social sectors (2030 Water Resource Group, 2009). Agriculture, energy, trade and urban development are all groupings dependent on water resources, while contributing to the well-being and growth of economic, environmental, political and social sectors. This makes the decrease in water supply a growing concern for the City of Cape Town and its stakeholders (Davies, 2008; Pegram and Baleta, 2014). As drivers of water demand and resource limitation, the effects of climate change, population growth, industrial development and urbanisation must be considered in future planning to ensure sufficient water supply within the City.

To ensure a sustainable future, legislation and governance must address the risks associated with water scarcity in the City of Cape Town (CoCT, 2017a). The water scarcity and drought in South Africa is resulting in agricultural decline, where consequences include higher food prices and loss of employment, which ultimately affects the country's GDP (Blignaut and van Heerden, 2009). These extreme impacts of water scarcity have escalated the need for establishing policies and guidelines aimed at reducing water demand, improving water conservation, establishing alternative water supplies and optimising the water usage in the City of Cape Town (Pegram and Baleta, 2014).

With regard to legislative actions, the Department of Water and Sanitation (DWS) is the national government entity responsible for the formulation and implementation of governing water and sanitation policies in South Africa. The national government is also responsible for the management, protection, development and conservation of water resources in a sustainable manner (Harpe and Ramsden, 2000). Whereas, local government (i.e. municipalities) is primarily responsible for the management of water and sanitation services (DPLG, 2007).

Although improvements and water savings have been made with the implementation of water policies and strategies, there is still more opportunity for improvement. With a shift towards sustainable development, the City of Cape Town is moving away from traditional water management, where water is extracted, treated, used and then disposed of, to a more sustainable approach, where used water is recycled or retreated and returned back into the water system for reuse (Sagen and T. Williams, 2016).

A sustainable environment must form an intricate part in the water system as it is required to support and maintain both economic and social growth. The urban water value chain can be described as a complex interconnected system consisting of elements that interact and behave in accordance with inputs, both internal and external to provide suitable water to users (Hyvarinen et al., 2016). Subsequently, by understanding how and where water is withdrawn and consumed from the water value chain, water risk areas, opportunities and interaction can be identified.

In light of water's strong link to socio-economic growth, water plays three roles in context of the economy (Balabanis, 2015). Water is either a resource, a product input or a stream of waste. As water circulates through its natural stages, a small fraction remains useful for human consumption and requirements, making the management of the water system critical (Jeffries, 2017). This means that water systems can no longer be seen as a resource for the economy, but rather as an integral part of the economy, from which the concept of water in the circular economy evolved (Andersen, 2007). By retaining and reusing water in a closed loop system water extraction can be reduced. However a holistic view of the water system is required to anticipate the behaviour and result of the system in response to actions taken (Ghisellini et al., 2016).

Current water supply sources in the urban water system cannot meet the growing demand, therefore alternative sources such as seawater desalination and wastewater reclamation have been identified as possible sources of water for the City of Cape Town (DWA, 2013b). In 2017, only 5% of water used by the City of Cape Town was treated for reuse, with the reuse limited to industrial or local irrigation purposes and not for potable usage (Braid et al., 2011; CoCT, 2017d).

Water is a constraint on the economic growth of the city and therefore, the private sector is concerned about the threat that water scarcity pose to the economy (Bronkhorst, Pengelly, et al., 2017). Private funds have been invested in research and the development of new technologies and systems to achieve sustainable water management. Potential for economic growth and more efficient resource use have led to new policies, strategies and actions being developed by both local and national governments. The accompanying new legislation may yield unpredictable and unwanted results that may be detrimental to the environment, society and the economy, all elements of importance in the Constitutional Bill of Rights (Ghaffarzadegan et al., 2010; South African Government, 1996).

Water strategies and legislation should be of such nature as to manage water sources and provide water services in a sustainable manner to benefit future generations equitably. To predict and evaluate the long term impact of current and new legislation and strategies, for the water value chain as a whole, is complex (Ghaffarzadegan et al., 2010). For example, the impact of optimising irrigation may result in an unexpected decline in aquifers and groundwater quality. Therefore, the water value chain must be viewed as a natural system with interacting elements, where losses and waste streams may present as a source further along the value cycle. These waste streams may present opportunities for value extraction (Pegram and Baleta, 2014).

Wastewater, categorised as water affected by the use of humans which include surface runoff (stormwater), can be recycled or reclaimed for reuse after a treatment process (Tilley et al., 2016). Rainwater, albeit not being wastewater, can also be collected and stored for reuse, subsequently retaining further value within the water system.

Although current legislation address both sides of the water balance, holistic system interventions and innovation will be required to ensure sustainable and equitable water supply for the future (Makropoulos et al., 2008). Incorporating a systems view in the decision making process, to support the evaluation and outcome scenario analysis, will assist policy-makers during policy development and implementation.

Before decisions and implementation of policies can be made, it is important to understand the behaviour and structure of the urban water value chain for the City of Cape Town. The implementation of demand management schemes and the search for alternative water resources are costly and require a relatively long period of time to implement (Basson et al., 2010). However, the water system in Cape Town is still experiencing water losses and unused potential for reusing wastewater in the system. These losses should be viewed as opportunities with potential economic benefit, whilst aiming to reduce the water stress experienced in the city in a sustainable manner.

1.2 Problem Statement

The problem is that **legislation and governance** aimed at extracting value from the **urban water value chain**, through the **retention** of **water streams** and the **reuse** of **wastewater**, as **potential sources** of water for the **alleviation of water stress** in the **City of Cape Town**, need to be **evaluated and tested** to ensure **economic, social and environmental sustainability**.

Thus, the results produced by an appropriate evaluation model, should serve as decision support to the policy-makers, by highlighting behavioural patterns and trends over time. To address this problem, the research study aims to answer the research questions through the achievement of the research objectives.

1.3 Research Questions and Objectives

The following research questions aim to address the research problem by providing insight and answers through objective research and investigation.

Question 1: How is water scarcity in urban cities addressed in an sustainable manner?

Question 2: How can legislation and governance address water scarcity in the City of Cape Town?

Question 3: How can policies and strategies be tested to ensure a sustainable and equitable water future in urban cities?

Subsequently, the following research objectives aim to answer the research questions for addressing the research problem:

1. Identify methods and approaches in literature used to address water scarcity, water management and value extraction in urban water systems for a sustainable and equitable future.
2. Identify methods aimed at supporting the decision making process.
3. Formulate the problem and develop a conceptual model for the urban water value chain.
4. Transform the qualitative model to a quantitative system dynamics (SD) model for simulation.
5. Address limitations identified in the conceptual and dynamic models using case study research.
6. Validate and verify the structure and the behaviour of the constructed decision support model.
7. Develop scenarios to be simulated for decision making, gap identification and result comparison.
8. Analyse the results obtained from the simulated scenarios.
9. Provide results and recommendations obtained from model evaluation and analysis.

There are limitations and boundaries to the research problem, that aim to focus the research study with consideration to the research purpose and the available resources and time. Thus, the research objectives lie within the scope of the research study to address the identified research problem.

1.4 Scope and Limitations

The scope of this dissertation is limited to the current urban water value chain for the City of Cape Town and the publicly available water service and management legislation and documentation. Therefore, model boundaries should be restricted to the scope of the research study.

Water service and management programmes are not funded solely at a provincial or municipal level but at a national level. Providing decision support for the implementation of policies or strategy decisions and the cost associated with these, need to be approved by the Minister of Water and Sanitation and should, therefore, be incorporated in the decision support process.

The research study aims to address the reuse and retention of water streams in the water value system to ensure sustainable socio-economic and environmental development, that are beneficial to South Africa as a whole. Scenario development will be aimed at addressing waste steams and unexploited water sources in the urban water value system through legislation to draw potential value from the system.

Similar models built for the South African water value chain will be used to validate the proposed urban water system model. Furthermore, literature, public documents, case study research, policy reviews and reports will be used as a source for model development and as support to model validation.

1.5 Original Research Contribution

Literature address a wide range of aspects relating to the field of knowledge investigating water scarcity in urban regions. Tariff structure, energy-water nexus, infrastructure and the reclamation of used water are some of the facets covered in literature, applied in different contexts and regions. However, a small fraction of literature found investigate the impact of reusing various waste streams as an alternative source of water to alleviate water stress. What is more, only a select few address the reuse, retention and reclamation of several water streams simultaneously, even less so in the South African context. Subsequently, the potential remain to evaluate the impact and behaviour of the complex urban water system in response to policy interventions stipulating the reuse and retention of water streams, individually or collectively, to reduce water stress experienced in urban cities.

The dissertation sets out to expand the field of knowledge by developing and documenting in-depth analysis of information and data extracted from available resources, subsequently contributing both theoretically and practically to the field of knowledge.

1.5.1 Theoretical Contributions

The research study aims to make the following theoretical contributions:

1. To define urban water roles for the City of Cape Town within the circular economy context.

2. Categorise water requirements, by distinguishing between the quality of water demanded and the consumer behaviour during constrained and non-constrained water allocations, based on the level of water restriction implemented as part of the City of Cape Town's water demand management actions.

3. Identify several alternative water sources derived from waste streams and unretained water resources within the City of Cape Town's urban water system.

4. Provide a decision support model capable of representing the urban water system holistically for the City of Cape Town.

5. Investigate the behavioural response of the system to simultaneous intervention actions within the water supply, demand and water waste management factions.

6. Construct an industry based decentralised wastewater treatment plant model to provide insight into the challenges and value such systems represent and to explore the feasibility of utilising on-site reclamation plants to address water shortage in urban regions.

1.5.2 Practical Contributions

The research study aims to make the following practical contributions:

1. For the constructed model to support policy evaluation and decision making by providing insight and understanding into the system behaviour and response to intervention actions. Therefore, serving as a base model for the City of Cape Town's urban water system on which further research can be build for in-depth analysis.
2. To identify the requirement for municipal treated effluent, potable water and groundwater, which serve as external input to on-site decentralised wastewater systems, in the event that the system is unable to produce adequate quantity of potable quality water to meet internal demand.
3. Allow for decision-makers to adjust input variables and evaluate the corresponding behavioural changes and system response of the urban water system for the City of Cape Town.

1.6 Research Design and Methodology

The research approach most appropriate for this study is a mixed method, exploratory sequential design. This approach begins with qualitative data collection and analysis, followed by quantitative data collection, modelling and results interpretation. Once the problem is formulated, based on data gathered, a conceptual model for the urban water system in the City of Cape Town is developed using system thinking and case study research techniques.

Thereafter, the qualitative model is transformed to a dynamic model through quantitative data gathering and analysis using results from case study research and secondary quantitative data. Once the quantitative system dynamics model is constructed, validation for both model behaviour and structure is applied to establish model confidence. Scenarios development for policy testing is based on both qualitative and quantitative data gathered, from which the outcome and results of implemented scenarios are presented and interpreted in the final phase of the exploratory sequential design process.

The research design and methodology aim to provide tools for achieving the research objectives and therefore, addressing the research problem. The layout of the research study is described per chapter in the next section.

1.7 Dissertation Outline

The project roadmap for this research study, shown in Figure 1.2, serves as the illustrated guide to the outline of this research study.

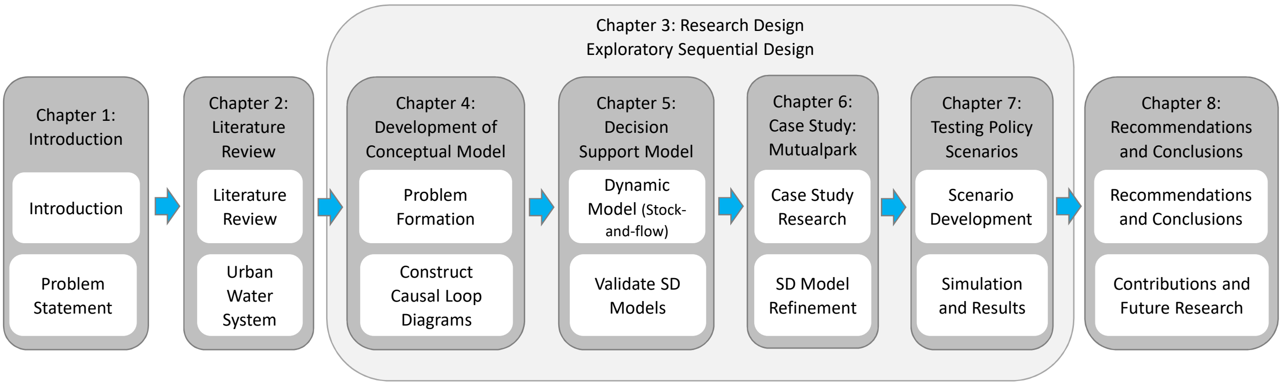


Figure 1.2: Project Roadmap

To support the visual representation of the outline, a per chapter discussion which highlights the aim of each chapter for the research study, follows:

Chapter 1 serves as an introduction to the research study, problem background and research questions. The chapter concludes with the proposed research methodologies for addressing the research problem and introduces the dissertation outline.

Chapter 2 serves as an in-depth literature review of methods and tools globally used to sustainably address water scarcity in urban areas. The methods are compared and critiqued for usefulness in extracting value sustainably from water streams in urban water systems, using circular economy principles. The literature review aims to identify a suitable approach to providing insight and understanding of how the components of urban water value chains for the City of Cape Town interact and behave within the complex system. The chapter further investigates the structure of governance, legislation and policy evaluation processes in the water sector to address socio-economic issues and water scarcity.

Chapter 3 aims to identify and introduce the research methodology selected, exploratory sequential design, for addressing the research problem. The chapter further introduces the design and methodology for system dynamic modelling and casy study research in relation to the selected research methodology. The techniques for validating policy decision support models are also investigated in the third chapter.

Chapter 4 aims to formalise the problem and to develop the conceptual model for the City of Cape Town's urban water system, based on selected modelling methodology's qualitative phase, through data gathering and analysis.

Chapter 5 aims to link the qualitative conceptual model with the quantitative model phase. Thus, the chapter develops the system dynamics model based on qualitative and quantitative data gathered for analysis. The dynamic model for the City of Cape Town's urban water system is validated for model confidence before scenario development and implementation can commence.

Chapter 6 intends to apply system dynamic modelling techniques to pursue the refinement of the decentralised wastewater model developed in Chapter 4 and Chapter 5. A single-case study is used to investigate the industrial application of decentralised wastewater treatment plants. Insights and key parameters extrapolated from the findings are used to support the validity of the urban water system model for the City of Cape Town.

Chapter 7 deals with the scenario development, implementation and analysis of results. This chapter serves as part of the final phase of the exploratory sequential research design, aimed at interpreting results.

Chapter 8 provides findings, recommendations for future studies and concludes the research study, which finalises the model interpretation phase for the research design.

1.8 Chapter Summary

Water is a key resource, that serves as a catalyst for economic and social development, which has become a highly constrained resource in the City of Cape Town as a result of population growth, urbanisation and the onset of climate change. Although Cape Town is one of the major urban areas currently experiencing water shortages, it is not deemed an unique problem, as water scarcity has been identified as the number one global risk in terms of impact.

Traditional solutions and augmentation programs are no longer sufficient and require new system-wide interventions to address water stress in urban areas. Through the identification of water roles within the water value chain areas of waste in the system can be identified as potential sources for the system. It must be emphasised that changes made to the water value system, through the implementation of value extraction actions, may result in unwanted and unpredictable results sometimes only presented years later.

To ensure the optimal and sustainable utilisation of water streams in the urban water system in the City of Cape Town, potential actions must be tested. These actions are mainly implemented by means of legislation or governance strategies. As water plays a critical role in the social, economic and environmental well-being, these resulting impacts must be aligned with the goals set out in the Bill of Rights, to ensure a sustainable and equitable future for all South Africans.

In conclusion, this research study aims to address potential value extraction from water streams in the urban water system for the City of Cape Town, to sustainably alleviate the water stress currently experienced in the City. As actions and mitigation responses are driven by governing policies and strategies, the research study aims to build a model for the urban water system to provide policymakers with decision support and the ability to test and evaluate the impact of potential legislation actions.

Chapter 2

Literature Review

> *"Education is the most powerful weapon which you can use to change the world."* – Nelson Mandela

The aim of this chapter is to establish a theoretical framework for the research study and to provide a critical review of literature related to the field of study. Furthermore, the literature review provides the foundation for addressing the research problem and research questions through the assessment and review of the available body of knowledge. Outcomes for this chapter include the critical review of water scarcity, methods for evaluating urban water systems, circular economy principles, systems thinking approach and policy evaluation methods. The literature review should provide sufficient evidence for the selection of appropriate modelling techniques for addressing the research problem.

2.1 Introduction

A literature review is undertaken to elicit information from available research literature, policies, and non-research sources to understand and comprehend the subject matter being studied (Hart, 1998). Aiming to become an expert in the field, is part of the process and allows the researcher to identify key issues and gaps in the area of knowledge, while critiquing methods used in literature to address similar problems. (Hart, 1998). A well written literature review should be critical in nature without personal bias and follow a clear structure for searching and selecting information (Carnwell and Daly, 2001). Furthermore, the literature review aims to provide the researcher with a thorough background and up to date information on the research topic from a wide range of sources, with a goal of providing evidence and support for addressing the research problem and identifying future research requirements on the investigated topic. Literature reviews are not only used for research studies, but also for policy development, process evaluations and increasing personal knowledge (Polit and Beck, 2006). The literature review for this research study is structured in such a way as to discuss and evaluate available literature per category.

Keywords, phrases, and databases are identified based on their relevance to the research topic and used to identify suitable literature, (Ely and Scott, 2007). To narrow the literature search, a time frame is applied to ensure relevance. Thus, a time frame of 5-10 years is selected to narrow the available literature (Cronin et al., 2008). Older references and sources are, however, included in the literature review to support current sources and to provide the basis for theory and frameworks (Baker, 2016).

An initial broad search for phrases and keywords relating to the research topic is done on the Stellenbosch University library database, which subscribes to the leading global academic databases, and Google Scholar using AND, OR and NOT operators (Easterby-Smith et al., 2008). In accordance with policy research, basic social aspects of the research problem are searched for using keywords such as *"water scarcity"*, *"urban"*, *"impacts on society"*, *"sustainability"* and *"water stress"*.

Thereafter, the technical aspects relating to the urban water system are investigated, with emphasis on how social problems relating to water scarcity are addressed in literature. Keywords used included: *"evaluating urban water system", "reduce water stress", "decision support", "methodology" and "value extraction".* Finally, the literature and sources associated with policy research and evaluation techniques are searched for using *"policy evaluating"*, *"policy process"*, *"public policy"* and *"policy making"* as keywords. The articles and documents retrieved from the Stellenbosch University library database and Google Scholar as per keywords, are listed in Appendix A.1

Once the initial overview of literature is done, it is necessary to establish structure for the systematic critical review, to ensure a focused literature review. In addition, the large amount of literature material should be indexed according to criteria (Jesson and Lacey, 2006). Although criteria for indexing differ among authors such as Burns and Grove (2007), Patrick and Munro (2004), Polit and Beck (2004), and Timmins and McCabe (2005), indexing is generally done according to article title, author, research methodology, purpose and findings. Additionally, Cronin et al. (2008) found it useful to add notes or responses to articles once reviewed with full reference for record keeping.

This literature study aims to investigate and identify the impact and opportunities embedded in the urban water value chain, to sustainably reduce the water stress experienced globally, and in particular, the City of Cape Town. Gaps and opportunities are identified, through the evaluation and critiquing of methodology, decision support techniques and policy implementation found in available literature. Consequently, the review process prove to be iterative in nature, as the research topic and questions become more refined.

Policies and legislation applicable to the water sector are scrutinised to identify opportunities for value extraction and process improvement. Once the water management structures and policy implementation processes for the City of Cape Town are analysed, further research within literature is conducted. Subsequently, the literature review for this research study, is structured in such a way as to discuss and evaluate available literature per category, starting with basic social research and a background study into the affects and causes of water scarcity.

2.2 Water Scarcity

In 2015, water scarcity was identified as the number one global risk in terms of impact, which pose a threat to the sustainability and well-being of socio-economic and environmental sectors (Chang et al., 2015; Ganter, 2015; Mekonnen and Hoekstra, 2016). As there is no substitute for water, the shortages experienced in the water system affects the socio-economic development, and the environment well-being of the city or country in which water shortages are experienced (Blignaut and van Heerden, 2009; C. Chen et al., 2017; Nahal, 2014).

Water scarcity is defined as the measurable mismatch between the demand for fresh water and the availability of suitable water sources, usually taken over an annual time period (El-Gafy and El-Ganzori, 2012). However, Mekonnen and Hoekstra (2016) added that the annual measurement of water scarcity, hides the irregularity throughout the year, leading to the underestimation of the degree of water scarcity. As fluctuation in seasonal water supply and demand is not captured in the annual measurement of water scarcity, specific areas experiencing water shortages for certain periods of the year, are not included in the per annual water scarcity measurement bracket (Mekonnen and Hoekstra, 2016).

Although Saleth (2011) incorporated the variation in water scarcity throughout the year, the requirements for environmental flows were not included, which also led to the underestimation of water scarcity. Thus, an holistic view of the water system is required to identify and account for the effects of water consumption further downstream (Marlow et al., 2013; Mekonnen and Hoekstra, 2016). It was found that densely populated areas with increasing economic growth, high levels of irrigated agriculture and low availability of natural water sources are drivers of water scarcity (Distefano and Kelly, 2017).

Blignaut and van Heerden (2009) classified South Africa as a country experiencing chronic water shortages, worsened by climate change and invasive plant species. The City of Cape Town, situated in the semi-arid Western Cape region, is evidently one of the urban areas in South Africa dealing with extreme water shortages as a result of high population density, low average annual rainfall, high water demands and limited water reuse capacity (Bugan, Jovanovic, and De Clercq, 2012; C. Wright et al., 2016).

What is more, the 2030 Water Resource Group (2009) predicted that by 2030 the global water demand will exceed reliable water supply by 40%, making water shortages a global issue. This supports, the Merrill Lynch Global Research group's view of water as a global crisis, with the report further elaborating that water stress will be experienced on a global scale with a risk of lost Gross Domestic Product (GDP) (Nahal, 2014). To measure the level of water vulnerability, indices have been developed to evaluate the water scarcity according to selected criteria (Brown and Matlock, 2011). Brown and Matlock (2011) provided an overview of methods and indices aimed at measuring water scarcity to assist political decision making with regards to water management.

Although water scarcity refers to the volumetric unavailability of water supply to meet demand, water stress refers to the inability of water sources to meet the demand for water quantity, quality and economic and environmental flows (DEAT, 2011; Schulte, 2014). To determine the scarcity of water resources, the demand (volumetric amount required) per district and the amount of usable water available in that district grid need to be identified (Brown and Matlock, 2011). To do this, measuring frameworks and tools were developed to determine the minimum demand based on human requirements. These tools included indices for human water requirements that serve as a measure of scarcity, with the water stress indices referring to the ratio of water used to water supplied (Rijsberman, 2006; Sun et al., 2008a; Wada et al., 2011).

The 1989 Falkenmark indicator, the 1996 Basic Human Water Requirements, the 2002 Social Water Stress Indicator, the Water Resource Availability and Cereal Import indices and the Water Supply Stress Index are some of the measuring tools used to categorise or measure water scarcity (Falkenmark, 1989; Gleick, 1996; Sun et al., 2008b; Yang and Zehnder, 2002). These indices exhibit similarities, but differ in approach. Table 2.1 gives a brief summary of definition and measurement elements of the indices.

Table 2.1: Summary of Water Scarcity Indices

Indicator	**Definition**	**Measure**
Falkenmark (1989)	Fraction of total runoff available for human use. Water usage per person (Capita usage). Individual usage.	No Stress, Stress, Scarcity and Absolute Scarcity. 1700 m^3 to 1000 m^3 per capita available per year.
Basic Human Water Requirements (1996)	Ability to meet water requirements for basic human needs. Minimum basic amount of water needed to sustain human life, independent of climate, technology and culture.	Minimum requirements: 1. Drinking Water: 5l 2. Sanitation : 20l 3. Hygiene : 15l 4. Food : 10l Benchmark indicator of 1000 m^3 per capita per year.
Social Water Stress Indicator (2000)	*Adaptive Capacity* incorporating the economic, technological and other affects on the availability of fresh water. The adaptability is a function of wealth, education, opportunities and political participation	Human Development Index (HDI) for weighted measurement of Falkenmark (1989) Water Stress Index
Water Resource Availability and Cereal Import	Using the quantity of food imported as an indicator of water deficit. Based on the food productions reliance on water. A threshold for defining a region water scarce or water abundant in status.	Food insecurity and poverty as a result of water scarcity. Based on the import of wheat (cereal) a threshold was set. Irrigation practices and water use efficiency play a significant role in the per capita requirement.
Water Supply Stress Index WaSSI (2006)	Water supply stress is equated as the ratio of total water demand (water withdrawals) to total water supply for consumption.	When WaSSI > 1, then demand exceeds available surface and groundwater supplies. Water stress indicated when WaSSI > 0.4.

The evaluation and measurement indices of water scarcity has evolved and improved since the initial 1989 Falkenmark index. Several water scarcity indices now incorporate the variation in consumption patterns, the relationship between demand and population as well as the necessity of ensuring ecological sustainability (Brown and Matlock, 2011). To measure the region's water stress, a holistic evaluation approach is necessary to account for the environmental, social and economic sustainability (Mekonnen and Hoekstra, 2016). The water supply stress index is identified as a suitable measurement tool, accounting for both water demand and available supply sources.

2.2.1 Sustainability

The socio-economic development of the country is affected by the availability of water resources, with water shortages restricting development and economic growth of affected urban cities (Chang et al., 2015; Distefano and Kelly, 2017). Droughts and water shortages result in lower agricultural output, causing a loss in the economy as a result of lower food export, increased food costs and loss of employment which ultimately adds more people to the poverty line. Evidence to this is the 0.2% loss of economic growth as a result of severe water shortages caused by the 2015 drought in South Africa (Colvin and Muruven, 2017).

In urban cities, access to sufficient cost effective water sources is essential to instilling sustainable investment opportunities. High water costs, contested water resources and water shortages are risks to various economic activities (Guarino, 2016; Hertel and Liu, 2016) . As the decline in economic investments hinder employment opportunities, migration and water are causally linked. The loss of livelihood and high water cost caused by a shortage of water, result in the migration to areas with sufficient and affordable water supplies (Jagerskog et al., 2016).

The importance of ensuring a sustainable water supply is undeniable. Therefore, water is addressed at the highest level in South Africa, with the South African Constitution obligating local government to take responsibility for ensuring sustainable environments (South African Government, 1996). Section 24 in the Bill of Rights states that:

> *"Everyone has the right:*
>
> *(a) to an environment that is not harmful to their health or well-being; and*
> *(b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that:*
>
> *(i) prevent pollution and ecological degradation;*
> *(ii) promote conservation; and*
> *(iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development."*

Farming, mining, manufacturing and forestry are all of economic importance to South Africa, however the cost and impact of water use in these sectors need to be evaluated (Blignaut and van Heerden, 2009). Therefore, the direct cost of water resource and the indirect cost to the environment and society need to be calculated and managed to ensure the well-being of South Africa in the long run (DWAF, 1997). The Department of Water Affairs and Forestry, now known as the Department of Water and Sanitation, has set the nation's water goal as the assurance of equitable and sustainable access to the limited water resources, now and in the future (DWAF, 1997).

The 2017 World Wide Fund (WWF) report also identified four main goals for addressing water scarcity in South Africa, namely: 1) Water Conscious Country, 2) Strong Water Governance, 3) Strong Regulated Water Supply and Demand, and 4) Water-Smart Economy (Colvin and Muruven, 2017). These primary goals were proposed to address the issues relating to the shared water resources and the impact and risk associated with water scarcity in South Africa.

Therefore, Colvin and Muruven (2017) found that to address water scarcity in South Africa, the country must become water conscious with strong water governance, regulating the supply and demand of water to establish a water smart economy. Furthermore the 2017 WWF report, identified six feasible actions to shape the sustainable future of water in SA. The proposed actions are described in Table 2.2:

Table 2.2: Actions Towards a Sustainable Water Future in South Africa

Action	Description	Methods
1	Improve awareness of water scarcity	Education, campaigns, media platforms
2	Maintain water infrastructure	Develop skills and capabilities
3	Maintain and protect ecosystem	Innovate and fund initiatives to protect ecological infrastructure
4	Water pricing	Strategic tariffing and price modelling
5	Water reuse and reduce	Improve quality and scale of water reuse and develop efficient irrigation technologies
6	Increase information access	Data availability and information on user impact to be made available

Historically the management of water shortages were addressed on the supply side of the water value chain through augmentation schemes, bulk water resource development and additional water supply infrastructure (C. Chen et al., 2017). This approach alone is not sustainable or feasible. Consequently, a shift towards the implementation of alternative water sources and the management of water demand has taken priority (DWA, 2009).

To address the water shortage, several actions can be taken on the water supply and demand side. In South East Queensland, Australia, proposed actions on the supply side included the implementation of alternative water sources such as desalination, the installation of rainwater collection units, network transfer and the recycling of wastewater (Lam et al., 2017).

Furthermore, ensuring the sustainability of water resources are hindered by factors such as climate change, regulatory requirements and limited resources (Ahmad and Prashar, 2010; C. Chen et al., 2017; Marlow et al., 2013). According to the National Water Policy of 1997, water conservation and reducing water demand are popular options in South Africa for improving the sustainability of water resources (DWAF, 1997; Lam et al., 2017). Sa-nguanduan and Nititvattananon (2011) also found that the reuse and recycling of water and wastewater are feasible actions taken toward achieving sustainability As wastewater, once treated, can be returned to the system as an alternative supply, aimed at alleviating water scarcity (Sharawat et al., 2014).

Yet, the direct and indirect impact of actions implemented in the water system may present unexpected and unwanted results and costs (Lam et al., 2017; Marlow et al., 2013; Sa-nguanduan and Nititvattananon, 2011). The interaction of water flows and role-players within the water system are complex and behave dynamically over time and is further affected by the implementation of legislation and sustainability strategies (Kotir, 2017). Thus, a thorough understanding of the water system is required for the sustainable implementation of strategies and actions to address water scarcity (Chang et al., 2015). Rijsberman and Ven (2000) found that sustainable development and management is a complex problem, with various solutions.

2.2.2 Water as a Complex System

The urban water system does not behave according to specified performance criteria with predictable behaviour, but continuously change and adapt with no apparent linear cause-and-effect relationship (Ma et al., 2015). However unlike pure natural systems, the urban water system is designed and managed to perform a set function (Kotir, 2017; Smith, 2012).

The urban water system displays similar behaviour to that of a natural system, containing non-isolate parts, which form part of a complex network of elements and relationships that interact to function as a whole (House-Peters and Chang, 2011). The characteristics and relational factors of these interacting elements, attribute to the properties of the system in its entirety, as the system cannot be viewed realistically if elements are investigated in isolation (Capra, 1983; Schenk et al., 2009). The system should therefore, be viewed holistically to provide realistic insight into the impact of optimising one section of the water value chain, whilst avoiding the detrimental expense to the system as a whole (Dzwairo et al., 2010).

The behaviour and relationship among elements and role-players in the water system will continually change over time. Due to the dynamic nature of the water system, problems can become complex and overwhelming with an abundance of available information and data (Kim, 1999, Kotir, 2017). There are several methods and tools for evaluating and organising data and behaviour in a complex system (Kim, 1999). One method of dealing with available information is known as the Mechanistic Analysis or Newtonian method (Smith, 2012). This approach separates the problem into smaller individual parts, with each part analysed and studied separately. This method aims to further the understanding of how feedback among elements change the system over time. However, the Newtonian method only applies to simple linear cause-and-effect problems, which is not suitable for investigating and understanding the complexities in a urban water system (Kotir, 2017; Smith, 2012).

A second methodology for studying a complex system is systems thinking. This approach places focus on studying how the individual parts interact and influence each other within the system, to produce a pattern of behaviour (Kotir, 2017). In addition, the systems thinking approach addresses the connections and interdependencies in the complex water system to examine and provide understanding of the system as a whole (Kim, 1999). In complex systems, the unintended consequences need to be anticipated, therefore system thinking requires a level of flexibility and creativity to embrace the complexities and variable changes over time, brought on by feedback loops among the elements and role-players in the system (Hamdani et al., 2011; Smith, 2012).

The problems associated with water scarcity fall within the complex system environment, as the urban water system is comprised of a complex structure of components that interact among each other in an unique way. Therefore, addressing the problem requires methods and processes capable of evaluating the impact of implementing legislation and programmes, aimed at extracting sustainable value from the urban water system, to address the water shortage experience in the City of Cape Town. As complex system problems cannot be defined and understood in isolation, multiple perspectives are required (Dzwairo et al., 2010; Rijsberman and Ven, 2000). Multiple stakeholders and decision-makers are involved in the policy-making process, when addressing complex systems with integrated elements and subsystems (Dzwairo et al., 2010). Even with multiple perspectives and contexts, policymakers still struggle to formulate and understand the complex water system holistically, especially when sustainability management is the aim (Collins et al., 2007).

There is an abundance of literature aimed at addressing water scarcity and sustainable water management in urban water systems, yet each region presents unique challenges and objectives. Nonetheless, lessons can be learnt through critical review of programmes and models built to evaluate and support decisions for managing water systems in other water scarce regions. These findings form the basis for evaluating and implementing alternative actions through legislation, to ensure a sustainable future for the urban water system in the City of Cape Town.

2.3 Investigating the Urban Water System

Different aspects of the water value chain have been modelled and simulated for other water scarce areas such as Las Vegas Valley, California, China, South Africa, and Ghana. These models studied different aspects of the water system, including the energy use in the water system, the involvement of stakeholders in the water management system, water conservation, and wastewater reuse (C. Chen et al., 2017; Kotir, 2017; Stave, 2003). Although there are similarities in these studies, they differ in the scope, detail, variables and objectives. Thus, clearly defined objectives for the research studies are important as they ultimately determine the inclusions and exclusions for the model conceptualisation (Cronin et al., 2008). The literature search, using keywords, brought about relevant articles, listed in Appendix A.1, aimed at addressing methods and approaches for management and evaluation of water systems.

Lam et al. (2017) found that although alternative water sources, such as desalinated seawater, present as a feasible solution for reducing water shortages in South East Queensland Australia, the associated high energy cost had to be accounted for during the evaluation of alternative water sources. Yekta et al. (2015) also found that the implementation of desalination initiatives served as a sustainable solution to the shortage of drinking water in the Iranian City Qom, however, the cost of alternatives were not directly related to energy use as per the energy-impact study by Lam et al. (2017).

Although objectives and evaluation approaches differ, the findings are based on the critical evaluation of actions implemented in the applicable water system models, to support the decision making process aimed at alleviating water scarcity. Makropoulos et al. (2008) reiterated that in order for policy and strategies to be implemented effectively, a thorough understanding of the complex water value chain and its behaviour is required. A review of similar studies is conducted to extract useful concepts and methodology for addressing water scarcity in a sustainable manner in urban regions.

2.3.1 Addressing Water Scarcity in Literature

In Melbourne Australia, it was found that solutions to water scarcity brought about distress, health risks and inconvenience to customers in the urban area (Marlow et al., 2013). Reiterating the fact that the impact on cost and performance, as a result of changes in the urban water system, is often not intuitive and can lead to dynamic changes up and down stream in the water cycle (Marlow et al., 2013). Taking this into account, Marlow et al. (2013) emphasise the need for assessment and evaluation of alternative scenarios, against multiple criteria, for addressing the water scarcity experienced in the urban system.

With the introduction of alternative solutions to address water scarcity in the urban water system, several system challenges may arise (Marlow et al., 2013). Including when benefits promised by implemented actions, result in secondary costs with unpredictable and sometimes undesirable consequences (Marlow et al., 2013). It was also reported that decision making usually relied on criteria based on human judgement, which adds more intricacies to the decision making process, and can increase in complexity with an increase in criteria and alternatives (Kotir, 2017; Yekta et al., 2015). Therefore, the factor or degree to which actions impact the system, can be used as a measurement in the comparative analysis of scenarios (Marlow et al., 2013).

In the study conducted by Yekta et al. (2015) to evaluate alternative drinking water supply systems for the Iranian city Qom, the system criteria were defined as either cost-related elements or benefit-related elements, to incorporate the affect of actions over the whole spectrum of criteria for decision making. And in another water scarce region, Chang et al. (2015) investigated the evaluation of water resource security in expanding urban areas in China, through the analysis of different development scenarios. The urban development scenarios were measured based on the comparison of water consumption. Although both studies aimed to address the problems associated with water scarcity in urban regions, the problem objectives, alternative scenarios, measuring criteria and methods differ vastly. Therefore, conceptual ideas and guidelines can be extracted from these similar studies to use in the evaluation of policies and programmes aimed at addressing the water scarcity in the City of Cape Town.

Yekta et al. (2015) addressed the complex process of evaluating alternative solutions to satisfying the demand for drinking water in the semi-arid city, Qom, in Iran. A hierarchical method based on the multi-criteria fuzzy logic (MCDM) was used as a decision making tool to improve the recognition of similarities and discrepancies in human judgement. Taking into account the imprecise nature of human judgements, linguistic terms were used to represent imprecise data as an approximated variable (Kotir, 2017; Yekta et al., 2015). The linguistic terms are equated to a range of fuzzy values between 1 and 0, transitioning the qualitative description into quantitative data. Additionally, the assumption must hold that all criteria must be relevant to the full range of alternatives. Fuzzy logic is a risk assessment approach that uses a cost-benefit analysis and ranking, as a multi-criteria decision model, for scenario evaluation (Velasquez and Hester, 2013). The method is capable of evaluating or solving problems with imprecise and uncertain data and is therefore, difficult to develop and require extensive simulation runs (Velasquez and Hester, 2013). Both qualitative and quantitative data is required to model and evaluate the set of potential scenarios for decision making (Yekta et al., 2015).

Subsequently, fuzzy logic multi-criteria decision making approach requires the use of weighted criteria to simultaneously evaluate alternative solutions on a ranking basis (Yekta et al., 2015). All sub-criteria are categorised as either related to cost or benefit in the hierarchical structure under the main criteria. A variety of specialists are assigned as equal weighted decision-makers, to conduct the evaluation of alternatives and to assign the level of importance to each criteria and sub-criteria. Although traditionally only four main criteria points, namely: 1) social, 2) environment, 3) technical and 4) financial are included in similar evaluations, Yekta et al. (2015) added 5) public health and 6) occupational health aspects to the evaluation criteria to improve the effectiveness of the process (Kotir, 2017; Yekta et al., 2015). A point to note from the findings presented by Yekta et al. (2015), is the effect of technology and system dependency from foreign countries, when considering the technical aspects. Furthermore, the hierarchical criteria and sub-criteria used in the suitable water supply model can serve as a valuable reference point for model conceptualisation.

In Urumqi China, water scarcity has become a problem with the extensive growth in economic development and the expansion of urbanisation in the semi-arid urban region (Chang et al., 2015). Chang et al. (2015) investigated the evaluation of the water resource security in expanding urban areas, through the analysis of different development scenarios using a system dynamics model over a 24 year period. The measurement for the evaluation of urban development scenarios were based on the level of water consumption for comparison. Chang et al. (2015) found that important actions towards relieving water stress in Urumqi China included the reuse of wastewater and reducing sewage. Furthermore the study found that system dynamics methodology was well suited to model the complex water system, without over simplifying the problem and resulting in unsatisfactory decision support (Chang et al., 2015). The model also allowed for the time delay associated with response time in the water system.

The City of Urumqi has experienced rapid urbanisation in the last two decades, similar to the growing rate of urbanisation in the City of Cape Town, with total residence in Cape Town increasing from 2,9 million in 2001 to over 4 million in 2017 (Bronkhorst, Pengelly, et al., 2017; Provincial-Treasury, 2017). In the system dynamics model developed by Chang et al. (2015), the development of Urumqi in comparison to the carrying capacity of water resources for the urban city was evaluated for sustainable utilisation of water resources. The evaluation took into consideration the effects of climate change, industrial development and population growth. The modelling process initially required the researcher to get familiarised with the precipitation, population, structure and climate of the urban city on which the model is built (Chang et al., 2015). Nicholson (2007) also found the initial familiarisation modelling step valuable for developing a thorough understanding of the complex system to be modelled for evaluation.

Thereafter, the complex water system model had to closely correlate to the growth in population, the economy and the environment. For Urumqi, the developed urban water model was divided into two parent sectors, 1) Water Demand (WD) and 2) Water Supply with five subsystems, 1) Economic WD, 2) Social Life WD, 3) Ecology and Environment WD, 4) Water Resources and 5) Recycled Water. Each system and subsystem consisted of feedback loops, based on the influence and interaction among elements in the system

(Chang et al., 2015). The degree of water shortage for the model was defined as the gap between water demand and water supply. Chang et al. (2015) found the simple, yet flexible software VENSIM® PLE to provide the visualisation tool for modelling and simulating the relationships and behaviour among elements and subsystems in the urban water system. Whereas, C. Chen et al. (2017) employed *iThink*® 8 software to develop the system dynamics model for the Shanshan Country water system model.

For both studies, the model variables and data sources must be identified to construct the dynamic system model. These parameters includes the flow rates among variables, the constants and functions (Chang et al., 2015). The time frame selected for the model was taken from 2006 to 2030 (a 24 year time scale), which is the same modelled time frame of 24 years for the Shanshan Country in China (C. Chen et al., 2017). However, system dynamic models for water systems can be modelled over a much longer period, as per the green economy transition model for the Western Cape Province in South Africa, which was modelled over a time horizon from 2001 to 2040 (Pienaar et al., 2017).

The analysis of Urumqi found that the limited supply of water sources could not be exploited further. However, the opportunity of water conservation and reuse have not been optimally extracted, with only 37% of industrial water output being recycled. The analysis of the system dynamics model found that the current development is unsustainable resulting in social, economic and environmental issues (Chang et al., 2015).

The system dynamics flow diagram in Figure 2.1 serves as the basis on which the system dynamics model was built for the evaluation of urban water resources, under urban expansion in Urumqi, China. This stock-and-flow diagram illustrates the relationship among system elements and variables with the five model subsections in the two main categories of Total Water Demand (TWD) and Total Water Supply (TWS).

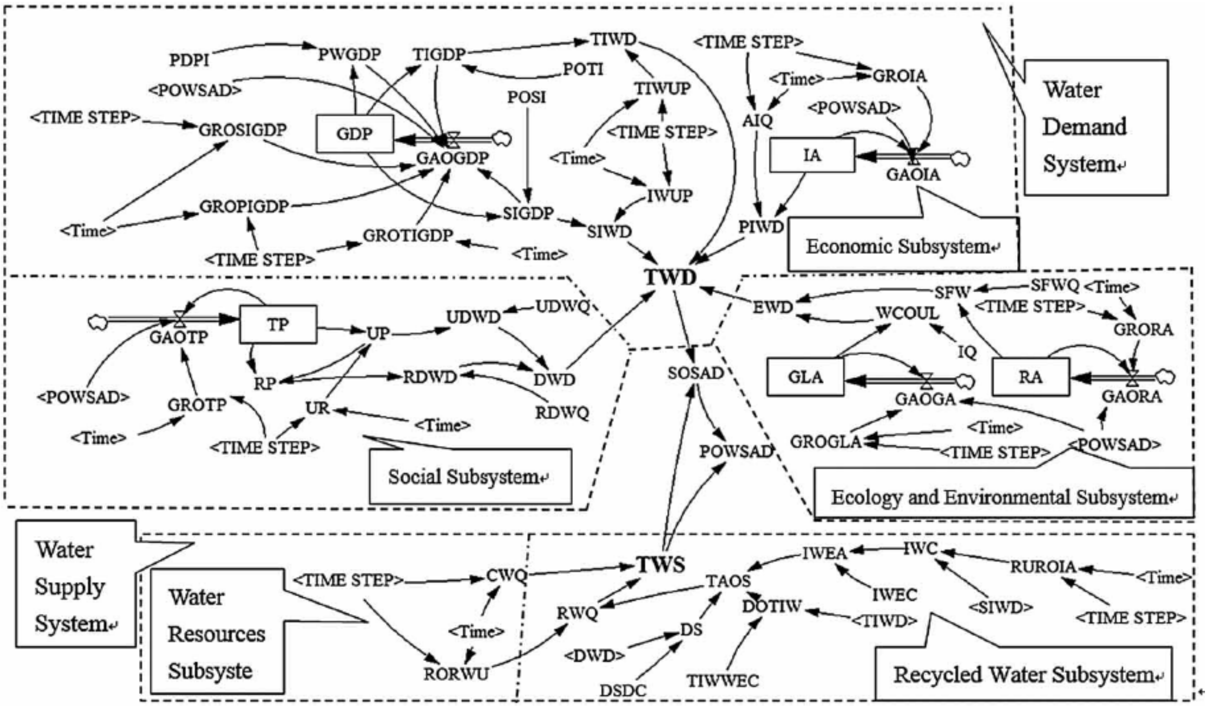


Figure 2.1: Flow Diagram Urumqi China

Another water system analysed to address water scarcity is modelled on the Shanshan Country, an arid inland region in the northwest of China, known for its overexploitation of groundwater (C. Chen et al., 2017). To address the associated environmental problems that occur as a result of the overexploitation of groundwater, C. Chen et al. (2017) developed a system dynamics model aimed at finding the best water resource management alternative and identifying the major factors affecting the response to implemented scenarios.

The low reuse of water, inefficient water-use and growing industrial demand for water were identified as the three main drivers of water problems in the Shanshan Country (C. Chen et al., 2017). Similarly, Chang et al. (2015) also identified the main drivers of water scarcity in Urumqi, China, to include population growth, inefficient water use and low levels of water recycling and reuse. Furthermore, the City of Cape Town experiences similar drivers for water scarcity problems. These drivers include the rapid urbanisation and increasing water demand, climate change, water loss in the system and limited alternative water sources (Bronkhorst, Pengelly, et al., 2017).

The Shanshan water supply and demand model was developed over the time scale 2006 to 2030, which aimed to provide insight into the behaviour and dynamic relationships among elements in the water system (C. Chen et al., 2017). C. Chen et al. (2017) found that water resources acted as a major constraint for socio-economic growth and environmental well-being. To manage the water resources, numerous policies were implemented in the Shanshan Country to restrict the industrial investment and to encourage efficient water use (C. Chen et al., 2017). As system dynamics models have successfully been implemented to facilitate and simulate policy options and decision making in the water sector, it was identified as the preferred tool for evaluating water resource management alternatives in the Shanshan Country (C. Chen et al., 2017).

Data for the system dynamics model was drawn from historical and official records and government sourced reports, with the model consisting of two main sections, *population and land use* and *water resource system* (C. Chen et al., 2017). Although the majority of water demand is driven by agriculture, the growing industrial sector drives the demand further. However principles in addressing the management and implementation of policy alternatives in the Shanshan research study can be translated to further studies, such as ensuring sustainability under rising urbanisation in the City. C. Chen et al. (2017) schematically structured the relationship and routes among the water supply and demand variables for the Shanshan Country water system in Figure 2.2. The relationship indicates that an increase in population, will lead to an increase in municipal water demand, as it was assumed that the demand per capita does not change during the model simulation (C. Chen et al., 2017).

Changes to the selected model parameters were made in 10% increments and the water shortage was compared to the status quo baseline scenario, with water shortage used as the measure of performance (C. Chen et al., 2017). Changes observes according to selected parameter-changes were then tabled and ranked (C. Chen et al., 2017). Thus, setting the baseline against which the implemented actions are modelled and measured, is a crucial step in the model development.

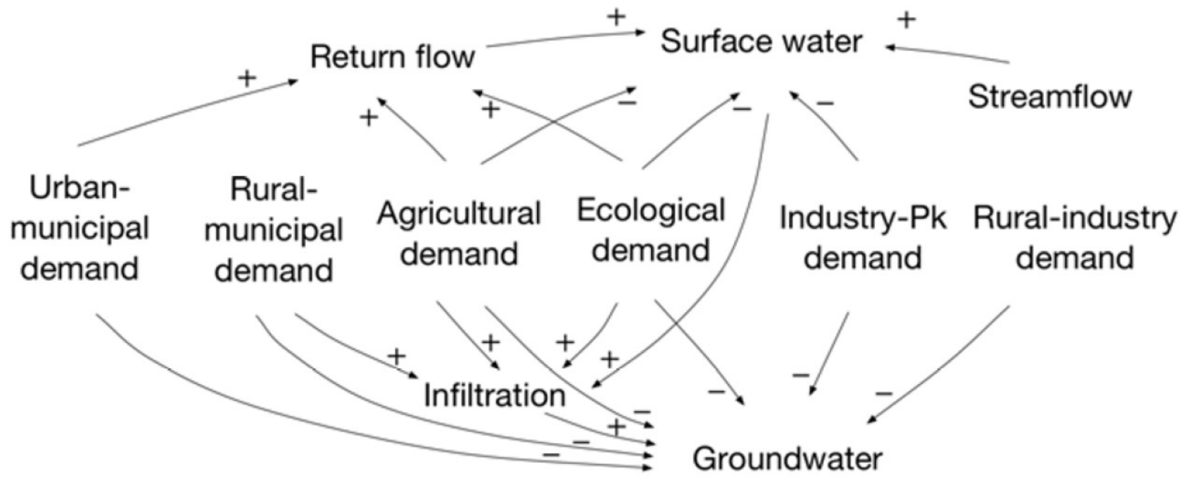


Figure 2.2: Shanshan Country Water Supply and Demand Variable Relationships

Urbanisation in the water system is a complex process with several potential influencing elements (Chang et al., 2015). An urban expansion index can be used to describe the urban development, taking into account factors such as population and economic growth, living standards, the environment, and infrastructure development (Chang et al., 2015). Furthermore, the index for urban expansion can be used to analyse the relationship with water resource security in the urban water system. In the Urumqi region the urban expansion index showed to increase with time, with each variable of the index increasing gradually (Chang et al., 2015).

As no other water sources are added in the Urumqi and Shanshan regions, the water reuse efficiency must be improved. Therefore, actions should be focused on exploiting the current outflow to draw value and conserve water (Chang et al., 2015; C. Chen et al., 2017). However, true to the complex nature of the water system, downstream impact of water saving scenarios reduced the pressure on the water system, which resulted in problems with sewage (Chang et al., 2015).

South East Queensland in Australia experienced severe drought between 2001 and 2009, leading to several water supply and demand responses (Lam et al., 2017). Using a life-cycle energy assessment, the paper largely examined the impact of supply side interventions on energy-use under different scenarios. Similar to Cape Town, the urban area is primarily supported by surface water sources and experience lower than average rainfall. Lam et al. (2017) focused on evaluating supply strategies and energy impact using an optimising simulation model, the Decision Support System Optimizer (DSSO). This model is used to test scenarios against categories, such as dry, high water demand or normal conditions, over a set time period. Scenarios for alternative water sources were evaluated on the basis of energy impact, while accounting for climate variability over a long assessment period (20 years) and using the conventional system as a baseline. The study emphasised the importance of assessing the quality of input data for transparency, ensuring that data sources are independent with a set method for data acquisition (Lam et al., 2017).

Additional to simulating the model, a Monte Carlo simulation was performed to quantify the uncertainty of input parameters (Lam et al., 2017). It was found that seawater desalination and potable water recycling are climate dependent sources and provide a mere 1% of total water supply to South East Queensland, while still resulting in high energy usage during minimum operation, using energy intensity (MJ/m^3) as a measurement (Lam et al., 2017). Rainwater tanks were found to be energy intensive and under-utilised, with tanks not internally-plumbed, the usage was found to be mostly limited to outdoor functions, which undermined the potential contribution to reducing water demand (Lam et al., 2017). The findings emphasised that the consideration of new water supply sources should be categorised as a source for regular use or drought operation, as the benefit of diversified water sources may result in high operation cost and energy inefficiency in "normal" conditions, when traditional water supply is sufficient (Lam et al., 2017).

The study conducted by Rauch et al. (2017) found that the total urban water system for Melbourne, Australia could be broken into two main sub-systems. The biophysical system, referring to urban development and water infrastructure, and the societal system that describe the linkage and functional relationship between agents. Rauch et al. (2017) presented an integrated water model aimed at dynamically connecting the biophysical and societal components. Although the system dynamics based model, Dynamic Adaptation for eNabling City Evolution for Water (DAnCE4Water), is limited to a sector of the urban water cycle, namely the stormwater management, the model has the ability to incorporate additional dimensions (Rauch et al., 2017). This model served as a tool to enable stakeholders to test alternative strategies and allowed for the exploration of future scenarios through an exploratory planning approach. The model aimed to identify suitable and robust water management strategies for a sustainable future by integrating water infrastructure, urban development and social systems (Rauch et al., 2017). The DAnCE4Water model in Figure 2.3, integrates the urban development, performance/evolution of water infrastructure and societal dynamics components into a single model for predicting system behaviour for long term planning and decision making under a range of future conditions.

In South Africa, the sustainability of water resources in the Western Cape Province play an intrinsic role in the transition to a Green Economy, which can be broadly defined as the process of improving the sustainability of the environment, economy, and society (Pienaar et al., 2017). The study found that water management structures and authorities are central to the sustainability of scarce water resources for the Western Cape's transition to a green economy (Pienaar et al., 2017). The study applied system dynamic methodology, to develop and evaluate the urban water model in Figure 2.4 for the Western Cape Province. The objective of this model was to provide insight and decision support with regards to the implications of management intervention and investment scenarios (Pienaar et al., 2017). The model was constructed using VENSIM® software and used historical data and trends to confirm the validity of the constructed model for the Western Cape water sector, which is similar to the approach taken by Chang et al. (2015) in the evaluation of water scarcity in Urumqi. It was found that the system dynamics model allowed for multiple role-players and complex behaviour to be evaluated as a whole, bringing society, economy and environmental systems together (Pienaar et al., 2017). Subsequently, the model results indicated that the Western Cape Region might face critical water shortages if sustainable water management and investment are not implemented in the current water system (Pienaar et al., 2017).

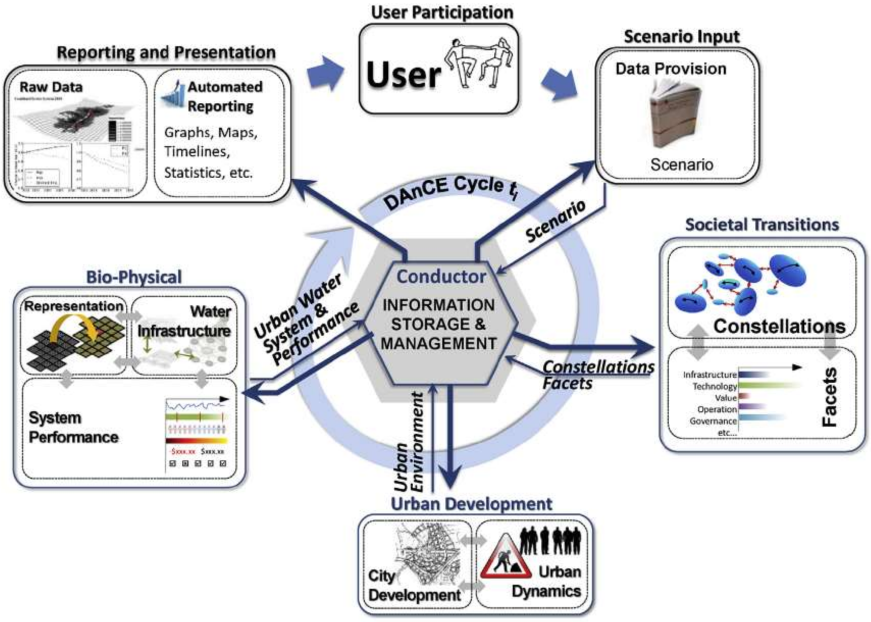


Figure 2.3: Components of the Dynamic Adaption for eNabling City Evolution for Water (DAnCE4Water) Model

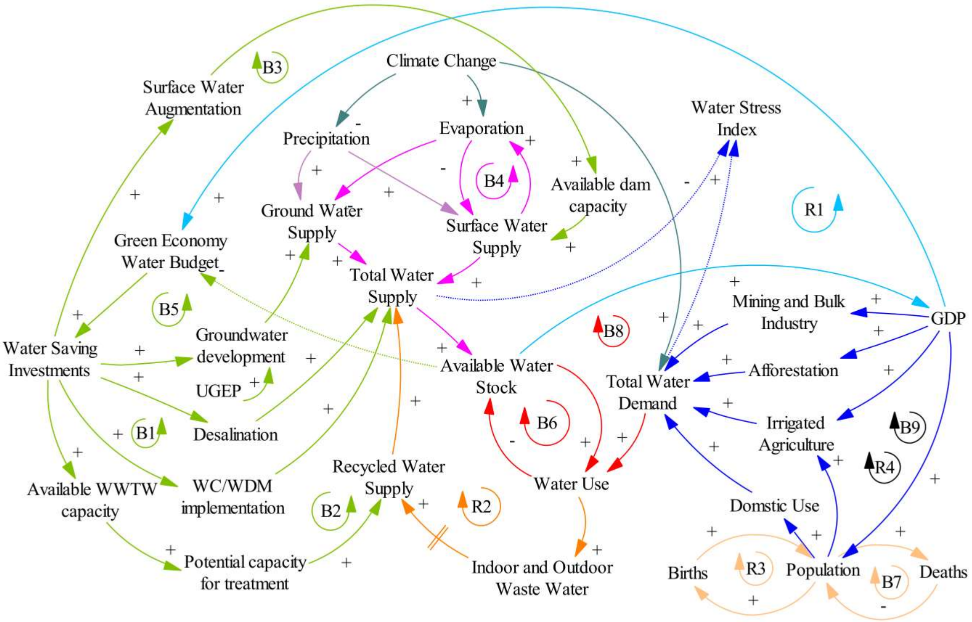


Figure 2.4: Western Cape Transition to a Green Economy: Water Resource Model

These evaluation methods should serve as decision support for dynamic criteria over a time period, which might be challenged by management complexity, resistance to change and performance uncertainties (Armitage et al., 2014; Marlow et al., 2013). A critical factor for ensuring urban sustainability is the effective management of water, as water plays a vital role in the well-being and growth of the economy, society and the environment (CoCT, 2017b; Marlow et al., 2013).

2.3.2 Water Management

Water management refers to the human intervention with regards to water resources, which include the use and exploitation of water resources, the conservation, protection and restoration of water bodies as well as the protection of infrastructure and society against water related disasters, such as flooding (Dimova et al., 2012). Forrester (1992) agreed that management is defined as the process of converting data and information into action or intervention. Thus, water management must continually adapt to address the challenges associated with population growth, environmental sustainability, socio-economic strain and climate change (Marlow et al., 2013).

Although the challenges differ for each urban region, the reality exists that water service providers are faced with the task of delivering quality water services under constrained budgets, population growth, environmental and socio-economic strain and climate change (Marlow et al., 2013). The collective term for the well-being of the environment, society and sustainable development have been labelled as "green issues", that together with legislative development, reflect the vulnerability of the environment to human interference (Bartone et al., 1994; Marlow et al., 2013).

Traditionally, heavy investment in water infrastructure and water supply systems have been used to address water shortages (Schenk et al., 2009). However these have had detrimental and unexpected effects on the environment, society and economy (CoCT, 2017b; Lam et al., 2017; Schenk et al., 2009). Furthermore, global water supplies have not been able to keep up with the rising demand (Nahal, 2014). Makropoulos et al. (2008) and Schenk et al. (2009) agree that new, more sustainable and integrated approaches towards water management are taking precedence over the traditional sectoral way of managing the water cycle.

The concept of sustainable urban water management (SUWM), is not a recent development, but one that has been evolving over the last three decades, with Hengeveld and De Vocht already discussing the concept in 1982 (Hengeveld and De Vocht, 1982). Subsequent to this, the SUWM concepts and principles were scrutinised by Marlow et al. (2013) in a critically review of the paradigm, to identify the strength and limitations of the model when addressing complexities in the urban water system.

Traditional methods of urban water management were developed in a stepwise manner, from initially providing only basic water services through piped water to the drainage and treatment of wastewater through sewage treatment, separation sewers and drainage systems (Makropoulos et al., 2008; Marlow et al., 2013). The drivers for this development of urban water systems and management paradigms can be attributed to the growing population in urban areas with associated demand increases, growing waste production, health impacts and degrading water resources (Marlow et al., 2013).

The escalating cost and complexity of infrastructure and water systems have led to the centralisation of management and funding (Marlow et al., 2013; Rauch et al., 2017). Therefore, the SUWM paradigm suggests an integrated approach to water management for the most efficient use of water resources and value extraction at all stages in the water cycle (Farrelly and Brown, 2011; Marlow et al., 2013). C. Chen et al. (2017) agree that an integrated approach to water resource management serves as an important tool to address challenges and concerns associated with water scarcity. Therefore, integrated urban water management falls under the umbrella SUWM paradigm for the transition to a more sustainable water future (Marlow et al., 2013).

Benefits associated with centralised urban water management for sustainability include the enhanced security of water resources through diversification and the efficient use of water resources in a more natural water cycle (Makropoulos et al., 2008; Marlow et al., 2013). The cost reduction associated with more efficient water management can be attributed to the minimisation of energy, water and chemical use (Marlow et al., 2013). However, management must consider the resistance to changes in the water system as the potable reuse of treated wastewater may result in significant resistance from customers (Hurlimann and Dolnicar, 2010).

Furthermore, the loss in revenue associated with the utilisation of alternative sources of water and a reduction in demand, will impact the revenue income for water service providers. Resulting in lower billable revenue with a higher portion of customer contribution dedicated to infrastructure costs (Marlow et al., 2013). The cost saving is therefore, not necessarily reflected in the cost to customer, decreasing the incentive to accept the sustainable management concepts (Marlow et al., 2013).

Unfortunately frameworks for evaluating the effectiveness of implementing holistic management programmes are lacking (Schenk et al., 2009). Jeffrey and Gearey (2006) agree that the practical benefits of implementing integrated water resource management have not been sufficiently tested against theory. The combination of interacting variables and concepts form part of the integrated water value system, including governance and administration (Mitchell, 2006). Farrelly and Brown (2011) also found that the effectiveness of existing SUWM policies are hindered by the transition process from concept to practical application. Numerous water management related issues with their variable feedback and interaction have been investigated. However, to identify opportunities and gaps in the value chain a holistic approach to system evaluation is required (Schenk et al., 2009). Therefore, an integrated systems approach is found to be a potentially suitable application to water management for the achievement of economic, social and environmental goals as set out in the South African Constitution.

2.3.3 Integrated Water Resource Management

The tendency to address the economy, environment and social development and problems in isolation does not allow for compatible objectives and sustainable development (Dzwairo et al., 2010; Makropoulos et al., 2008). Therefore, actions and decision taken today should not be done in ignorance and isolation as the consequences will stretch throughout the system, affecting the future development and well-being of the economy, society and the environment (Dzwairo et al., 2010).

Governing institutions should not fail to recognise the need for understanding the water sector as an interconnected system that requires the decision making process to consider the sustainable development of integrated sectors, such as the economy, the environment and society (Dzwairo et al., 2010; Loucks and Beek, 2017). Schenk et al. (2009) and Makropoulos et al. (2008) found that integrated water resource management (IWRM) considers the different uses of water resources together with sustainability in mind. Consequently the National Water Act of 1998 recognises the need for integrated management of water sources in South Africa, yet water as a natural system is under pressure (Claassen, 2013; Harpe and Ramsden, 2000).

Water users and sources have proven to be in conflict with one another, especially in water scarce areas where the water reserve required to protect the natural ecosystems, are under threat (Rijsberman and Ven, 2000). As per the 1998 National Water Act, great emphasis is placed on achieving the social good, however the economic and social benefits are short term as the sustainability of water resources have been compromised to a certain extent (Claassen, 2013).

Schenk et al. (2009) described the urban water system as a complex system, with internal and external variables that behave and interact in dynamic ways. Even external variables play a role in the behaviour and response of the water value system and should be included in the integrated approach to water management and decision making (Schulenberg, 2007). Ryu et al. (2012) reiterates that external variables form part of the complex water system and must be accounted for. In support of this, Ryu et al. (2012) found that these external drivers of the urban environment are non-stationary and require a more flexible system to cope with changing conditions. As the urban water system evolves gradually, the dynamic process of system-evolution can, therefore, not be explained by narrow assumptions and linear cause-and-effect relationships (Rauch et al., 2017).

Government entities, including in South Africa, require competent people and suitable tools to address the provision of water resources in an equitable and sustainable manner, while considering the complex integrated socio-economic and environmental aspects (Dzwairo et al., 2010). Claassen (2013) identified that there are gaps in the methods and mechanisms for decision support and monitoring in the South African's integrated water resource management structure and governance that must be addressed to achieve system wide sustainability. Schenk et al. (2009) also found that IWRM evaluation frameworks were generally lacking in some departments. Claassen (2013) agrees that IWRM aims to ensure a sustainable future, through coordinated and integrated water governance, however achieving sustainability requires strong institutional support. Although the social and economic value of water are inherent in the South African practices and policies and the need for participation is addressed, the complete system view is still needed as no legislation in South Africa addresses the water system as a whole (Claassen, 2013).

For the successful transition to a holistic approach, the challenges associated with decision support for interrelated systems need to be addressed, these include motivating stakeholder participation and linking measurements to actions (Dzwairo et al., 2010). Claassen (2013) and Tippett (2005) agree that stakeholders must be encouraged to view decision implications over the entirety of the systems lifespan and to improve the decision process through participation.

Although an integrated management approach aims to incorporate all relevant sectors in the water value chain, Dzwairo et al. (2010) found IWRM to be reductive in nature, with an tendency to break the complex system into simple subsystems that can be fully understood. Alternative approaches such as Systems Thinking (ST), aim to address the complex system problem in a truly holistic manner, recognising the complete system as a whole, and not a sum of subsystems and parts (Dzwairo et al., 2010). To ensure equitable and sustainable division of water sources in urban regions in South Africa, potential alternative decisions and policy actions for integrated water management should be evaluated over an extended time period. The results and findings should provide urban water system insight and behavioural patterns which may serve as decision support to governing authorities and stakeholders.

2.3.4 Decision Support for Integrated Management

The process of decision making involves a set of alternatives from which a decision-maker must choose to achieve the desired outcome or result (Lunenburg, 2010). With the importance of decision making being based on the significant effect such actions will result in (Lunenburg, 2010). The complex urban water system requires a decision making process capable of dealing with the inherent socio-ecological and socio-economic complexities (Elsawah et al., 2015). According to Elsawah et al. (2015) such a decision support system must be multi-actor, multi-scale and dynamic. Therefore, the decision support model must account for multiple actors, different strategies and objectives as well as multiple levels of outcomes that affect various actors within the system (Elsawah et al., 2015; Lunenburg, 2010).

The literature on evaluating decision impact in the urban water system emphasised the need for evaluation criteria and assessment measures (Marlow et al., 2013). The response to various changes in process actions do not result in equal reaction, therefore the process of decision making and policy implementation cannot be seen as a linear system (Forrester, 1992). In support to this, Hamdani et al. (2011) and Rauch et al. (2017) found that complex behaviour of urban water systems cannot be explained with linear solutions.

One of the shortfalls in the sphere of water value chains is that there is often insufficient data, unclear processes and fractional governance (2030 Water Resource Group, 2009). Thus the decision support model should allow for model boundaries, inclusions and exclusions (Cronin et al., 2008). Model expansion and inclusion, as well as the ability to test various future conditions, were requirements set for the decision support model used to plan infrastructure in Melbourne Australia in an integrated manner (Rauch et al., 2017). In addition to this, the model had to allow for the integration of social aspects with the performance of water infrastructure (Rauch et al., 2017).

The literature showed that several techniques and methodologies, aimed at supporting decision making for addressing water scarcity, have been used to evaluate and measure the performance and appropriateness of sustainable supply and demand side interventions. To quantify the potential savings in the water system, a systems approach that measures the reduction, reuse and retention of water in the total water system is required (Hieminga, 2017). Furthermore, literature found that losses are prevalent in the urban water value chains due to a lack of total system understanding, fractional policies and ineffective allocation of funds (2030 Water Resource Group, 2009). As the water value chain is circular and integrated in nature, the systems approach of circular economy is a fitting alternative to sectoral and linear water management.

2.4 Circular Economy

Traditional linear economy models that follow the *extract*, *use*, *waste* approach, have been found unsustainable and are characterised by several challenges (Balabanis, 2015; Stahel, 2016). These challenges include constrained natural resources, increasing demand, cost of resources, environmental impacts and reduced water quality (Vullierme, 2017).

Consequently, the circular economy concept is an alternative model, that aims to draw value from all facets in the value chain and advance the performance of resources (The Ellen MacArthur Foundation, 2013). This transition from linear water management to a circular economy model has the potential to unlock value embedded in the water value chain (Money, 2017). Carden, Ellis, et al. (2016) also suggested an alternative approach to traditional water management, which aim to transition from a *water-wasteful* culture to a *water-sensitive* culture in South Africa. The study focussed on the engagement of stakeholders, information exchange and learning with a Water Sensitive Design (WSD) programme (Carden, Ellis, et al., 2016).

Ellen MacArthur Foundation and McKinsey emphasised in the 2013 report *Towards the Circular Economy*, that thinking in terms of systems is crucial to a circular economy (The Ellen MacArthur Foundation, 2013). The report stated that what differentiates circular economy from a traditional linear resource management approach, is that the circular economy principles allow for the creation of internal value and opportunities, which are driven by four sources (The Ellen MacArthur Foundation, 2013). These sources include:

1. **Power of the inner circle** → Minimise resources used
2. **Power of circling longer** → Maximise usage time and cycles
3. **Power of cascaded use** → Diversify reuse in the system
4. **Power of pure circles** → Avoid contamination and maintain quality

Stahel (2016) found that circular economy models can be categorised in two groups. The first focus on reusing and extending life cycles and the second focus on the re-purposing and recycling of resources. Both these models find relevance in the four power sources. Therefore, the power in a circular economy approach lies in the reduction of resource intake, by exploiting internal system resources, while striving to become a closed loop system (The Ellen MacArthur Foundation, 2013).

Makropoulos et al. (2008) found that the categories in the urban water cycle are 1) water supply, 2) wastewater disposal, and 3) stormwater drainage, which are traditionally considered separately. However, for a sustainable future, the subsystems in the water value chain can no longer be viewed in isolation. Therefore, exploiting interacting streams among these isolated systems, by extracting value and retaining by-products, require an integrated approach as the potential value of utilising these so called waste streams are foregone in an isolated system (Makropoulos et al., 2008).

Balabanis (2015) also found that water takes on three roles, however the focus was in context to circular economy. Water can be categorised as either, 1) a resource, 2) a product input or 3) a waste stream. Thus, the system role-players are divided into the three groups as illustrated in Figure 2.5. This figure has been adapted from the water use system in the 2015 EcoWater Project (Balabanis, 2015).

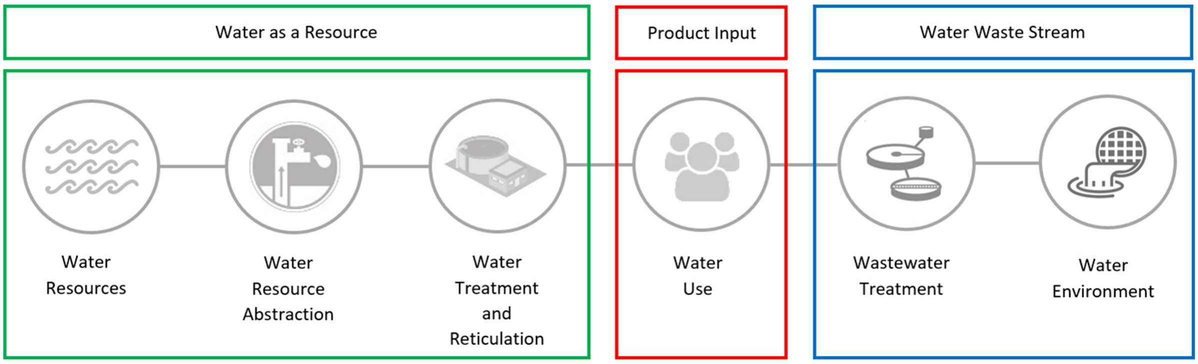


Figure 2.5: Water Roles in Circular Economy Model

The first role in the system was identified as *water as a resource*. The sources of water for the City of Cape Town include: 1) surface water, 2) groundwater, 3) rainwater and 4) retreated water (van Rooyen and Versfeld, 2010). These correspond with water sources identified for other water scarce regions such as Bangalore (Drangert and Sharatchandra, 2017). Alternative water supply sources, such as desalination are potential contributors, however at present the percentage of water added to the total water supply is negligible in the City of Cape Town (Hieminga, 2017; Pienaar et al., 2017).

The second role, *the product input or user*, controls the demand for water resources. When water supply reaches its limit demand cannot be met resulting in regional water stress (Drangert and Sharatchandra, 2017). Therefore, opportunity for reducing water stress lies in addressing the usage habits of the second role. Methods for managing the demand of users include progressive water tariffs, water restrictions, pressure management, campaigns and educational programmes (Bianco, 2018; van Rooyen and Versfeld, 2010). The cost involved in implementing these programmes and strategies must be taken into account as well as the potential loss of income revenue obtained from contributing users (Drangert and Sharatchandra, 2017).

The final role, the *water waste stream*, plays a crucial part in the water strategy (Drangert and Sharatchandra, 2017). Bianco (2018) found that wastewater is one of the largest untapped resources in the water value chain. Furthermore, waste can be defined as a pillar of circular economy (Hieminga, 2017; Murray et al., 2017). The capacity of wastewater treatment plants limit the amount of wastewater treated for reuse or safe disposal. In addition, damaged infrastructure results in wastewater flowing into stormwater drains impacting the quality of groundwater and surface water through pollution. Thus, the cost of maintaining, operating and service provision for the treatment of wastewater is high according to Drangert and Sharatchandra (2017). Two-thirds of the total water bill should accounts for these costs. Measuring factors for the waste management strategy include capacity of treatment plants, cost of service provision, total recycled water and total wastewater entering the system.

Consequently, circular economy promotes innovation and opportunities in the water sector (Hieminga, 2017). According to the 2017 Urban Water Service Report for the City of Cape Town only 5% of portable water was treated and reused for irrigation or industrial application (CoCT, 2017d). Additionally the 2017 GreenCape Water Market Intelligence Report indicated that 9% of all water supplied to the system account for real losses due to faulty water infrastructure (Bronkhorst, Pengelly, et al., 2017). This translates to 9% of all treated water in the system being lost as non revenue water. These identified opportunities require investment, strong governance, innovation and participation from all stakeholders to draw as much value as possible from the scarce water resources in the City of Cape Town.

Although large companies, such as SABMillers and Coca Cola, are currently implementing circular economy principles to use water sustainably and to add value throughout their operation chain, the circular economy approach is not without its pitfalls (WWF-UK, 2009). Hindering regulations and unclear market conditions are some of the transitional challenges experienced (Sagen and T. Williams, 2016). Other barriers include the resistance from users and service providers, the lack of knowledge and know-how for the implementation and management of such a system as well as the investment cost thereof (Balabanis, 2015; Stahel, 2016). Additionally, quantifying the impact of water shortages and the benefit of implementing circular economy principles in the water value chain is a difficult task (Hieminga, 2017).

Limited resources, high demand, urbanisation, cross sector cooperation and a change in consumption patterns are key drivers toward the implementation of a circular economy model in the water sector (Vullierme, 2017). As water is closely linked to the growth and health of economic performance and social well-being in the City of Cape Town, the sustainability of water resources receive high priority (Bronkhorst, Pengelly, et al., 2017). However, it should be noted that conflicting interest may arise among role players in the water value chain (Rijsberman and Ven, 2000; Vlachos and Braga, 2001).

Circular economy implementation in the water value chain does not only recover water resources, but additional resources are extracted from the water value chain for other purposes, such as energy generation and nutrients from water waste (Hieminga, 2017). The International Water Association (IWA) found that circular economy, in addition to improving water demand management and reuse techniques, can be used to diversify resources (Sagen and T. Williams, 2016).

It is evident that a systems approach with integrated management is required to identify lost opportunities in the current urban water cycle for the City of Cape Town. Through the implementation of principles embedded in the circular economy model, waste can become an opportunity for economic and social growth with sustainability in mind. Additionally the IWA found that consumers, regulation, economies and environment protection serve as the drivers for the transition to a circular water economy (Sagen and T. Williams, 2016).

2.4.1 Circular Economy Principles in Water Management

Bangalore, India, is one of the urban regions experiencing erratic water supply due to growing water shortages in the region as a result of urbanisation and population growth (Drangert and Sharatchandra, 2017). Opportunities for addressing the looming water crisis were explored using a “flexible water balance” dynamic approach aimed at exploring the interaction among water supply sources to identify opportunities for reuse, reduce and treatment of water in the system (Drangert and Sharatchandra, 2017). The aim of the study was to provide local government with options and support for identifying and implementing policy action that endeavour to avoid overuse and the extension of resource boundaries, while not compromising the environment, social health and comfort as well as the economy (Drangert and Sharatchandra, 2017). Water resource management is traditionally split among two policies, water supply management and water demand management. However, a third more recent policy, reuse management, has become prevalent in urban areas such as Bangalore (Drangert and Sharatchandra, 2017).

Water supply management responds when users *ask for more*, which results in a moving target as population increases (Drangert and Sharatchandra, 2017). This leads to the management of water demand, which aims to restrict the per capita use of water. Demand management wants to know *what do users do* with the supplied water and if the amount at the user's disposal can be reduced without compromising well-being and comfort (Drangert and Sharatchandra, 2017). The third policy, water reuse management, looks at *what users add to* the water during use and whether the amount of contaminants can be reduced for treatment and reuse.

The model addressed shortcomings in the Bangalore water balance knowledge field, incorporating the groundwater sources, run-off water, water resource extraction from surface sources and water waste. Water shortages in the region led to water supply becoming erratic with potable supply provided for a few hours every couple of days (Drangert and Sharatchandra, 2017). Thus, traditional policies for management of scarce water sources are not sufficient and attention must be given to the new emerging reuse management of the water strategy. These interventions should be innovative, sustainable and cost efficient, which requires the management approach to become removed from traditional approaches. Decentralised treatment and plumbing are potential solutions to reducing water treatment requirements in-turn preventing the overflow of untreated wastewater to be disposed of in stormwater drains, impacting the quality of groundwater and surface water sources (Drangert and Sharatchandra, 2017). Sgroi et al. (2018) agree that decentralised water reuse systems often add more sustainable value than centralised system, increasing the potential water conservation and reducing costs and wear on centralised water infrastructure.

Furthermore, the Sustainable Development Goals (SDG) require committed governments to reduce the fraction of untreated wastewater and to increase the safe reuse in an sustainable manner (Gounden, 2018). The circular economy concept aims to address the unexploited value embedded in used water whilst simultaneously decoupling economic growth from finite water resources (Gounden, 2018). The International Water Association reports on the efforts of several global cities aimed at addressing wastewater challenges and opportunities for reuse in light of zero-waste principles. Durban, South Africa, is one of the cities found to have adopted innovative solutions to water recycling, reclaiming approximately 47.5 million litres a day for predominantly industrial consumption (Robbins, 2004). Subsequently, lowering the demand for municipal water sources whilst simultaneously reducing pollution and wastewater discharge into the environment.

This integrated systems approach allows for the extraction of value from the urban water system, to not only provide additional water sources, but also to extract energy value and improve sustainable water management in urban areas (Jeffrey and Gearey, 2006). In the research study, the flexible water balance model closely represents the key principles of circular economy for urban water systems, which aim to intentionally extract value from the system to reduce the pressure and extraction of external resources. It should be noted that the flexible water balance model required an in-depth understanding of the system behaviour and structure, before construction and evaluation for reuse potential could be conducted.

2.4.2 Extracting Value from Urban Water Systems

Removing waste elements in the water value system not only reduces the usage and water lost to the system, but also reduces the risk associated with the unavailability of usable water and, therefore, the risk to the economy (The Ellen MacArthur Foundation, 2013). According to Maani and Cavana (2007), the first phase of implementing a systems thinking approach is to structure the problem, which requires a understanding of the environment and the system in which the problem lies.

Therefore, a basic overview of the hydrological cycle for the City of Cape Town is the first step in formalising the water value chain and its interactive components. The October 2017 report on the urban water cycle and services for the City of Cape Town forms the basis on which the water system is presented. The system components and water services for the City of Cape Town are represented by fourteen stages in the urban water cycle, illustrated in Figure 2.6 (CoCT, 2017d).

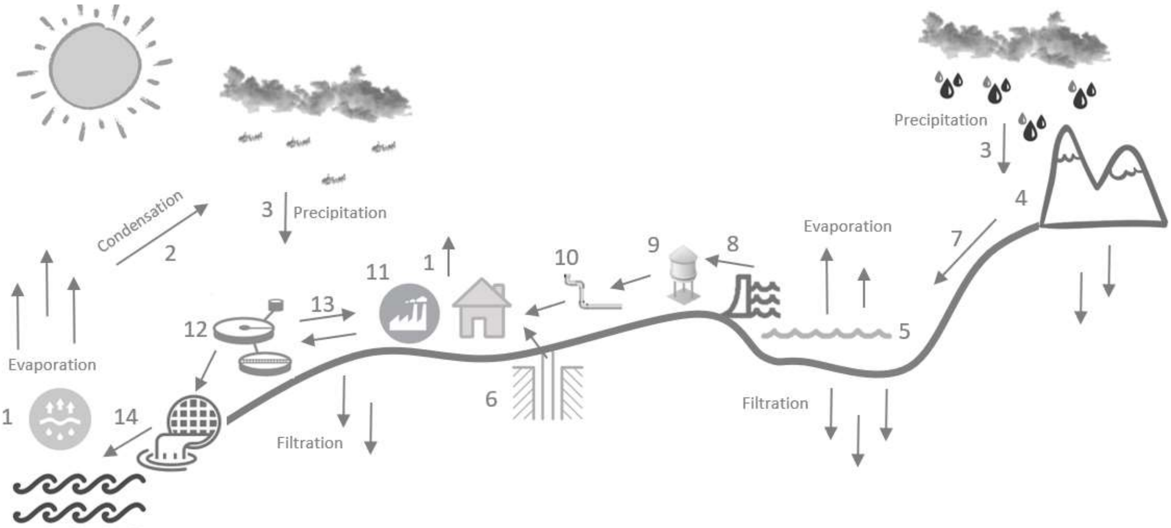


Figure 2.6: Urban Water Cycle for the City of Cape Town (Adapted from the CoCT Urban Water Service Report)

Rain in the City of Cape Town comes predominately from clouds formed by water vapour that has evaporated from the Atlantic Ocean (stage 1). What is more, evaporation can also occur on land, from plants, rivers, reservoirs and even skin. Condensation is the process of water vapour changing to its liquid form (stage 2). Clouds are made up of a number of water droplets, formed by water vapour that has cooled down to condense into liquid water. Precipitation can be in the form of rain, dew or snow and is Cape Town's main source of water (stage 3). Precipitation is notably higher in the mountainous areas from where the water moves down into streams and rivers. A portion of the water is captured in dams for storage and the remaining water is returned to river systems (stage 4) or filtered down to aquifers (groundwater). The stored water in the catchment area provide approximately 98% of the City's raw (untreated) water (stage 5). Whereas, groundwater attributes to the remaining 2% of drinking water for the City of Cape Town (stage 6). (CoCT, 2017d)

The water value system is a complex network of dams, pipelines and treatment facilities governed and managed by the National Department of Water and Sanitation and local governance for the City of Cape Town. Decision making with regards to alternative water resources and water management require cooperation among all stakeholders and role-players. Six major dams supply 99.4% of surface water to the Western Cape Water Supply System (WCWSS) (Bredell, 2012). The Department of Water and Sanitation owns and maintains the three largest dams Voëlvlei, Theewaterskloof and Berg River dams. The remaining dams are owned and managed by the City of Cape Town (stage 8). The WCWSS is an integrated system of dams, pipelines, pump stations and tunnels aimed at optimising the use of water resources while allowing for the transferral of water between dams and catchment systems as required. (CoCT, 2017d)

Groundwater is recharged through seepage of rainwater into the ground. As rivers do not form in sandy areas, underground water bodies known as aquifers are formed as a result of infiltrating rainwater. Areas such as Atlantis in the City of Cape Town are dependent on groundwater as a source of drinking water (Bugan, Jovanovic, Israel, et al., 2016). In other areas groundwater is a source of irrigation for farming. Municipal facilities and urban housing also rely on the City's aquifers for irrigation and consumption (stage 11). Water, not filtrated through the ground, gather in streams and rivers and run off into the ocean, many of which form estuaries (river mouths) and marshlands (stage 7). (CoCT, 2017d)

Raw water is treated at water treatment plants. In 2017 the City of Cape Town had a total of 12 treatment plants. The treatment capacity ranges from 31 Ml per day to 500 Ml per day per facility, all complying with national standards for drinking water quality (CoCT, 2017d). Collectively an estimated 1600 Ml of water can be treated daily by the City of Cape Town's treatment works (stage 8) (CoCT, 2017d). Once water is treated, it is transferred to bulk-and distribution reservoirs (stage 9). These reservoirs play an important role in the water reticulation system, addressing the fluctuating water demand throughout the day. Reservoirs are generally positioned at an elevated height to provide the right pressure in the water pipes. (CoCT, 2017d)

The reticulation system for the City of Cape Town is the water distribution network responsible for distributing potable water to consumers through pump stations, reservoirs, pipelines and connections (stage 10). The reticulation system is also responsible for the transfer of wastewater to treatment stations. Subsequently, the City is responsible for keeping the reticulation system operating, costing the city over R6 billion annually (CoCT, 2017d). The growing population in the City of Cape Town continuously require new connections to provide water and sanitation services to these users. In formal properties water is billed according to water usage as recorded by meter readings. In 2016 and 2017, 55.6% of potable water consumption could be attributed to formal housing consumers. (CoCT, 2017d)

Wastewater from consumers are treated at wastewater treatment plants in the City of Cape Town to ensure that wastewater discharged to the environment is safe (stage 12).

The quality of treated wastewater is monitored and must be comply with national standards. However, the City of Cape Town currently limits the use of treated effluent to irrigation and industrial use. In 2017, approximately 5% of water used was recycled for reuse (stage 13). The remainder of the wastewater, which is largely untreated, is discharged deep into the ocean through marine outfalls (stage 14) or natural water bodies. (CoCT, 2017d)

In 2015/2016, 70% of potable water used in the City of Cape Town was attributed to total residential use (CoCT, 2017d). Therefore, changing the behaviour and water utilisation habits of city residence will have a significant impact on the water demand. The urgency and effectiveness of water demand management will affect the total water demand of the City, extending the timeline for when the total water demand will exceeds the total water yield.

Various non-potable demands for water in the urban area can be met through alternative water sources to further reduce the demand for treated water in the CoCT (Marlow et al., 2013). With regards to the reticulation infrastructure, in 2010, the water loss through the City's distribution system was estimated at a staggering 79 000 million litres per year due to leakages and burst pipes (CoCT, 2011).

More opportunities lie in the waste stream as only 5% of wastewater is currently being treated for reuse in the City of Cape Town (CoCT, 2017d). With spare capacity of the water treatment plants estimated at 55% according to the May 2017 Business Briefing on the current water supply situation in the City of Cape Town (Flower, 2017).

The reuse of waste in the water cycle may lead to innovative alternative uses, business opportunities and energy extraction, adding to the economic potential (Hieminga, 2017). Additional conservation and value can be drawn from the retention of water through rainwater harvesting, using water saving techniques in gardens and farming such as insulating top soil or retention of lakes or wetlands as natural reservoirs (Fisher-Jeffes, Armitage, et al., 2017; Hieminga, 2017). However, research conducted by Armitage et al. (2014) and Fisher-Jeffes, Armitage, et al. (2017) investigate the application, performance and limitations of rainwater harvesting systems within regions of the City. The study found that due to the cost of installing and maintaining rainwater harvesting systems, the catchment area for runoff and end user consumption are to be maximised for economic feasibility. The research found that the use of harvested rainwater for toilet flushing has the potential to significantly reduce the domestic water demand.

Further research by Emmons et al. (2013) and Fisher-Jeffes, Carden, et al. (2017) report on the environmental and societal benefits stormwater harvesting can provide to urban regions. What is more, technology and engineering potential lie in the development of techniques for recycling and retreating used water to expand reuse opportunities (Murray et al., 2017).

The demand side of the water value chain calls for new approaches to how water is managed to ensure socio-economic equity, environmental sustainability and efficiency (DWAF, 2004). Strategies such as Water Conservation and Water Demand Management (WCWDM) aim to minimise the waste and loss of water resources through the efficient and effective use of water and to influence the consumer to use water in a sustainable manner (DWAF, 2004). The conservation and recycle approach is an intermediate step between a linear economy and a wholly circular economy, referred to as a reuse economy, depicted in Figure 2.7 (Nederlands, 2016).

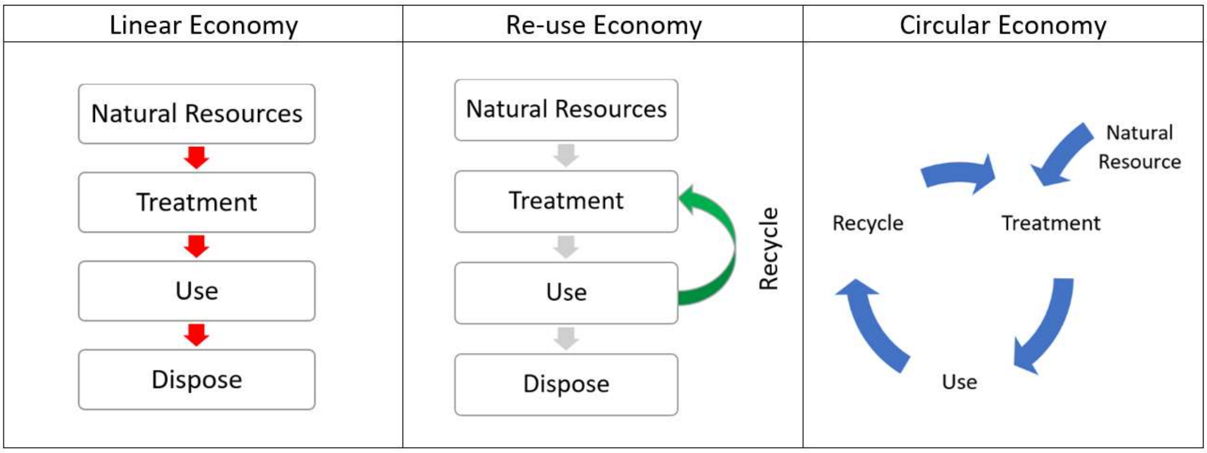


Figure 2.7: Phases towards a Circular Economy (Adapted from the the Government of the Netherlands)

Benefits of applying circular economy principles in the water sector include the energy and resource savings due to reuse, retention and recycle actions. Other benefits are a reduction in waste, preservation of natural resources, innovation and advancement of new products and uses which lead to sustainability advancement of the region and creation of employment opportunities (Jeffries, 2017).

In conclusion, a linear approach to managing water resources has been found to be environmentally and economically unsustainable and therefore a holistic approach to water management within in the economy is required. This allows for value retention within the closed water economic loop. The reuse and retention concept imitates the natural water cycle, moving away from waste creation through preventative and innovative management. The urban water system must be investigated as a whole to identify potential for reuse, retention and recycling of water sources and waste in the water cycle. Multiple water system entities and stakeholders interact and behave in a causal manner with the goal of providing sufficient water sources to users. These causal relationships require a systems thinking approach capable of dealing with the inherent complexities.

2.5 System Thinking Approach

Peter Senge in his book the Fifth Discipline in 1990, described systems thinking as *“a framework for seeing interrelationships rather than things, for seeing patterns rather than static snapshots. It is a set of general principles spanning fields as diverse as physical and social sciences, engineering and management”.*

There may be several solutions for achieving sustainability in a complex system, however appropriate tools are required to evaluate these potential solutions for complex problems (Rijsberman and Ven, 2000). Systems thinking is an approach aimed at assessing the future implication and behaviour of complex systems as it provides insight and understanding to the system as a whole (Dzwairo et al., 2010; Claassen, 2013). Kim (1999) noted that implemented actions are not immediately evident, as some systems change slowly or imperceptibly, resulting in a time delay between the cause and effect in a complex system. Moreover, for complex systems the past can not always be relied on to predict the future when solving problems (Jabeen, 2017). And as the complex system continuously evolves and changes with new perspectives, the systems thinking process becomes iterative (Kim, 1999).

As water plays an integral role in the socio-economic growth and well-being, the impact of water shortages can be devastating (Bronkhorst, Pengelly, et al., 2017; C. Chen et al., 2017). Therefore, for the urban water system to reach its purpose of providing equitable and sustainable water resources, the problems associated with water scarcity need to be addressed. Vullierme (2017) emphasised that an enabling factor for a healthy economy is the identification of potential sources of water in the waste streams of the urban water system. Thus, systems thinking principles and tools, such as system dynamics modelling, are well suited for addressing the limited water resource problem in the City of Cape Town. Providing insight and tools for identifying potential value streams within the complex system. Alternative management methods to the traditional approach toward water stress and socio-economic well-being in the water system are models aimed at addressing waste streams, such as circular economy models. However, these models require the insight provided by systems thinking to reduce the intake of resources in the system through conservation activities (Drangert and Sharatchandra, 2017).

Maani and Cavana (2007) argues that systems thinking is not only a way of thinking, but a language, which involves graphically representing the holistic system view in a serious of feedback loops and interdependencies. The book suggested a five phase process for implementing systems thinking and modelling. These steps are illustrated in Figure 2.8.

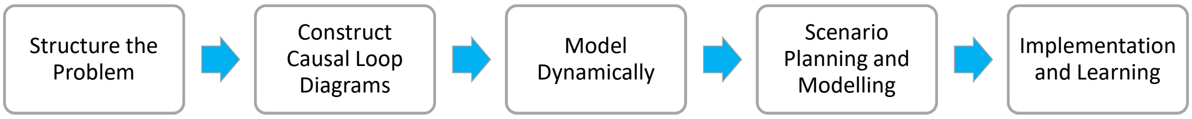


Figure 2.8: Systems Thinking Process for Complex Systems

To quantify the potential savings in the water system, a systems approach that measures the reduction, reuse and retention of water in the total water system is required (Hieminga, 2017). From literature it is found that losses are prevalent in the urban water value chains due to of a lack of total system understanding, fractional policies and ineffective allocation of funds (2030 Water Resource Group, 2009). Using a holistic systems view to identify inherent causes of behaviour in the urban water system allows decision-makers to evaluate and test exogenous actions or policies aimed at addressing water scarcity. These interventions may display counter-intuitive and unforeseen behaviour as a result of complex system adaptation over a time period. Subsequently, policies must be evaluated with a total systems view, to provide trends and insights into system behaviour that serve as decision support.

2.6 Policy Evaluation and Analysis

The conversion process of changing information and data to actions or interventions for resources management is known as *decision making* which is controlled by various legislation and policies (Forrester, 1992). Therefore, management relies on the conversion process of decision making and the selection of information for its success (Forrester, 1992).

The accelerated changes in environmental, society, economy and technology has challenged decision-makers with implementing strategies and management programmes to balance the complex system over which they govern (Nicholson, 2007). Consequently, in the water sector, strategies and policies must evolve and change to meet challenges that threaten a sustainable future. Nicholson (2007) placed emphasis on the importance of understanding the behaviour and tendencies of the relevant system, in addition to applied policies and technologies impacting that system, to be capable of addressing these evolving challenges.

Policy evaluation allows for understanding and identifying consequences resulting from public policy and can either form part of the continuous policy-making process or as a separate section of the policy process (Matt et al., 2013). The purpose of policy evaluation can therefore, be summarised as the process of evaluating the performance of the policy by determining how and to what degree policy objectives were met (Cloete, 2009). For evaluation at a discrete stage, policy evaluation can either be conducted before policies are designed and implemented, or policy evaluation can be conducted after the implementation of the selected policy (Matt et al., 2013).

On the other hand, for continuous evaluation of policy, the impact and performance at each stage of the dynamic policy process is investigated and measured (Matt et al., 2013). Proving clear benefits for policy assessment in comparison to static policy evaluations conducted before or after implementation, as it allows for the uncertainties, dynamic changes and unexpected consequences (Matt et al., 2013). However, the linear static approach remains popular in policy evaluation practice. Although, policy evaluation is generally conducted by governments, academia, governing bodies, business groups may also influence the evaluation process to suit their own interests (Matt et al., 2013).

Determining the success of policy objectives has proven difficult to measure and require extensive data for analysis, which led to a process of performance evaluation of policy goals (Matt et al., 2013). Unfortunately, the interpretation of policy performance was based on stakeholder perspectives and became increasingly perceived as a political tool for influencing the policy-making processes (Matt et al., 2013). To address these shortcomings of the subjective nature of policy evaluation, a third approach to policy evaluation was suggested. This approach relies on both qualitative and quantitative data and research methodology to provide insight and understanding of policy impacts while encompassing the subjective nature of the policy process (Matt et al., 2013). Therefore, the context of the system and environment, over which the policy governs, should be clearly defined and understood.

2.6.1 Policy-Making in the South African Context

Matt et al. (2013) found that the policy evaluation process is inherently a political practice with several evaluation criteria for outcome analysis. The criteria generally include the evaluation of economic, environment and social impacts as a result of policy actions (Matt et al., 2013). In the South African context, performance measurement of policies took precedence over impact and outcome assessments (Mouton, 2010). Although monitoring and evaluation (M&E) activities were present in public policy and governance before 2007, the sectoral performance tracking initiatives lacked the integration of government spheres and sectors (Mouton, 2010; Presidency, 2007).

Policy monitoring is defined by Cloete (2009) as the process of systematic data collection and reporting based on progress indicators for goal and objective achievement. Whereas, policy evaluation is the process that systematically judges the outputs of policy programmes against intended goals and objectives, through the assessment of resources and process conversions in the system (Cloete, 2009). Prior to 2005, monitoring and evaluation (M&E) activities in South Africa were mostly conducted by governing departments for annual departmental reporting (Cloete, 2009).

The analysis of public policy has increasingly been evaluated on the basis of evidence, however it is a recent emerging paradigm in South Africa (Cloete, 2009). In light of this, the Presidency published a standardised framework for policy analysis in 2007 to address the shortcomings of policy monitoring and evaluation in the South African Government (Presidency, 2007). The Government-Wide Monitoring and Evaluation (GWM&E) programme intends to establish a consistent framework for monitoring and evaluating policy actions in the national, provincial and local government spheres (Cloete, 2009; Presidency, 2007). The GWM&E system intends to achieve outcomes through a process of recommended actions. These actions start with the initiation of policy development as a result of public concern and leads through the policy design, funding, implementation, verification, performance evaluation up to the final acceptance of action taken to address the identified public concern in a sustainable manner (Presidency, 2007).

The indicators for performance measurements in the GWM&E system does not include comprehensive environmental aspects, accept for green house gas emissions. Unfortunately, the current GWM&E system only describe *how* monitoring and evaluation activities should be structure and not *what* needs to be monitored and evaluated (Cloete, 2009).

Therefore, additional supporting documents and programmes from stakeholders aim to support shortcomings in the performance evaluation and monitoring of government policies. Programmes such as the Water Sensitive Design (WSD) in South Africa, aim to link stakeholders, knowledge and reflective learning for connected policy development in urban water design to move towards a more water-sensitive and sustainable environment (Carden, Ellis, et al., 2016). While, the Department of Environmental Affairs (DEAT) list several environmental sustainability indicators, of which water indicators include *freshwater*, *groundwater*, and *water stress* (DEAT, 2011).

2.6.2 Water Management Policy in South Africa

The Constitution of the Republic of South Africa is the legal cornerstone and highest law in South Africa (Constitutional Assembly, 2015). Comprising of fourteen chapters, the Bill of Rights is the second chapter of the 1996 Constitution (South African Government, 1996). All laws are subject to the Constitution and can therefore not contradict or challenge any part of the Constitution (Constitutional Assembly, 2015). The right to sufficient water, the right to basic sanitation and the right to an environment that is not harmful to personal well-being or health are all lawful statements made in the South African Bill of Rights (DoJ & CD, 2014). As a result, national, provincial, and municipal laws must adhere to the laws set out by the Constitution.

The government is responsible for passing legislation and policies that provide access to the available resources (Constitutional Assembly, 2015). Therefore, all water laws, by-laws, policies and reports need to adhere to the Bill of Rights (Constitutional Assembly, 2015). However, supplying sufficient water to all citizens in South Africa is still a national challenge (DWA, 2013a).

In 1994, 12 million South Africans did not have access to adequate *water supply* and 21 million South Africans did not have access to *basic sanitation*. Subsequently the post-1994 Government aimed to address these shortcomings through policy and governance as water is a limited resource in South Africa and vital to the Reconstruction and Development Programme (RDP) goals for eradicating poverty, social development and sustainable economic growth (DWS, 1994). To maximise the benefit for all South Africans, as per the South African Constitution, water must be properly managed in an integrated manner as a key national asset (DWA, 2013a).

According to the 2013 National Water Policy Review (NWPR), the main Water Policies that underpin the legislation administered by the Minister of Water Affairs are:

1. White Paper on Water Supply and Sanitation (1994)
2. White Paper on National Water Policy for South Africa (1997)
3. White Paper on Basic Household Sanitation (2001)
4. Strategic Framework for Water Services (2003)

The purpose of a policy review is to refine and review current legislation and to provide guidance for amendment actions to the national government for the achievement of national objectives and future pursuits (DWA, 2013a).

Water functions fall into three main categories: 1) Legislative and Governing; 2) Water Resource Management; and 3) Water Services. The Department of Water and Sanitation (DWS), Catchment Management Agency (CMA) and Water User Association (WUA) are responsible for water resource management. The Water Board (WB), Water Service Authority (WSA) and the Water Service Provider (WSP) are responsible for providing water services. Figure 2.9 shows the division or key roles among water institutions in South Africa (CoCT, 2011; DWA, 2013a).

Water Service Authorities provide sanitation and water supply services themselves, or through contract with private water service providers. Municipalities with constitutional responsibility to conduct planning, provide access and regulate water service provision within their jurisdiction, are know as Water Service Authorities (Bronkhorst, Millson, et al., 2016).

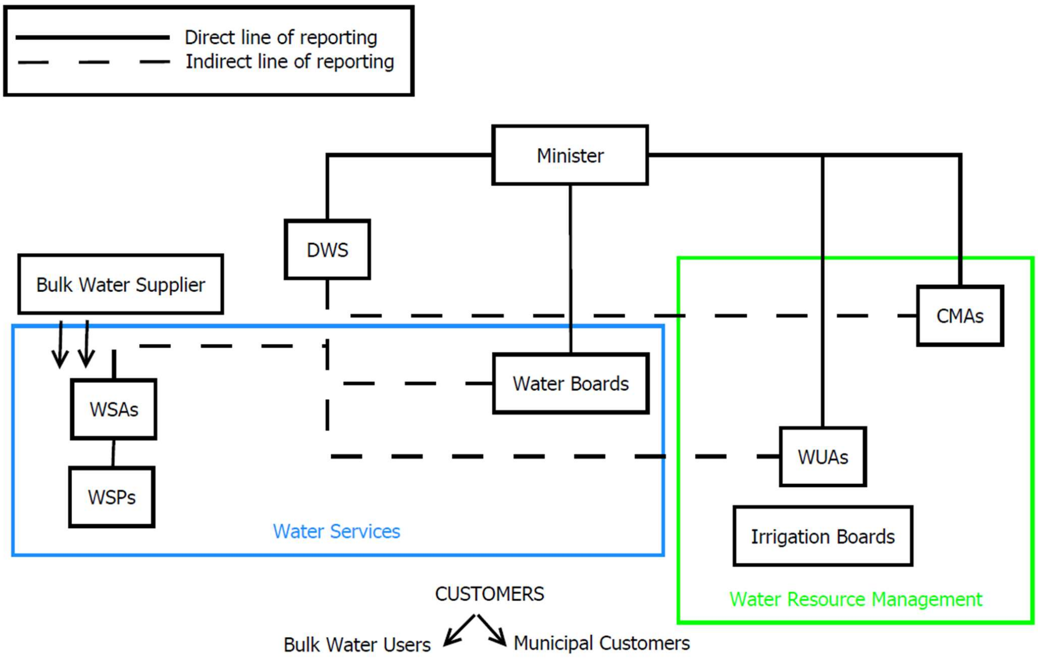


Figure 2.9: South African Water Resource Management and Services (Adapted from the National Water Policy Review 2013)

The City of Cape Town Municipality, is a Water Service Authority (WSA), responsible for the provision of water supply and sanitation services to the City. The Municipality it is divided into three municipal divisions: 1) Waste Management; 2) Water and Sanitation; and 3) Integrated Environmental Management. Water supply activities fall within the water and sanitation responsibilities of the municipality.

To assist the service provision activities of local government, the following policies, reports and strategies address elements of the water supply side in the water value chain:

1. White Paper for Water Supply and Sanitation Policy (WSSP).
2. White Paper on the National Water Policy.
3. Strategic Framework for Water Services.
4. White Paper on Basic Household Sanitation.
5. Water Service Act.

The Water Supply and Sanitation Policy states that water and sanitation services should be paid by the user, unless the basic services cannot be afforded. As water has economic value, the cost of operating, maintaining and replacing water service infrastructure lies with the consumers and not solely on the Government (DWS, 1994). The White Paper on the National Water Policy promotes access to water-and-benefit equity. Furthermore, the paper aims to direct water management and water law development to identify challenges and ensure the availability of scarce water resources in South Africa (DWAF, 1997).

The Strategic Framework for Water Services aims to address water supply and sanitation services, as the Water Service Act and the National Water Act only address the development, management, control and protection of South African water resources. The White Paper on Basic Household Sanitation responds to the sanitation challenges highlighted in the White Paper for Water Supply and Sanitation Policy. Emphasising that water services should be managed sustainably, as the lack of access to water supply and sanitation services inhibit the economic and social growth of South Africa (Colvin and Muruven, 2017).

Furthermore, Water Services Authorities are responsible for assuring access to basic water services and the prevention of wasteful and unlawful use of water and water services through the implementation of water by-laws (DWAF, 2001).

Unfortunately in South Africa, usable water is a scarce limited resources and will not be able to continually meet the increasing demand (Blignaut and van Heerden, 2009; Pienaar et al., 2017). The demand side of the water value chain must therefore also be addressed. Furthermore, the conservation, development and management of water resources fall under the National Water Act. The Act ensures the protection of water sources and the environment through legislation in accordance with the Bill of Rights and is dependent on the right support for water resource decision making (Dzwairo et al., 2010). As the National Water Act provides the foundation for water conservation, it underpins the Water Demand Management Policy (WDM). Subsequently, the WDM Policy treats water as a scarce resource with a zero tolerance towards water wastage (DWAF, 2001). With the Water Demand Management Implementation Strategy aimed at reducing the demand of water in Cape Town through the implementation of the WDM Policy.

Strategies such as water demand management and water conservation aim to minimise the loss of water, educate and encourage user to use water efficiently and to ensure equitable, affordable and sustainable water sources for citizens of South Africa (DWA, 2013a; DWAF, 2001).

Ghaffarzadegan et al. (2010) found that traditional methods of resolving policy problems are impeded by several policy characteristics. These characteristics include: 1) policy resistance, 2) cost of experimentation, 3) achieving consensus among role-players, 4) overconfidence and the 5) need for endogenous perspective (Ghaffarzadegan et al., 2010). In addition, there is a tendency for policymakers to attribute unwanted events to external rather than internal sources (Babcock and Loewenstein, 1997). However, an endogenous (internal) perspective allows role-players to improve their behaviour and learn from the organisation and the environment.

To evaluate the impact of actions taken by decision-makers to address the water scarcity in the City of Cape Town, an appropriate modelling tool or methodology is required to serve as decision support for potential policy actions.

2.6.3 Policy Evaluation and Analysis Methods

To evaluate the policies implemented, the value added must be measured. Defining how value was added and to which stakeholders value was added, is part of the evaluation process (Tsoukias, 2011). A deep understanding of the water value system is required to define value elements for policy evaluation. Yet, evaluation is a difficult task, as value is perceived differently by different stakeholders and as a result can only serve as a decision support activity (Tsoukias, 2011). Thus, models aim to provide decision-makers with information and aid, to support the decision making process.

In the article *"How small system dynamic models can help the public policy process"*, the main difficulties of policy-making was discussed, which emphasised the complex nature of policy-making and the environment in which it serves (Ghaffarzadegan et al., 2010). System dynamic modelling provided the necessary tool for evaluating the complex system and drawing insightful findings from policy decisions (Ghaffarzadegan et al., 2010). Other policy evaluation methods can include comparative studies, benefit-cost analysis, impact assessment or various other methods aimed at extracting useful results.

In Ohio, a system dynamic tool was developed to support sustainable development through policy assessment and impact evaluation. The tool was labelled the T21-Ohio, which aimed to provide insight into the outcomes and impact of implemented policies over a wide range of sectors (Cimren et al., 2010). The social, environmental and economic impacts of implemented waste reuse activities in Ohio were modelled for scenario evaluation to determine the potential benefit and impact of implemented policies (Cimren et al., 2010).

Cimren et al. (2010) noted that the process of policy assessment is ongoing and that no mathematical model can accurately predict future outcomes. Thus, a flexible tool is required, capable of investigating the impact, cost, benefit or risk based on the implementation of potential scenarios as a result of policy decisions (Cimren et al., 2010). The author found that system dynamics allowed for the integrated evaluation of policy alternatives with regards to social, economic and ecological systems. Advantages of such a model include the ability to provide insight into future system behaviour with little historical data to extrapolate from (Cimren et al., 2010).

The T21-Ohio model investigated the impacts of waste management actions to address questions relating to the effectiveness of waste recycling, conversion of by-products and waste reuse to inform policy-making decision (Cimren et al., 2010). Although optimisation, econometrics and simulation models were found to be widely used to analyse policy actions, the system dynamics approach was found to be the most suited for addressing waste and profit management for sustainable development in the integrated urban Ohio region (Cimren et al., 2010).

Furthermore, modelling allows the decision-maker to asses the future impact of policy intervention, within a complex dynamic system, over a selected time period (Nicholson, 2007; Probst and Bassi, 2014). As the impact of policy intervention may only realise years after implementation, it requires an evaluation model capable of predicting potential outcomes (Ghaffarzadegan et al., 2010). In addition, the implementation of evaluation programmes are hindered by the complexity and challenges associated with complex relationships and structure as well as competing interest among stakeholders (Fredericks et al., 2008). Fredericks et al. (2008) found that system dynamics modelling allowed for the balancing of competing interest due to the model's ability to capture across departmental boundaries and to extend the scope as new problems arise.

2.6.4 Policy Decision Making

The State of Environment Report, although not a requirement in terms of South African legislation, strive to aid the decision making process and policy formulation by providing insight and information relating to environmental aspects (DEAT, 2005). In 2013 the Western Cape Department of Environmental Affairs and Development Planning released an Environment Outlook Report to present the current state of environmental resources, including inland water resources. This report not only presents the socio-economic elements for environmental sustainability, but also aimed to provide guidance and information on the current conditions for improved decision making and policy development in the Western Cape (van Weele and Maree, 2013).

Forrester (1992) found that decision making is a continuous process that consists of three phases:

1. Formulate a set of concepts that indicate the conditions that are desired.
2. Observe the apparent actual conditions.
3. Generate corrective actions to bring apparent conditions towards the desired goal.

Thus, the action of taking the corrective step is generated by the decision and is done in accordance with the deviation between the desired condition and the apparent actual condition as seen in Figure 2.10 (Forrester, 1992).

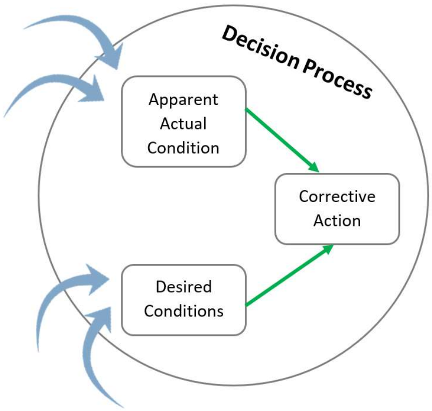


Figure 2.10: The Decision Process for Policy Implementation (Adapted from Forrester 1992)

The response time in both apparent and actual conditions, before and after corrective actions, will be delayed and most likely distorted (Forrester, 1992). Furthermore, the decision model for policy evaluation should not just rely on numerical data, but should incorporate all kinds of information, both qualitative and quantitative, from various sources (Forrester, 1992). Therefore, system dynamics is found to be a well suited approach for supporting the policy decision making process, incorporating both qualitative and quantitative data to develop a holistic representation of the complex system.

2.6.5 System Dynamics for Policy Evaluation

Decision-makers often face challenges with the design, implementation, and evaluation of programmes and policies, due to the complex network of structures and variables in the system (Fredericks et al., 2008). The behaviour of complex systems can be counter-intuitive and unpredictable, making behavioural and performance prediction nearly impossible. Fortunately, system thinking models allow for the structuring of system causal behaviour and feedback loops among system variables. It is important to note that the system's goal drives the response and behaviour, albeit not intuitively (Newman et al., 2003). The dynamic modelling and system mapping allow for the evaluation of potential intervention programmes and policies, using system dynamics simulation techniques, to provide insight into the outcomes and behaviour of the complex system which serves as decision support to policymakers (Fredericks et al., 2008).

In Seoul, Korea, policy scenarios aimed at promoting community well-being in the City, were evaluated using system dynamics models, to provide support to policymakers and stakeholders involved in ensuring community well-being (Choi and Jang, 2017). The dynamic complexity associated with social systems, requires decision-makers to become system thinkers to enable the understanding of complex system structure and behaviour for effective decision making. System dynamics is a mathematical modelling technique that recognises the structure and causal relationships of a complex system, and not only the sum of parts, to investigate and predict the behaviour of the whole system. These characteristics make system dynamics a favourable methodology for evaluating policy alternatives, as the properties of the system are not built on the collection of system parts' properties (Choi and Jang, 2017).

For the well-being analysis in Seoul, policy scenarios were simulated over a ten year period, using system dynamics computer simulated software, to identify behaviour and trends associated with implemented actions. As local finance affect the level of local culture, the various economic growth percentages were chosen as policy scenarios to predict future system response and behaviour, which includes future community well-being (Choi and Jang, 2017).

In addition, the arid Xinjiang Uygur Autonomous region in China, experience water shortages which led to policy and decision support requirements for allocating available water resources among water users (Dai et al., 2013). Policies aimed at addressing the water stress in the region were evaluated using a system dynamics model, with simulations carried out over a forty year period, from 2010 to 2050 (Dai et al., 2013). The model investigated the effectiveness of six policy options. These options included water recycling in the urban system, to determine whether potential solutions indicated sustainable trends (Dai et al., 2013).

To support the transition towards sustainable urban water management, governing frameworks and organisational learning methods capable of accommodating the uncertainties and complexities of socio-economic and environmental aspects, are required (Farrelly and Brown, 2011). System dynamics modelling is thus found to be a suitable methodology for evaluating policy decisions aimed at addressing complex systems with inherent socio-economic and sustainability factors. System dynamics models also allow for the evaluation of complex dynamic structure over a time period, using modelling feedback and behaviour patterns of a system derived from non-linear equations and feedback loops (Dai et al., 2013).

There are three sources of information on which a system dynamics model relies. These sources are numerical data, programme documentation and expert knowledge (Fredericks et al., 2008). The mathematical relationship between variables, developed during the system dynamics modelling process, often expose unintuitive behavioural relationships in the system (Fredericks et al., 2008). In light of this, system dynamics modelling deems to be an appropriate framework that allows for the evaluation of integrated urban water management policies aimed at sustainably addressing water scarcity in the region, while ensuring equitable and sufficient water resources to users in the City of Cape Town water system.

2.7 Chapter Summary

The urban water system for the City of Cape Town is not unique in its ability to adapt and evolve with the changing environment over time. Globally, several urban regions experience similar water shortage problems. The literature review and investigation into the processes and approaches used to address water stress and policy decision evaluation in the applicable knowledge field, has provided insightful concepts and consideration. From these an appropriate model for evaluating policy actions in the urban water system for the City of Cape Town can be developed. Furthermore, to ensure sustainable growth in urban cities, smart strategies are required to ensure inclusion and resilience to the system, considering long term social and environmental impacts.

Hence, the development of decision support models should be of such nature as to provide policymakers with insight and understanding into the complex system for the evaluation of policy, actions and scenarios aimed at alleviating water stress through the extraction of value from water streams in an sustainable manner, in line with national goals and objectives. The literature review has brought to light criterion for appropriate modelling techniques, aimed at providing decision support for addressing the water shortage problem in the urban water system for the City of Cape Town.

Intervention actions that require evaluation include the retention of water within the system and the extraction of value from waste streams to address water stress in a sustainable and equitable manner. It is essential that the urban water system model be capable of providing holistic insight into the behaviour of the complex system, including the causal feedbacks among system variables and stakeholders. System dynamics was found to be a predictive and flexible decision support modelling tool, capable of assisting policymakers in making inclusive and informed decision for sustainable water management.

Chapter 3

Research Design

> *"Discovery consists of seeing what everybody has seen and thinking what nobody has thought."* – Albert Szent-Gyorgyi 1962

The aim of this chapter is to describe the research methodology process for the research study and to provide a review of dynamic modelling theory in relation to the research field. Furthermore, the research design strives to provide structure to both the qualitative and quantitative phases of modelling, which include an introduction to validation techniques, scenario development and result evaluation aimed at sustainably addressing water scarcity problems in the urban water system for the City of Cape Town.

3.1 Research Methodology

Research methodologies fall into one of three categories, namely: 1) Qualitative, 2) Quantitative or 3) Mix Method research (Patton, 2002). For each of these research categories there are various methods for data collection and analysis that continuously evolve with changes in social science and technology (Silverman, 2016). Depending on the field of study, the aim and purpose of research methods may differ which influence the selection criteria for appropriate research methodology.

Qualitative research ultimately aims to establish the background, reasoning and an in-depth understanding of the behaviour displayed by the urban water system and its role-players. Themes and system behaviour in the research environment are identified by exploring the intention and meaning of text, visual or narrative data (Denzin and Lincoln, 2005). Quantitative research on the other hand, serves as support to qualitative findings. Through the application of mathematical techniques, such as statistics, natural or social sciences are investigated and unbiased results are yielded (Garbarino and Holland, 2009). Finally, the third category, mixed method research, allows the user to do an initial qualitative investigation and prepare the initial phase of the research study (Cameron, 2009; Garbarino and Holland, 2009). Thereafter, the research problem is tested and explored with quantitative methods to explain the results in the first phase. This application of mixed method research is referred to as exploratory sequential design (Creswell, 2012).

The mixed method research methodology allows for widening of research boundaries and provides organisational research to incorporate the various disciplines involved in decision making (Cameron, 2009). According to Cameron (2009), the exploratory sequential design is the mixed method type that collects and analyses qualitative data and then connects the findings to the next phase of quantitative data collection and analysis and finally provide collective findings for interpretation and decision making. Subedi (2016) also found that qualitative data collected in the first phase of the exploratory sequential research process, serves the purpose of explaining the relationship and behaviour found in the quantitative data for the second phase of the research process. The sequence of the exploratory research process in Figure 3.1 is based on the research design, as described by Subedi (2016), which has been adapted with inputs from the sequential exploratory model found in Cameron (2009).

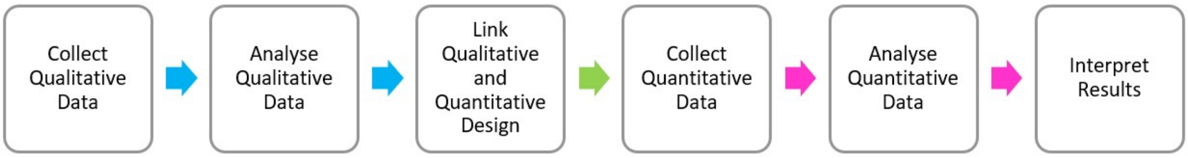


Figure 3.1: Exploratory Sequential Design Process (Adapted from Subedi 2016)

This sequence of research activities support the problem solving process, by extracting and analysing both qualitative and quantitative data aimed at providing insight and understanding to assist policymakers in the decision making process. The socio-economic and environmental complexities inherent in urban water systems require an approach capable of incorporating the dynamic relational structure associated with complex systems. Research in the knowledge field found that a systems thinking perspective allows for non-linear causal relationships and dynamic depiction by providing insight and understanding into the behaviours and trends of a complex system. This approach uses its unique vocabulary to describe the system in a holistic manner, through visual representations of the system using several techniques (Kim, 1999).

Systems thinking tools offer the researcher the ability to model the causal relationships and behaviour within the system, using a conceptual modelling technique of feedback loops referred to as causal loop diagrams (CLD). These causal loops provide insight into the interrelationships that exist among system elements (Kim, 1999; Smith, 2012). Behaviour-over-time graphs is another systems thinking technique, used to provide understanding into the behaviour of a system over time, indicating whether the process and response within the system is balancing or reinforcing (Kim, 1999). As the focus of this research study lies in assisting the decision making process, tools capable of representing system behaviour is required. Systems thinking techniques provide the basis for predicting both intended and unintentional outcomes, resulting from implemented actions aimed at sustainably reducing water stress in the urban City of Cape Town.

The conceptual modelling of causal feedback loops among variables fall in the qualitative data gathering and analysis domain of the exploratory sequential design of the research process (Subedi, 2016). Furthermore, the qualitative feedback loops and behavioural links among variables should be connected with mathematical equations and numerical data to enable the quantitative analysis of system behaviour. The link between systems thinking and dynamic simulation lie in the transition to system dynamics techniques in the quantitative phase of the exploratory sequential design (Cameron, 2009).

Causal loop diagrams (CLD) serve as the conceptual basis for stock-and-flow (STD) simulation models, which allow for detailed analysis of system behaviour over time (Fredericks et al., 2008). The quantitative phase allows for system dynamics simulations, that capture the structure and behaviour of the system, to provide insight into different policy actions and interventions (Fredericks et al., 2008). In lieu of findings presented in the literature review and the capabilities of systems thinking and system dynamics modelling approaches, the exploratory sequential mixed research design incorporates both these qualitative and quantitative research methods for addressing the research problem.

However, to develop and refine the knowledge field, appropriate methods of additional research is required. Case study methodology allows for the capturing of a complex single case within both social sciences and practical fields, such as environmental studies, to reveal important features of the system's nature (Bryman et al., 2014; Johansson, 2003). The object of the study is referred to as the *case* and should be a complex functioning unit investigated in its natural context using various methods to illuminate the case (Johansson, 2003). What is more, case study methodology is a robust research method which allows for the understanding and exploration of complex issues in a holistic manner, such as wastewater management in the urban water system (Zaidah, 2007). Therefore, case study methodology utilises combined research methods to investigate a singular unit or case, specific within space and time, to provide an in-depth explanation of the problem (Zaidah, 2007). Hence, case study methodology can lie within the mixed-method investigation paradigm and allow for specific focus on a relevant subject to support research findings (Labaree, 2019).

A brief introduction to systems thinking, system dynamics and case study research provide a theoretic background to the modelling process. Addressing the problem of reducing water stress in the City of Cape Town, using circular economy principles to extract value from waste streams and to retain water within the system, require a dynamic and versatile research approach. System dynamics was found to be a suitable technique for addressing complex socio-economic problems and testing policy alternatives for interpretation. Whereas, case study research serves to provide insight and refinement to the constructed models. Thereafter, the simulated results can be evaluated against policy objectives to provide understanding and insight into the complex behaviour and performance of the urban water system to ultimately assist the decision making process.

The research phase, procedure and product for each step in the exploratory sequential design is summarised in Table 3.1 to indicate the methodology used to conduct the research study.

3.2 Systems Thinking and System Dynamics

Systems thinking provides the theoretic basis and methods for investigating the interactions and relationships among system variables, drivers of change and process impacts (Kotir, 2017). This conceptual framework represent feedback among system variables and draws attention to the interrelationships among system elements in a holistic manner. Thus placing the decision-maker in a better position to understand the cause-and-effect behaviour as a complete system and not just as parts of the system (Kim, 1999).

Table 3.1: Exploratory Sequential Design Research Layout

Process Phase	Research Methods	Product Outcome
Collect Qualitative Data	Narrative literature review	Text data and system variables
	Policy Evaluation	Text data and system variables
Analyse Qualitative Data	Problem formulation	Model Boundaries Time Scale and Limits
	Causal-Loop Diagrams	Conceptual Model
Link Qualitative and Quantitative Design	Object Identification and Grouping	Identify roleplayers in CLD variables
Collect Quantitative Data	Numerical data extraction from literature and construct mathematical variable relationships	Numerical Values Relational Equations and variable units
Analyse Quantitative Data	Stock-and-Flow Diagrams	Dynamic Model
	Case Study Research	Model Refinement
	Model Validation	Structural and Behavioural Validation
Interpret Results	Scenario Development	Policy scenarios alternatives
	Model Simulation	Comparison results
	Interpretation of Results	Insight into system behaviour

As a result of growing global sustainability challenges, social, economic and natural environments can no longer be investigated independently (Kotir, 2017). Consequently, the linkages and interactions between these subsystems result in uncertainties and insufficient knowledge for decision making. The subsystems should therefore be viewed as a coupled system to improve the understanding of complex interactions, which can be addressed by the formulation of feedback loops, to consider the complex and non-proportional interrelationships among social, economic and environmental sectors simultaneously (Kotir, 2017). System dynamics is a modelling tool, using a systems thinking approach, capable of representing the intricate and complex behaviour of an urban water systems over a time period. In addition, the modelling tool accounts for the adaptive nature and delayed response to triggers within the system.

The system dynamics approach include several elements, namely: 1) feedback loops, 2) variables, 3) flows, 4) stocks and 5) delays (Albin, 1997; Maani and Cavana, 2007). These elements aim to provide tools for evaluating the behaviour of the system as a whole and not an accumulation of the behaviour of parts. These variables are arranged in feedback loops to simulate the behaviour of the system structure for future decision making insight and understanding. Furthermore, the application of system dynamics throughout history, indicates that it is a tool capable of simulating and evaluating sustainability problems (Bangerter et al., 2018).

It has been found that system dynamics is a well suited approach for modelling social problems, such as water scarcity in urban regions (Bangerter et al., 2018). Furthermore, system dynamics for policy modelling allow for the analysis of policy, exploration of future scenario possibilities and assist management purposes (Qudrat-Ullah, 2010; Sharawat et al., 2014). Decision making was traditionally evaluated under discrete, static conditions, however this approach could not accurately represent the behaviour of complex systems (Vicente, 1996). Vicente (1996) emphasised the importance of understanding the factors and role-players that affect decision making in complex systems, as the resulting consequences could be severely detrimental to the performance of that system.

The model aimed at addressing the sustainability of the urban water system for the City of Cape Town is developed according to an exploratory sequential design, using system dynamics methodology and case study research. What is more, the process of model building is incremental and iterative, which allows for the development of a system model with insight (Moore and Derry, 1995). These system dynamics models can be easily extended to include different elements and stakeholders unique to the system problem (Moore and Derry, 1995). It is good practice that complex systems should originate with simple models, from which the basic mathematical development and dynamic behaviour can be scrutinised and expanded in increments, to include all relevant actors for addressing the system problem effectively (Moore and Derry, 1995).

Tools for system dynamic modelling include: 1) causal loop diagrams (qualitative), 2) stock-and-flow diagrams (quantitative) and 3) equations and simulation with system dynamic modelling (quantitative). The research phases and progression flow for modelling the complex urban water system for the City of Cape Town, as per Table 3.1 can be categorised in three main sectors: 1) Qualitative, 2) Quantitative and 3) Interpretation.

The proposed research design is based on the five steps for dynamic modelling in Maani and Cavana (2007)'s book on systems thinking, which fall within the exploratory sequential research design phases for the development of a system dynamics model (Cameron, 2009; Maani and Cavana, 2007). These five steps are problem structuring, causal loop modelling, dynamic modelling, scenario planning and modelling and finally, implementation and organisational learning (Maani and Cavana, 2007). The process steps for the qualitative data collection and analysis phase include the problem formulation and model conceptualisation. These qualitative steps aim to set model boundaries, identify time scales and select variables for constructing causal loop diagrams to model the urban water system.

The quantitative phase is linked to the initial qualitative phase by transitioning from causal loop diagrams to stock-and flow-diagrams. Quantitative data extraction and mining falls within the dynamic modelling method for developing stock-and-flow diagrams that serve as the dynamic representation of the urban water system. Outcome measurements, calibration and software application form part of the dynamic model, which is verified and validated to establish the model confidence and usefulness before policy testing and evaluation can be conducted. The final implementation phase of the modelling process includes the development of policy scenarios, scenario simulation and results evaluation. Thereafter, the system scenarios are tested against measurable outcomes to evaluate potential policy decisions aimed at achieving sustainability in the urban water system.

3.3 Case Study Research

Case study methodology is a popular qualitative research method, that provides the researcher with tools to study complex systems within their environment (Baxter and Jack, 2008; Darke et al., 1998). However, case study research goes beyond qualitative results, utilising both qualitative and quantitative data to understand and explain the process and behaviour of the case (Hancock and Algozzine, 2006; Zaidah, 2007). Subsequently, mixed method research design techniques support case study research, providing both qualitative and quantitative techniques to merge research findings and data for evaluation (Bryman et al., 2014; Cameron, 2009; Johansson, 2003).

Ground-breaking findings and insights are often provided to management by case studies (Gibbert and Ruigrok, 2010). However, the research requires rigor to ensure the relevance of findings in the management field. This refers to the soundness and precision with which planning, data collection, analysis and reporting is conducted (Marquart, 2017). To ensure rigor or precision in the case study methodology, criteria in terms of how the case study is constructed, internally and externally validated and the reliability of the case study should be explicitly defined (Gibbert and Ruigrok, 2010). Furthermore, the reliability and validity of strategies and how these actions are reported are critical to ensure soundness of published work (Gibbert and Ruigrok, 2010). Subsequently, it is important to establish *what* actions or strategies will be used to conduct case study research and *how* these actions are reported to best represent accurate and precise findings.

Tellis (1997) and Yin (1994) found that the structure of the case study methodology should address the 1) protocol design, 2) how the case study is conducted, 3) the analysis of case study evidence and 4) the development of the conclusions and recommendation of the evidence. Furthermore, practical consideration should be given to the availability of public documented data, time constraints and access to information that influence the selection process of the case.

To validate case study research, qualitative and quantitative data collection methods and sources can be triangulated, using several combined methods to correlate results (Johansson, 2003; Zaidah, 2007). What is more, the sample and sources of validity and repeatability should be selected to ensure methodological rigor. Case studies published in high-ranking journals associated with addressing water scarcity in urban regions are reviewed to support the case study research conducted in this study. The complex urban water system consists of several subsystems and parameters, which are extensively more than the amount of available data points (Yin, 1994). Hence, several qualitative research techniques are used to collect case study data, including document analysis, observation and causal loop diagrams (Gibbert and Ruigrok, 2010).

Case study research ultimately strive to determine *why* decisions were made and *how* they were implemented to result in *what* outcomes (Yin, 1994). Therefore, the purpose of the case study in this research paper is to extrapolate key decisions, results and parameters to support the urban water system model, allowing for the illumination of hidden challenges in the real-world system. In addition, the case study allows for the refined understanding and identification of recommendations for improving efficiency and current operational performance.

3.4 Qualitative Phase

The qualitative phase aims to extract useful data from literature, public documentation and technical reports, as well as to establish the background for the problem environment. A narrative literature study, with systematic literature review elements, is conducted to provide insight into the urban water system environment and the evaluating techniques used to address similar problems in the research field.

The problem formation phase consist of problem identification, with emphasis on policy, management and stakeholder concerns, data collection and problem structuring (Maani and Cavana, 2007). This first phase of the dynamic modelling process, as per the exploratory sequential design, is the collection of qualitative data which include data extraction from media reports, policy documentation, statistical records and similar or previous research and studies (Cameron, 2009).

A clear understanding of the specific model goal for addressing the identified need, will focus the study and modelling process to include the necessary elements of the system without trying to incorporate the whole complexity of the system (Sharawat et al., 2014). According to Albin (1997), defining the model purpose requires the narrowing of the model audience and the refinement of the problem. Hence, a clear and specific problem formulation identifies the system model boundaries.

The boundary of the system dynamics model must be defined to include all final components for the model (Albin, 1997). An initial list of relevant system elements is to be evaluated, throughout the iterative modelling process, to identify the final list of variables for inclusion in the final model. Subsequently, the model boundary is defined by the elements necessary to represent the behaviour or properties of the model for achieving model purpose (Albin, 1997). The boundaries of the model should match the purpose of the constructed model, which means that system boundaries can shrink, expand and shift with the changes in model purpose (Shreckengost, 1985). Boundaries include physical, time, geographical and variable bounds, which require system elements to be categorised and the model purpose to be continuously refined to ensure inclusion of all relevant system elements (Trimble, 2013)

For the qualitative analysis phase, the conceptual model of the urban water system is constructed using causal loop diagrams to represent the complex system, through visually represented system components and their interactions (Albin, 1997). This conceptual tool is capable of revealing the origin of the cause of effects in the system, by tracing the related variables in the dynamic process (Maani and Cavana, 2007). Thus, concepts or elements involved in causal loop diagrams need to be defined for the model to provide information on system behaviour over time (Albin, 1997). These model variables are defined as the quantitative and qualitative measurements of the system parts, both constant and time varying.

The relative parts of the system are represented by variables and their influencing links, which form closed loops and connections, used for structuring the model (Maani and Cavana, 2007). These causal relationship among system variables are represented by directional feedback loops, either as reinforcing (R) or balancing (B) feedback (Simonovic and Rajasekaram, 2004).

Key measurement indicators require the model objectives to be clearly defined for alignment of output measurements with system analysis. When the problem requires different aspects to be addressed such as water quality, the index or outcome measurement used to measure the performance of interventions should be suitable to do so. In the CanadaWater model, the unit-based water quality index was used to compare the system's performance to acceptable standards of water quality (Simonovic and Rajasekaram, 2004). In turn, the deficit identified in water quality, determines the level of intervention needed. During the model development, the performance indicators must continuously be refined to ensure relevance with potential changes in model purpose.

Furthermore, exploratory case study research is used to reveal new understanding about the research problem, by providing an in-depth analysis into unknown or uncertain aspects of the single complex system or unit (D. Williams, 2005). Case study research have been found to be complementary to simulation-based modelling such as system dynamics, yielding understanding and careful guidance for data collection, subsequently increasing the robustness of results (D. Williams, 2005). Although case study research predominantly lie in the qualitative domain, a quantitative component forms part of the methodology, which serve to support evidence and findings in the study.

3.5 Quantitative Phase

The quantitative phase of the modelling process allows for the quantification of the dynamic model, using qualitative information and conceptual models as the basis on which the quantitative model is built and simulated, as per the exploratory sequential design (Simonovic and Rajasekaram, 2004). System dynamics is a well suited modelling technique aimed at addressing water resource problems, although not capable of predicting exact future outcomes, the model effectively indicates the behaviour and tendencies of the complex system in relation to alternative policy decisions (Simonovic and Rajasekaram, 2004).

Although causal feedback modelling provides insight and understanding into the behaviour and system reactions, additional advantage can be gained from dynamically modelling the system (Tulinayo et al., 2012). System dynamics provide a transition from causal loops to the quantitative domain by constructing stock-and-flow diagrams, based on the conceptual model's causal loop diagrams, using appropriate software. In addition, the mining, collection and analysis of applicable information and numerical data form part of the quantitative phase of the exploratory sequential design.

Stock-and-flow modelling is a system dynamics technique, capable of distinguishing between the parts of a system, while allowing for the quantitative specification and interrelation of each part (Forrester, 1961). This technique allows for the dynamic simulation of system behaviour over time and enables the user to explore the behaviour and effect of changes (Albin, 1997). The popularity of system dynamics simulation models lie in its ability to link behavioural patterns and underlying structures of a complex system and has therefore, been applied to both policy issues in organisations and operational problems (Qudrat-Ullah, 2010).

The simulation program, VENSIM® PLE was found to be a suitable software tool for modelling the complex urban water system, based on the mapped stock-and-flow structures for subsystems. Before the model can be simulated, initial values and equations for variables must be defined. In addition, unit verification and checks are required to ensure unit consistency throughout the system. The VENSIM® software has a built-in capability to check variable units (Hillman, n.d.). The identified model time frame, time steps and other model settings should also be confirmed before simulation can be conducted (Hillman, n.d.). Once all values are entered and units are checked, the simulation can be saved and run.

What is more, case study research in the quantitative domain serve to validate system dynamics models, testing the reliability and validity of the constructed model (D. Williams, 2005). Case study research serve to identify key parameters that may impact the results of an activity through observation, while system dynamic simulations investigate the manipulation of these parameters and the effect thereof on the outcomes (D. Williams, 2005). Although system thinking and system dynamics provide tools to study the behaviour of complex systems to predict potential outcomes of policy implementation, case study research serve to add to theory building and testing by providing in-depth understanding of the problem and descriptions of real-world functions. Subsequently, case study research serve to support the simulation model to build accurate models and test policies on them (D. Williams, 2005).

3.6 Case Study Validation

To ensure the logical approach and quality of the research design, four tests are widely recommended (Yin, 1994). These are 1) construct validity, 2) internal validity, 3) external validity and 4) reliability.

Construct validity focus on the data collection phase and aims to determine to which extent the research study investigates what it set out to investigate, subsequently assuring accurate observation of the real-world system (Gibbert and Ruigrok, 2010). Triangulation is used to look at the same phenomenon from different angles, using different strategies for collecting data and data sources (Gibbert and Ruigrok, 2010; Yin, 1994). Where direct observation, interviews, published interviews, archival sources (company reports) and data extraction are different sources of data for triangulation. This should be done in such a manner as to provide a clear process of evidence collection for repeatability (from initial research questions to reporting final conclusions) (Yin, 1994). Furthermore, planned versus actual process of data collection should include the circumstances of data collection (including access to organisation), the selection process, data analysis procedures and the relevant time frame (Gibbert and Ruigrok, 2010).

Internal validity investigates the causal links between the variables and results, ultimately aiming to prove that research findings are based on the critical investigation of all available data (Gibbert and Ruigrok, 2010). Therefore, the researcher is responsible for establishing the validity of research design and analysis through a proses of introducing multiple variances, including comparisons and deviation cases. The research framework should clearly demonstrate the relationship between variables and their outcomes, while identifying patterns and comparisons between the conducted study and previous research (Gibbert and

Ruigrok, 2010). This process should report on the different perspectives and methods used to extract data, develop research frameworks, analyse data and interpret findings.

On the other hand, external validation aims to show that the research process accounts for studies of the selected phenomenon within the identified environment as well as in other settings. Although generalisation cannot apply to statistical conclusions, the process of analysis and theory can be generalised, emphasising the rationalisation used for case study selections and the context within which the case study is conducted (Gibbert and Ruigrok, 2010). Subsequently, providing the reader with insight into sampling selection and the research approach.

Reliability enables future researchers to arrive at equal conclusions and insights, should they conduct the research study using the same process steps (Gibbert and Ruigrok, 2010). This provides a degree of consistency and address the influence of underlying assumptions. Hence, the process of data collection, careful documentation, archiving and research procedures should be of such nature as to allow for future replication of the study.

3.7 Model Validation

Simulation models are useful in many areas of management where understanding, forecasting and insight into the system mechanisms are useful for limiting wrong decision making (Lemke and Katuszynska, 2013). However, such a model must meet a level of quality and accuracy for representing the complex system, which can be tested through a process of model calibration, verification and validation (Lemke and Katuszynska, 2013; Qudrat-Ullah, 2010).

Both verification and validation approaches must be clearly defined to avoid difficulties in the process of establishing the model confidence (Lemke and Katuszynska, 2013). Verification aims to establish whether the computer or operational model has been correctly transformed from the formal descriptive model and specifications according to the author (Lemke and Katuszynska, 2013). Validation, on the other hand, refers to the testing of the accuracy and applicability of the constructed operational model, for its intended use and representation of the real urban water system (Lemke and Katuszynska, 2013). Thus, the validation process is critical to the establishing the usefulness of the constructed model.

There are three parts of a system dynamics model, the model structure, the model behaviour and the policy themes. For each part of the model, there are several techniques for validating and verifying these parts. These techniques include tests for fitness, purpose, effectiveness and consistency of the model. The validation process should consider both the conceptual and the computer simulated models (Lemke and Katuszynska, 2013). Figure 3.2 illustrates the verification and validation process for a dynamic model from conceptualisation to simulation, as adapted from Lemke and Katuszynska (2013).

Firstly the conceptual model validation is aimed at testing whether the model includes the sufficient and appropriate amount of details to meet the next dynamic modelling step. Secondly, data validation is required to determine if the data used for model construction is accurate enough (Lemke and Katuszynska, 2013).

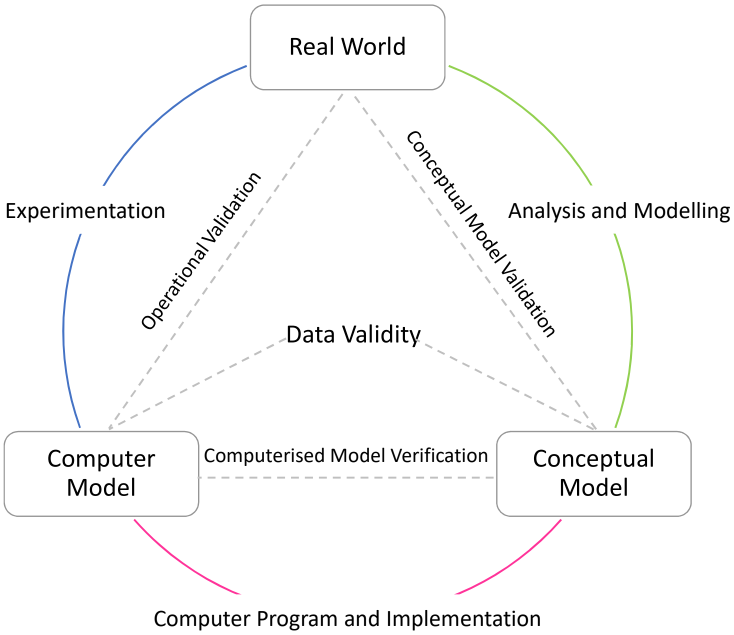


Figure 3.2: Validation and Verification Process for Computerised Models

Once the appropriateness and accuracy of data has been validated, the verification of the computerised model is conducted, to confirm the correctness of the transformed model. Thereafter the operational validation process tests the accuracy of real system representation of the computer simulated model (Lemke and Katuszynska, 2013).

For system dynamics models it is crucial that the dynamic properties are evaluated during the validation process. The validation process can be categorised in the three main groups: 1) structure, 2) behaviour and 3) policy implementation (Lemke and Katuszynska, 2013; Qudrat-Ullah, 2010). The first step for model validation needs to correlate with the first phase of the model process (Qudrat-Ullah, 2010). Thus, the accuracy and credibility of the model purpose in the problem formulation step and the causal relationships development in the qualitative conceptual modelling are crucial for model acceptance and the successful transformation to the quantitative simulation model (Qudrat-Ullah, 2010).

Furthermore, testing both individual parts of the system and the model as a whole is recommended for model validation (Lemke and Katuszynska, 2013). Model boundaries and mathematical limitations should also be considered when validating the process. These include restrictions such as non-negative stock values and maximum capacity.

Once the model has been validated in accordance with available sources of information and data, and the parameters have been calibrated to ensure the correct representation of model behaviour, the model can be used to test the impact of policy interventions for achievement of model goals.

3.8 Conclusion

There are three categories for conducting research studies namely; qualitative, quantitative and mixed method research, each of which has various methods of data collection and techniques for analysis. For this research study a sequential exploratory design was selected, as the research design provides the advantage of using both qualitative and quantitative data collection and analysis techniques in sequence to achieve research objectives.

The qualitative phase provides background and structure for the conceptual model, using a narrative literature review to extract data and information for the problem formulation and the development of causal loop diagrams. These are constructed using appropriate variables and their relational links to represent the real-world urban water system.

The subsequent quantitative phase, include the extraction of numerical data and statistics from various sources in literature and the public domain. During the transition to the quantitative phase of the modelling process, the causal loop diagrams are expanded to include mathematical equations and descriptive variables to construct the dynamic stock-and-flow diagrams in the quantitative phase. Stock-and-flow diagrams consist of additional variables explaining the relationship and assumptions made in causal loop diagrams, to improve model transparency and validity. These diagrams represent the behaviour and structure of the real-world urban water system. Thus, the process of variable calibration, value selection, case study research and model validation becomes critical to the success of the constructed model.

Parameters and results from case study research are used to support the validation and representation of the constructed dynamic model. Once the model is established as a suitable reflection of the real-word urban water system, the final phase in the exploratory sequential design commences. Policy alternatives are implemented as various scenarios for evaluation. The results, generated over the simulation time frame, allow for the analysis of system behaviour and result comparisons. Consequently, providing decision-makers with insight and information into the potential behaviour of the complex urban water system.

Chapter 4

Development of the Conceptual Model

> *"You think that because you understand 'one' that you must therefore understand 'two' because one and one make two. But you forget that you must also understand 'and'."* – Donella H. Meadows, Thinking in Systems: A Primer

The aim of this chapter is to develop the first phase of the decision support model, that primarily lie in the qualitative domain of the system dynamics modelling process. The development of the conceptual model for the urban water system in the City of Cape Town is conducted in two main steps, namely problem formulation and model conceptualisation.

System dynamics is selected as the appropriate modelling tool for constructing a decision support model for urban water system policy evaluation. This support model aims to test potential policy intervention actions for extracting value from waste streams and retaining water resources in the urban water system as an alternative water management approach. This chapter provides the steps involved in developing the qualitative phase of the system dynamics model for evaluating legislative actions in the urban water system for the City of Cape Town. Although the modelling process is sequential in nature, the development of the model is iterative and continuously refined and reviewed to ensure an accurate representation of the real-world system.

4.1 Problem Formulation

The initial qualitative phase of the system dynamics approach allows for the understanding of system behaviour, structure, boundaries and constraints to accomplishing the model's purpose. Subsequently, the first phase of the system dynamics modelling approach requires a clear understanding of the research objectives for addressing water scarcity in urban areas. The problem formulation step provides guidance for problem structuring by extracting themes, appropriate variables, time scales and concepts from available literature and documentation.

The purpose of the model formulation step is to provide a clear articulation of the model purpose by defining the problem, identifying key variables and establishing the time scale and boundary of the system dynamics model. The hydrological cycle for the urban City of Cape Town as reviewed in Chapter 2.4.2 and the circular economy framework is used as the basis on which the conceptual model is built. This model should serve as a decision support tool for evaluating potential legislation and governance strategies aimed at extracting value from waste streams and retaining water within the urban water system, to sustainably alleviate water stress experienced in the City of Cape Town.

The process of identifying system boundary elements is iterative as the model is built in the conceptualisation phase and may later change or adjust as the problem and model becomes more refined (Albin, 1997). As the model dynamically change and adapt, in response to changes in rates and variables, the time scale for the modelling evaluation should be appropriate for useful analysis.

The model purpose is the determining factor in selecting the time scale for the model to avoid obscuring behaviour that may be important to providing insight accordingly (Albin, 1997). It is evident from literature that the system dynamics modelling method is capable of simulating the system response over extended time periods, to provide indicative behavioural patterns and responses to changes in variables (Tulinayo, 2009). To extract useful information and data for model construction, supporting literature and technical reports used should be identified and recorded for modelling transparency and record keeping.

4.1.1 Supporting Literature

Various documents and policies support the sustainable and equitable management of water resources in South Africa in order to ensure a sustainable environment for future generations according to the Bill of Rights. These documents include national, provincial and local policies, reports and tools for addressing various elements of the water system. Consequently, a thorough understanding of the water system and the applied strategies and governance is required to effectively evaluate policies and strategies against national and local objectives.

The national regulatory documents in Table 4.1 and regional and provincial reports and audits in Table 4.2 are identified as supporting data and information for the development of the urban water model for the City of Cape Town.

Table 4.1: National Regulatory and Supporting Literature for Model Development

Document	**Year**	**Author**	**Description**
Water Service Act	1997	RSA Presidency	Provide fundamental reform of the law relating to water service.
National Water Act	1998	RSA Presidency	Provide fundamental reform of the law relating to water resources.
National Water Policy Review	2013	Department of Water Affairs and the WRC	Review and refinement of the water policy in SA.
National Water Resource Strategy II	2013	Department of Water Affairs	Focus on ensuring equitable and sustainable water resources.
WWF Report: Scenarios for the Future of Water in SA	2017	WWF for Nature and Boston Consulting Group	Investigating scenarios of water scarcity in South Africa.

Table 4.2: Regional and Provincial Supporting Literature for Model Development

Document	**Year**	**Author**	**Description**
Water Service By-law	2003	The City of Cape Town (CoCT)	Empowers City Council to restrict or limit water usage for water conservation resources.
Water By-law	2010 2018	The City of Cape Town	Incorporates water conservation and demand management.
State of Environment Outlook Report for the Western Cape Province	2013	WC Department of Environmental Affairs	Report on current state of environmental resources.
Water Service Departmental Sector Plan	2015	CoCT Water and Sanitation Department	Align the DWS requirements with the water service development plan.
Service Guidelines and Standards	2015	CoCT Water and Sanitation Department	Provide standards and guidelines for water and sanitation services.
GreenCape Market Intelligence Report: Water	2015 to 2019	GreenCape	Highlight business opportunities for water in the WC green economy.
Five-Year Integrated Development Plan 2012-2017: 2016 Review	2016	CoCT Municipality	Strategic framework for building the city according to objectives.
Water Demand Management and Strategy	2016	CoCT Water and Sanitation Department	Serves as an update on the WCWDM strategy of 2007.
Annual Water Service Development Plan Performance-and Water Services Audit Report	2017	CoCT	Report on implementation of water services development plan, including an annual water service audit for CoCT.
Water Services and the Cape Town Urban Water Cycle	2018	CoCT Department of Water and Sanitation	Provide an overview of the CoCT's urban water cycle.
Cape Town Water Outlook Report Western Cape Province	2018	CoCT Department of Water and Sanitation	Present an overview of the CoCT's New Water Programmes to address water scarcity.
Cape Town Water Strategy	2019	CoCT	Sets out CoCT commitments to constitutionally mandated responsibilities.

These regulatory documents and technical reports provide both qualitative and quantitative data and information, useful for developing an appropriate model, serving as a representation of the real-world urban water system.

4.1.2 Model Boundary and Time Scale

The geographical boundary for the model is restricted to the urban City of Cape Town, for the evaluation of local and national policy actions for sustainable and equitable water management. The regulatory literature has encumbered the City of Cape Town Municipality with the responsibility and objectives of providing adequate, sustainable, financially viable and equitable water and sanitation services to the urban City. These water and sanitation services are to comply with national goals set out in the National Water Act, the Water Service Act and relevant local and national policies.

The primary governing stakeholders in this urban water sector, include the national and local Department of Water and Sanitation (DWS), the Berg-Olifants and Breede-Gouritz Catchment Management Agencies (CMA) and the relevant Water User Associations (WUA) (Bronkhorst, Pengelly, et al., 2017). The South African water structure and urban water system for the City of Cape Town, as elaborated on in Chapter 2, §2.4.2 and §2.6.2, are used as the model basis. These entities are responsible for ensuring safe and sustainable water to consumers by planning, implementing and managing effective water management activities (Colvin and Muruven, 2017). However, water risks should be managed by all stakeholders in the water system to collectively support the sustainable management to secure water for the future. Thus, the boundary of the model aims to include water users, the private sector and affected departments or water entities as stakeholders in the water system.

The research problem places emphasis on the extraction of value from water waste elements and the retention of water streams in the urban water system as potential water supply sources, using circular economy principles. A clear and refined purpose of the model is to evaluate and test potential legislative decision actions aimed at addressing waste streams and losses in the urban water system for the City of Cape Town, to ensure a sustainable economic, social and environmental future. Hence, the audience of this model is narrowed to decision-makers and stakeholders in the urban water system for the City of Cape. The model is required to provide a holistic view of the sustainability factors influencing the urban water model, to provide insight and understanding for decision making.

Model structures representing socio-economic systems are modelled over a period of time to incorporate the intricacies of social and environmental response, thus accounting for the delay in system effect. Similar studies reviewed in Chapter 2.3.1, addressing the water resource management environment, modelled the system over a period of 24 to 40 years. The availability of validation information and data should also be considered when selecting the time scale and time steps of study evaluation.

The patterns in rainfall and drought events are considered during the identification of an appropriate time scale over which the model is simulated. The pattern of weather events are of importance for understanding and replicating the behaviour of the total urban water system for the City of Cape Town. A method of comparative measurement is required to measure and compare the response and effectiveness of potential policy actions on the urban water system. Therefore, a suitable model measurement index is required that will allow for behavioural indication within the model boundary and time scale.

Furthermore, the model exclusions, which fall outside the boundary of this model, is summarised in Table 4.3. The excluded variables highlight the exogenous variables, which are not affected by the system and the endogenous variables impacted by the model exclusion. These exclusions allow for the simplification of the model, to gain understanding and holistic insight into the behaviour of the urban water system, in relation to policy and legislative decisions aimed at addressing water scarcity in the City of Cape Town.

Table 4.3: City of Cape Town Urban Water System Model Boundaries

Excluded Variables	**Exogenous**	**Endogenous**
Climate Change	Precipitation	Raw Water Supply
Electricity Requirements	Electricity Costs	Consumption Patterns
Employment	Industrial Growth	Industrial Water Demand
GDP Growth	Industrial Consumption	Total Water Demand
Population Drivers	Urban Population	Domestic Potable Demand
Public Perception	Acceptance of Reuse	Total Water demand
Raw Water Allocation	Raw Water Decline	Potable Water Supply
Tariff Structure	Tariff Steps	Consumption Patterns
Urban Housing Transition	Number of formal and and informal housing	Basic Water Supply, Rainwater Harvesting
Water Treatment Quality	Water Treatment	Total Water Supply

Population changes in the urban water system is based on predicted growth patterns and calibrated historical census data for the estimation of growth in population for the City of Cape Town. However, detailed investigation and models for the Western Cape population fluctuation can be found as a sub-model in the WeCaGEM model by Musango et al. (2015). As a result of time, data and scope constraints, various system variables are excluded from the model and serve as the model boundary. Although these excluded variables impact the urban water system, they are not included in the detailed investigation and model construction.

4.1.3 Model Indices

Becoming a water-smart economy is one of the main goals proposed in 2017 for a sustainable water future in South Africa, which require the enhancement of information sharing and improved decision support to stakeholders (Colvin and Muruven, 2017). To monitor the performance of interventions, suitable indicators for measuring and monitoring must be established. The level of suitable water availability can be monitored using various measurement indices, including dam capacity and the percentage of wastewater treated.

Observing indicators, such as rate of urbanisation, water tariffs and per capita water usage are measurements that indicate the rate of change for water demand. The quality of water and the availability of water are also factors that influence the water supply in the urban water sector. The amount of wastewater treated and available potable water are suitable indices for measuring the supply and quality of water resources. For demand

and supply management, indices such as Gross Domestic Product (GDP) growth, urbanisation rate, water usage per capita and the change in water tariff price are useful for monitoring the system performance (Colvin and Muruven, 2017).

Key water supply options identified in the 2017 GreenCape Market Intelligence Report include water reuse, groundwater development and desalination as potential options within the Western Cape Water Supply System (WCWSS) (Bronkhorst, Pengelly, et al., 2017). However, emphasis is placed on the protection of water quality and Water Conservation and Water Demand Management (WCWDM) schemes. Usage and behavioural restrictions as well as tariff increases are some of the intervention actions implemented in the City of Cape Town as part of the demand management strategy. Focus on extracting value from the water waste stream, as part of water waste management, have yet to become a priority for inclusion in current governing strategies and policies implemented in the City of Cape Town and South African as a whole.

The water supply stress index (WaSSI) used by Sun et al. (2008b) and the water scarcity index (WSI) used by Wada et al. (2011) are similar measurement indices employed to contrasts the quantity and quality of water supply sources against the total demand, which can include the requirements for environmental flow. The cost of intervention actions, both capital and operational costs, serve as consideration for policy evaluation and scenario comparison. Furthermore, the cost per water unit aims to provide consideration to ensuring affordable water supply to customers. Consequently, the model indices must serve the model purpose by measuring the urban water system's performance against intervention. This can be done through the evaluation of system behaviour in relation to changes in variables as a result of policy actions.

In lieu of this, measurement indices aimed at providing comparative results for decision making, are required to provide decision-makers with relevant results and insights. As both water quality and water availability hinder the usability of water sources, the water supply stress index explored in Chapter 2.2, is found to be a suitable measurement indicator, capable of providing information about the deficient gap between water demand and water supply. Furthermore, the economic cost of intervention, aimed at reducing water stress in the system, is capable of serving as the cost factor for achieving system benefit by reducing water demand or augmenting water supply, subsequently lowering water stress in the region.

4.2 Model Conceptualisation

Brzezina et al. (2015) found that the distinction made among system variables in the problem formation stage improve the modelling structure and visualisation, by using colour keys to distinguish between exogenous, endogenous and data variables in the system conceptualisation phase. To further assist with preparation for model construction, Brzezina et al. (2015), in combination with inputs from Walker et al. (2013), developed a model-based policy analysis framework that provides guidance to conceptual modelling for policy evaluation based models. The structure in Figure 4.1 is an adaptation from the framework presented by Walker et al. (2013) and Brzezina et al. (2015).

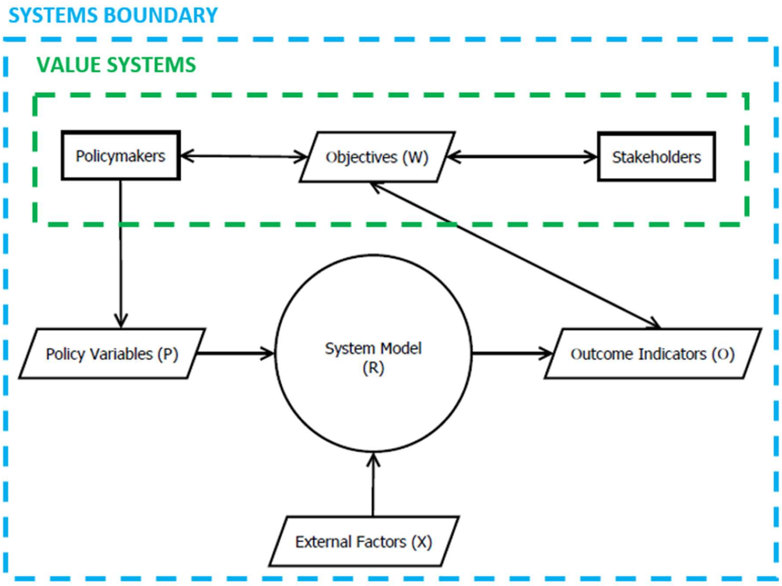


Figure 4.1: Model-Based Policy Analysis Framework (Adapted from Brzezina et al. (2015))

The framework provides a starting point for the identification of model parameters for the conceptual model aimed at evaluating policy implementation. The value system (stakeholders and policymakers) aim to set model objectives (W), while the outcome indicators (O) are based on the objectives set to measure the performance and impact of policy alternatives. The system interventions aim to improve the outcomes through the implementation of policy variables (P), while the affect of external uncertainties (X) on the system model (R) are included for a total systems perspective. (Brzezina et al., 2015). These elements strive to represent the real system within the selected system boundary and ease the conceptualisation process.

The model conceptualisation phase has proven to be successful in building graphical information systems, while bridging the gap between the experimental and mathematical representation (Tulinayo, 2009). Mental models of variable behaviour over time can also provide insight to the model structure. Historical data and dynamic behaviour of these elements are extracted from literature and incorporated in the conceptualisation design phase, which is used to check the plausibility of the model in the validation phase. This valuable step in preparing formal model structures can be in the form of verbal descriptions or a graphic representation of system behaviour graphs and statistics (Albin, 1997).

In the validation stage, the comparison of model output with historical data or information gathered in the conceptualisation data collection phase, becomes particularly useful. Model sectors and key modelling issues can be categorised according to problem requirements, which serve as the subsections and variable groups for describing the system as a whole (Simonovic and Rajasekaram, 2004). Causal loop diagrams are useful in the qualitative analysis phase, as it provides the researcher with the visual representation of system linkage and variable feedback behaviour. The identification and selection of system variables for causal loop diagrams are essential for ensuring the useful representation of the real world system.

4.3 Model Variables

To select variables, an understanding of the system is required with emphasis on the sources, users and influencing facets of the model. In South Africa rainfall serves as the predominant source of fresh water, yet the Western Cape and the City of Cape Town generally experience low average annual rainfall. With only approximately 30% of rainwater runoff becoming usable water supply, mostly prevailingly as surface water (Colvin and Muruven, 2017). Thus, the average annual rainfall in millimetres, can be translated to available water per capita per annum in cubic meters (m^3/person/annum).

Water demand in the City of Cape Town is driven by four main drivers of demand; municipal, industrial, agriculture and urban sector demands. Furthermore, population growth, water usage and urbanisation can be monitored by measuring the rate of households increasing in the urban City, the usage per household in the City and the amount of households with access to potable water. Furthermore, the price of water, in terms of tariffs, as well as water restrictions are variants aimed at curbing the demand for water, while promoting the reuse of water sources.

Urbanisation also results in an increase in total water usage per household, in addition to an increase in households with access to water in the City and reduced percolation of rainwater. Consequently, these variables impact the water stress in the urban City and should be incorporated in the system model. The variables directly impacting the behaviour and outcomes of the urban water system are referred to as key variables, which are influenced by several other variables, either endogenous or exogenous.

The urban water system model for the City of Cape Town is divided into three main subsystems based on the roles of water in the City as discussed in Chapter 2.4, namely: *water as a resource*, *water as a product input* and *water as a waste stream* (Balabanis, 2015). The key variables for each water role are identified for the development of the conceptual model through an iterative process of model refinement and parameter identification.

For each sector an initial list of elements must be defined as either endogenous or exogenous variables. While endogenous components refer to the dynamic variables within the system feedback loops, exogenous variables are the components not directly affected by the system, seen as external system actors, usually based on statistical or historical data (Albin, 1997). These system elements can be defined as either a stock, flow or constant. It should be noted that exogenous variables are usually defined as either a constant or time varying constant and not as a system flow or stock (Albin, 1997).

The development of the conceptual urban water system model is derived from a combination of inputs and information sources. Chapter 2.3.1 identified several key contributing sources supporting model development, which include the City of Cape Town urban water cycle, constructed water management models found in literature and the Western Cape Green Economy Model (WeCaGEM) spheres. Subsequently, variables are identified and refined to fit the purpose of the research study.

4.3.1 Water as a Resource

The water supply for the City of Cape Town is supplied primarily by six major dams, which form part of the Western Cape Water Supply System (WCWSS). Although the storage capacity of the major dams are 900 million m^3, the current prevailing drought has brought storage levels to as low as an average of 24% in February 2018. As the last 10% of dam water cannot be used, the realistic available water supply is lower. With approximately 2% of water used for drinking in the City being sourced from other sources.

According to the Water Services and the Cape Town Urban Water Cycle report for March 2018, the WCWSS contributes 64% of total drinkable water in the system to the City of Cape Town, which is estimated at 345 Mm^3 per annum (CoCT, 2018e). Although treated wastewater has the potential to be a source of drinking water, the current treatment plants in the City can only provide treated wastewater suitable for industrial and irrigation use.

The standard and quality of drinking water is measured using the Blue Drop certification programme, set out by the Department of Water and Sanitation. This programme is an incentive-based regulatory strategy which aims to ensure that the City's water supply meet a minimum of 95% of regulatory criteria, ensuring the provision of excellent quality drinking water. The City of Cape Town treatment plants provide high quality drinking water to urban users, with a maximum total treatment capacity of 1612 million litres per day (MLD), which is far above the 2017/2018 restricted target maximum for the provision of 450 MLD (CoCT, 2018e).

The variables impacting the water resources of the urban water system for the City are listed in Table 4.4 and serve as model elements for the first water as a resource subsystem. These parameters form part of both the qualitative and quantitative model development.

Table 4.4: System Variables for Water as a Resource Subsystem

Main System Variables	**Endogenous or Exogenous**	**Stock/Flow/ Constant**
WCWSS Raw Water	Endogenous	Stock
Volume of Stored Rainwater	Endogenous	Stock
Volume of Industrial Stored Rainwater	Endogenous	Stock
Capacity of Desalinated Water	Endogenous	Stock
Industrial Reuse Plant Capacity	Endogenous	Stock
Groundwater Abstraction Capacity	Endogenous	Stock
Precipitation	Exogenous	Time varying constant
Secondary System Variables	**Endogenous or Exogenous**	**Stock/Flow/ Constant**
WCWSS Dam Capacity	Endogenous	Stock
Reticulation Losses	Endogenous	Flow
Water Treatment Capacity	Endogenous	Constant
Total HH Roof Catchment Area	Endogenous	Constant
Capacity of Rainwater Tank	Endogenous	Constant
Runoff per Year	Exogenous	Time varying constant
WRYM Evaporation	Exogenous	Time varying constant

There are several impacting variables that influence the supply side of the system model, that are not listed in Table 4.4, however these are included in the model construction and quantitative equations in Chapter 5. The water resources are consumed by users at a demand rate, dependent on various factors such as population size, daily requirements and industrial inputs. Subsequently, the variables associated with the consumption of water resources form part of the second role of water as an input.

4.3.2 Water as a Product Input

Water demand is driven by several sectors, including agriculture, industry, mining and urban users. However, unlike the Western Cape agricultural regions, the City of Cape Town predominantly demand water for urban usage (CoCT, 2018c). In March 2018, it was found that over 650 000 metered connections provide water to consumers in the City. With a population size of more than 4,1 million residents, the per capita demand has a significant impact on the total water demand. Consequently, the management of water demand and usage behaviour significantly impact the total water required as input to the system.

Reticulation water losses can be attributed to damaged mains, faulty connections and meter inaccuracies (Nzima and Sigenene, 2017). However, ongoing water conservation and demand management schemes include the implementation of smart water meters, leak detection, pressure management, water restrictions and tariff steps to reduce water losses in the system (De Sousa-Alves, 2015).

Although domestic demand contributes to the largest portion of water users, industrial, commercial and municipal sectors are also contributing factors to the total water demand in the City of Cape Town. Subsequently, the economic growth and development is dependent on the availability of water resources, which results in growth in the GDP in the province and vice versa. The variables for the *water as an input* subsystem in Table 4.5 is aligned with water demand variables found in similar water models investigated in Chapter 2.3.1.

Table 4.5: System Variables for Water as an Input Subsystem

Main System Variables	**Endogenous or Exogenous**	**Stock/Flow/ Constant**
Urban Population	Exogenous	Stock
Potable Consumption	Endogenous	Flow
Domestic Water Demand	Endogenous	Time varying constant
Total Industry Water Demand	Endogenous	Time varying constant
Secondary System Variables	**Endogenous or Exogenous**	**Stock/Flow/ Constant**
Population Growth Rate	Exogenous	Time varying constant
Growth in Industrial Demand	Exogenous	Time varying constant
Avg People per Household	Exogenous	Time varying constant
Per Capita Consumption Limit	Endogenous	Time varying Constant
Restriction Level	Endogenous	Time varying Constant

According to the 2016/2017 annual Water Services Development Plan Performance Audit Report, the City of Cape Town water users are predominantly residential, with portions of educational, institutional, commercial and industrial users (Nzima and Sigenene, 2017). The water usage leads to generated waste, which results in various impacts on system elements further downstream.

4.3.3 Water as a Waste Stream

There are several treatment processes for wastewater, which depend on the intended requirements and purpose of treated wastewater. In South Africa the quality of treated wastewater and the compliance to national standards are monitored on a regular basis, as per the Green Drop certification initiative. Although the City of Cape Town only use treated wastewater for industrial and irrigation purposes at present, the potential for treated wastewater as an added source to the total potable water supply is a viable option for alleviating water shortages in urban cities.

The daily water usage in the City of Cape Town is over 500 000 m^3, of which only 8% is recycled for reuse in industry and irrigation (CoCT, 2018e). Furthermore, the treated water is piped in a separate piped network (orange pipeline) to the various treated effluent consumers (CoCT, 2015). The capacity of the wastewater treatment plants for reuse, totals to 164 MLD, however only a small percentage of treated water is reused.

What is more, marine outfalls are used to discharge pre-treated wastewater into the ocean. These marine outfalls are designed in such a way as to minimise the ecological output. However, the quality of discharged and spillage should be managed by educating the consumers on the quality of waste produced, as the input in waste streams severely impact the treatment process and harmfulness of waste discharge (CoCT, 2018e; Nzima and Sigenene, 2017).

The key variables in the wastewater sector are listed in Table 4.6.

Table 4.6: System Variables for Water as a Waste Stream Subsystem

Main System Variables	**Endogenous or Exogenous**	**Stock/Flow/ Constant**
Potable Reuse Yield	Endogenous	Stock
Municipal Effluent Capacity	Endogenous	Stock
Wastewater Input to WWTW	Endogenous	Time varying constant
Reused in Industry	Endogenous	Time varying constant
Secondary System Variables	**Endogenous or Exogenous**	**Stock/Flow/ Constant**
Domestic Greywater per Capita	Endogenous	Stock
Industrial Greywater Stock	Endogenous	Stock
Increase CoCT Effluent Capacity	Endogenous	Flow
Fraction of Treated Effluent to Industry	Endogenous	Constant
Domestic Wastewater Generated	Endogenous	Time varying constant
Generated Industrial Wastewater	Endogenous	Time varying constant
Spillage to Stormwater	Exogenous	Time varying constant

The total water usage impacts the amount of water received by the wastewater treatment plants and therefore, the amount of discharge into the ocean and natural water bodies. These dependent variables respond and change in a mostly non-linear way to variation in linked variables. The potential for value extraction in the wastewater sector has not reached total capacity and is therefore, a point of interest for addressing water scarcity.

4.4 Causal Loop Diagrams

Causal loop diagrams (CLD) are introduced in Chapter 3 and are an essential part of the conceptual modelling phase. These causally linked models aim to provide insight into the model behaviour and dependencies with directional feedback loops. The variables identified in the previous sections are grouped in subsystem models, from which the complete conceptual model is built.

In the causal loops, variables will either move in the same direction (+), for example as part A increases the linked variable part B increases, or on the contrary variables move in opposite directions (−), for example as variable A (Weight Loss) increases the linked variable B (Adult Body Weight) decreases (Albin, 1997). Furthermore, the time that elapse between the cause and effect in the system, is referred to as the delay, which is displayed as "||" on the arrow in the causal loop diagrams as seen in Figure 4.2.

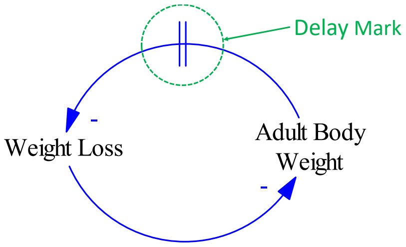


Figure 4.2: Body Weight Example Delay Indicator

The balancing (−)/(B) feedback loops aim to regain system stability through goal seeking and dampening, whereas the reinforcing (+)/(R) feedback loops seek to build or decline through a process of growing and amplifying (Maani and Cavana, 2007). The causal loop diagram example for purchasing in Figure 4.3 shows a reinforcing and balancing loop.

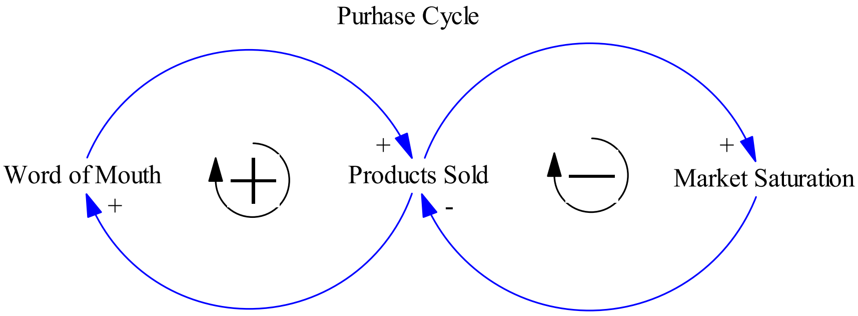


Figure 4.3: Purchase Cycle Example for Reinforcing and Balancing Feedback Loops

For this example, the number of products sold serves as the stock in the simplified system, which can be measured at any given time. As the number of products sold increases, the word of mouth relating to the product will likewise increase (+) and as the word of mouth increases, the number of products sold will also increase (+), therefore the cycle of feedback is reinforcing. However, if the number of products sold increases, the market becomes more saturated and as a result market saturation increases (+). If market saturation increases, the amount of products sold will decrease (−), resulting in a feedback loop that stabilises and balances the system.

A minimum of one stock for each causal loop is required to represent the dynamic behaviour over time (Albin, 1997). Therefore, causal loops bring qualitative variables into the systems thinking approach for model conceptualisation. However, Albin (1997) argues that causal loop diagrams are also useful after model simulation, as a method that provide insight and explanation to the simulated model and that stock-and-flow diagrams should be constructed in the conceptual modelling phase. However, for this study the causal loop diagrams, developed in the conceptual modelling phase, serve as the link to dynamic modelling during the conversion from causal loop diagrams to stock-and-flow diagrams (STD) for quantitative modelling (Tulinayo, 2009).

The six major dams in the Berg-Olifants WMA, with a capacity of 900 million m^3, supplies water to industry, domestic and agricultural users through a integrated structure of supply networks, referred to as the Western Cape Water Supply System (WCWSS). The system includes the transfer of water from the Breede River catchment area. With the continual growth in demand for water resources, the WCWSS yield will likely be exceeded in the near future. Thus, efficient and sustainable planning and regulating of water demand and supply is required in the City of Cape Town. The causal loops serve to provide insight into the behaviour and interdependencies in the urban water system for the City of Cape Town, to improve the transparency and understanding of the system response to policy and intervention actions.

Various causal loop diagrams for each water role is used to represent the directional interdependencies among system variables. These diagrams are constructed in each section to depict the finer details and connections within the water role, before a summarised conceptual representation of the urban water system for the City of Cape Town is constructed.

The literature review brought to light several water management models aimed at alleviating water scarcity in both urban and agricultural regions. For example, Musango et al. (2015) and Pienaar et al. (2017) constructed in-depth models aimed at evaluating the water system response to changes in population growth, economic development and water resource capacity in the Western Cape.

Consequently, parameter and causal links may align with other models to a certain extent. The developed model serves to provide decision support to policymakers within the urban water sector to identify uncapped water streams for value extraction and to ultimately reduce the demand on scarce potable water resources. Simplified causal loop diagrams are constructed to represent different aspects of the urban water system model.

4.4.1 Water Resource CLD

Water resources for the City of Cape Town are predominantly sourced from surface water supply, groundwater supply and recycled water. However, rainwater is retained in domestic households and used for irrigation and non-drinking purposes, which add to the total water stock in the urban City. Each source of water supply adds to the total water resources in an unique way and are represented in partial causal loop diagrams.

The effect of climate change on the total system yield is erratic and fluctuating, making forecast and trend predictions difficult to determine. However, evaluating the effect of both high water requirements and low water requirements, provide a suitable range for demand and supply planning (Flower et al., 2015). Therefore, water allocation is either constrained or unconstrained, depending on the availability of water resources.

Figure 4.4 illustrates the current sources of water supply for the City of Cape Town, with the impact and costs thereof on the water stress experienced. The balancing loop B1 indicates that as water is withdrawn from the system, the available water stock declines, subsequently leading to a decrease in water withdrawal. Furthermore, the causal relationship between demand management activities and water consumption in the City of Cape Town is indicated by the balancing loop B2. As water is withdrawn from the system the available stock declines, resulting in an increase in water supply stress. Demand management initiatives increase with added water stress, which leads to a reduction in water demand and therefore, a reduction in withdrawal.

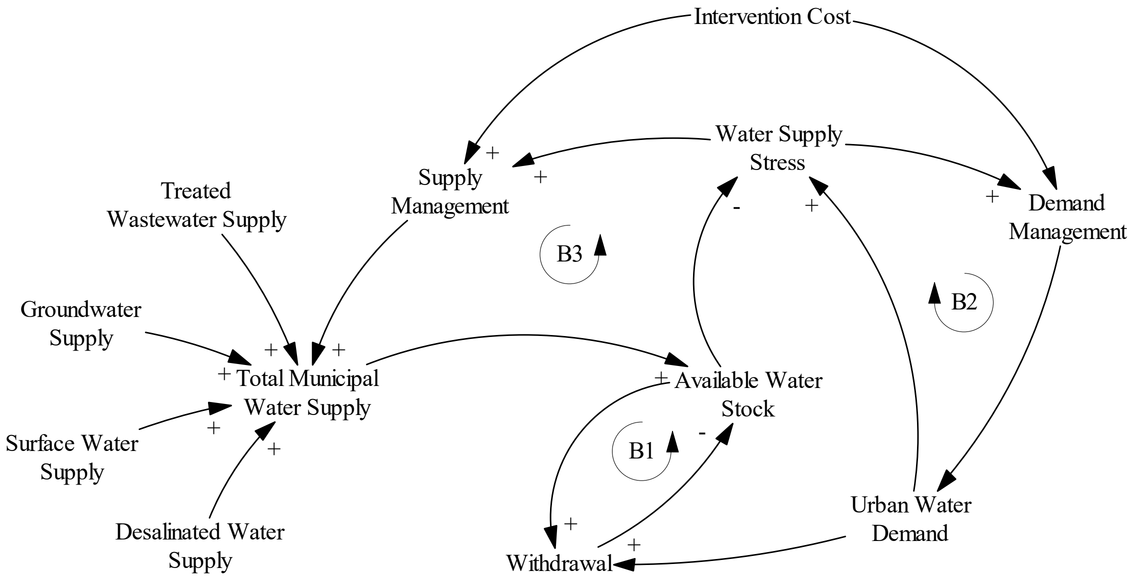


Figure 4.4: Current Water Stress and the Cost of Intervention CLD

In addition, the quality and availability of water stock impacts the water supply stress experienced in the City, which results in an increase in supply management and demand management activities. These intervention actions require funding referred to as the intervention cost, which allows for improvements in management activities, either through legislation or goal orientated programmes, to reduce water demand and increase water supply.

Surface Water Supply

Surface water accounts for the majority of fresh water stock for urban usage in the City of Cape Town. Augmentation schemes to add additional supply capacity is planned for 2021, which aim to yield an additional 23 million m^3 water annually. However, this is not a sufficient increase in yield to address the shortfall and over allocation of water sources (Pengelly et al., 2017). Precipitation, surface water runoff, transfers and recharge serve as input streams that raise the level and storage of surface water, limited by the dam capacity which may be increased through feasible augmentation schemes. These projects require investment, in addition to annual maintenance and depreciation mitigation funding. Furthermore, surface water is subjected to evaporation, filtration and transfers, that reduce the stored water levels.

According to the 1998 National Water Act (NWA), the total water resources for allocation, is the remaining supply after all legal obligations and requirements are met. These include water for strategic use such as electricity generation, international agreements and ecological reserves as per Figure 4.5 (Pengelly et al., 2017).

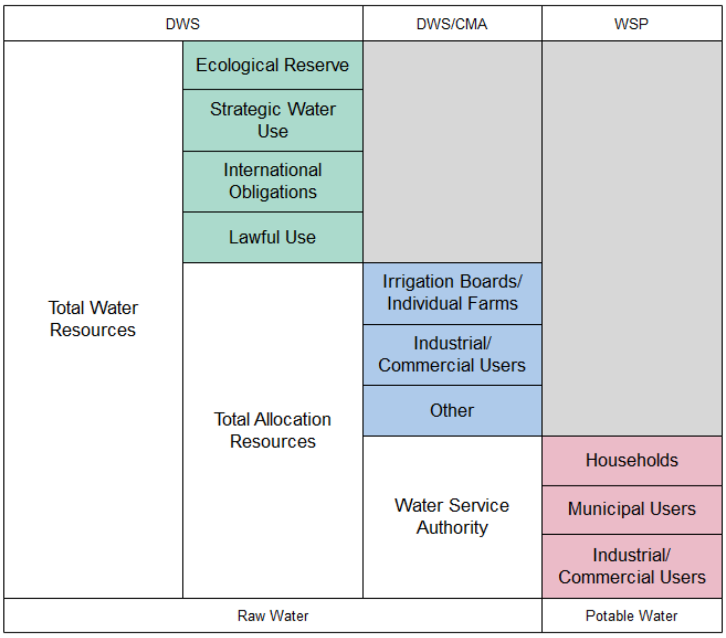


Figure 4.5: The Water Allocation Process (Pengelly et al., 2017)

The remainder of raw water stock (surface water and groundwater) is allocated by the DWS or the relevant CMA. Furthermore, all extracted water, raw or otherwise, require a permit from the DWS and is allocated as dictated by the priorities prescribed by the NWA and relevant strategies. Subsequently, shortfalls have been identified with regards to the clarity of the allocation process and available allocation quantity.

Precipitation is an exogenous variable that impacts the amount of runoff and direct catchment of surface water. The major dams supplying surface water to the urban City are open and thus exposed to warm windy summers, which cause an increase in evaporation rates. The higher the surface water supply, the larger the surface area and therefore, the higher the amount of evaporation.

As per balancing loop B5 in Figure 4.6, the increase in evaporation leads to a decrease in surface water supply, which subsequently leads to a reduction in evaporation. As surface water supply increases, the total water supply is increased, which results in the available water stock rising. In the balancing loop B4, it is evident that a rise in available water stock causes a decrease in the experienced water supply stress. In turn, the efforts towards the management of water supply declines in response to a reduction in water stress. Ultimately resulting in less effort expended in providing total water supply, resulting in a decline in total water supply. However, in the reinforcing loop R1, the decline in available water stock, causes an increase in water supply stress that ultimately impacts the economic growth of the City, reducing the available budget for intervention, resulting in a decline in augmentation schemes or upkeep further reducing the dam capacity.

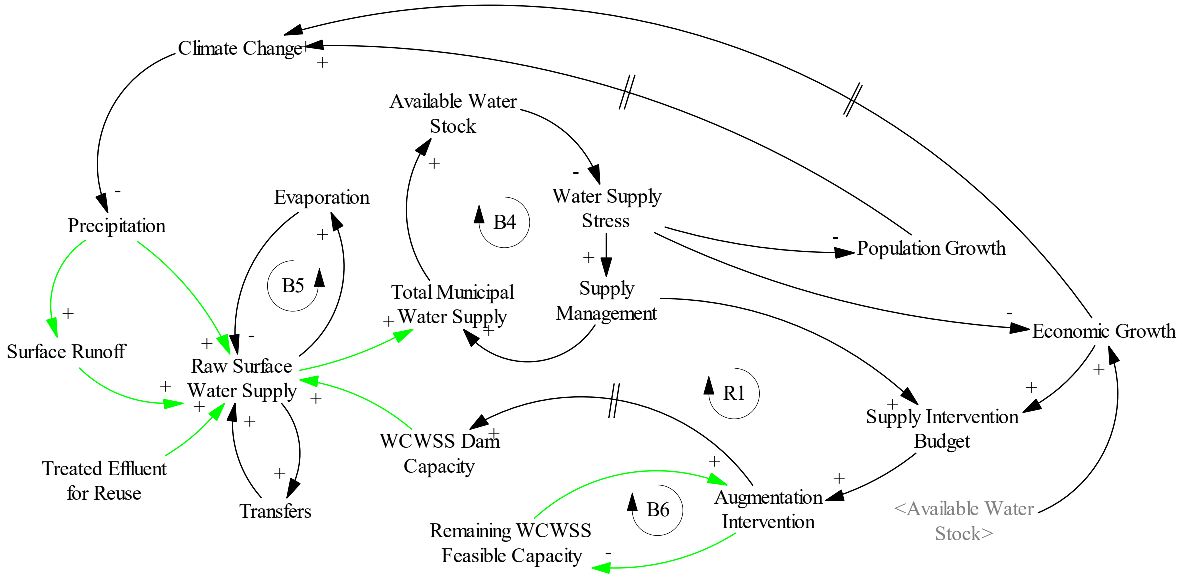


Figure 4.6: Surface Water Supply CLD

A reduction in dam capacity leads to further reduction in surface supply, ultimately increasing the water supply stress. However, the increased supply management actions as a result of increased water stress, require augmentation interventions. After a period of time, referred to as a delay, the capacity of the dam is increased, resulting in potential surface water supply increase and therefore, a reduction in water supply stress.

Chapter 2.3.1 reviewed literature addressing water shortages in urban cities. The investigation brought to light several causal links and variables for assisting the development of *water as a resource* sub-models for the City of Cape Town. Therefore, similarities exist among the City of Cape Town and general supply management models found in literature. To highlight variables of importance to the *water as a resource* subsystem for the City, the links are indicated by light green arrows. These variables are central to the alleviation of water supply stress and addressing the supply side of the water balance.

Groundwater Supply

In nature, the groundwater system remains in equilibrium as a result of approximately equal water recharge and discharge in the system over a period of time. Recharge occurs through precipitation, which percolates to the water table, or water stock is recharged by inflows from wetlands, dams and rivers. Water is discharged from the groundwater stock through evaporation, abstraction and flow into dams, wetlands, saltwater bodies, springs or rivers. The abstraction of groundwater changes the natural recharge patterns, thus mitigation actions are required to ensure the groundwater system remains in equilibrium.

There are government imposed restrictions on groundwater extraction to ensure sustainable water sources for the future. These restrictions, as prescribed by the City of Cape Town, include the restriction to groundwater application that impose limits on the use of groundwater for irrigation and non essential purposes. Furthermore, the restrictions on groundwater resources must adhere to the National Environmental Management Act (NERA), which undertakes programmes aimed at protecting the environment. Restricted drilling zones, approval processes, licensing and the development and management of recharge sources are programmes taken on by the City as part of the responsible and sustainable usage of groundwater resources to supplement surface water sources.

The Utilisable Groundwater Exploitation Potential (UGEP) manages and restricts the volume of groundwater abstracted based on the maximum allowable water level drawdown, which change with drought conditions. Thus, the UGEP is always less or equal to the Average Groundwater Exploitation Potential (AGEP), stipulated in the National Water Act (1998). In the 2017 State of Environment Outlook Report for the Western Cape Province, the drought condition UGEP is reduced to 659 $\mathrm{M}m^3$ from 1049.3 $\mathrm{M}m^3$ per annum (Adams et al., 2017).

Both water quality and the aquifer yield are affected by overexploitation, which results in unsustainable usage as a result of lowering groundwater levels and pollution. Consequently, the importance of effective management and monitoring of these groundwater sources must not be underestimated. Figure 4.7 illustrates the fundamental groundwater causal loop diagram, which serve as a source of water supply to the City of Cape Town.

As groundwater is withdrawn from the available groundwater supply, the total water supply increases. However, as per the balancing loop B7, the available groundwater supply decreases. Groundwater is recharged by various external and internal variables, where natural and synthetic recharge streams increase the available groundwater supply. The balancing loop B8 is similar to the surface water supply loop B4, increasing intervention actions as a result of a rise in water supply stress.

An increase in total water supply leads to a decrease in water supply stress, the need for supply management is decreased, subsequently lowering of supply intervention budget. Reduced intervention funds and legislation control lowers the capacity of extraction pumps, withdrawing less groundwater and ultimately causing a decline in available water stocks. However, the reinforcing loop R2 indicates that an increase in experienced water supply stress results in a drop in the GDP and therefore, less available funding for supply intervention. As water supply stress rises, constrained conditions apply that decrease the UGEP extraction allowance, which is unique to this conceptual model.

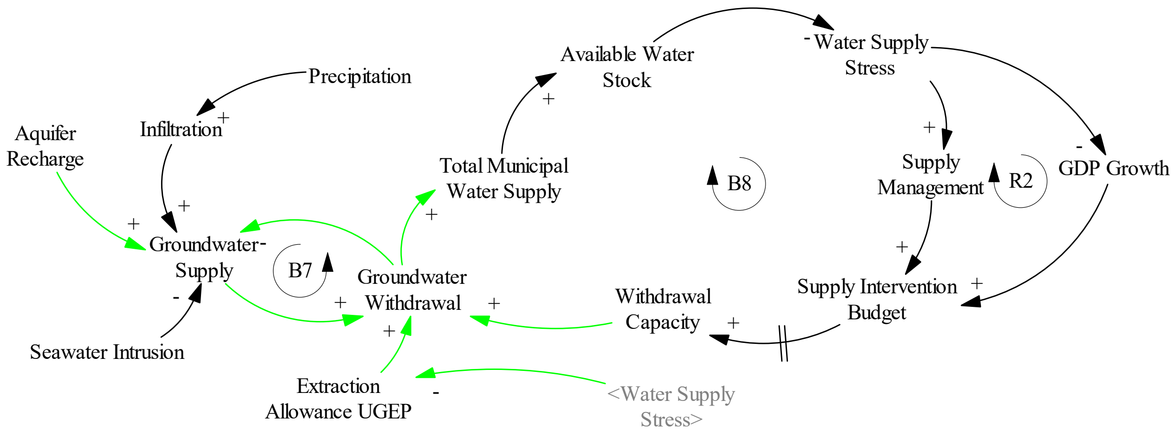


Figure 4.7: Groundwater Supply CLD

Water Treatment Works

The City of Cape Town boasts high quality drinking water, as a result of high calibre treatment processes and mostly unpolluted sources of fresh water, both from aquifers and mountain catchment areas (CoCT, 2018e). The South African National Standards (SANS) for drinking water is strictly adhered to and is awarded as a top performer by the DWS based on the City's Blue Drop scores, an incentive based quality adherence programme for freshwater treatment facilities.

The collective water treatment capacity for the City is approximately 1600 MLD. Once water is treated and dissolved or suspended particles and pathogens have been removed from the raw water, the treated water is stored in the City reservoirs. Water reservoirs are part of the reticulation system and serve as a form of demand management, coping with the fluctuation in urban demand throughout the day.

During non-drought years when water allocations are unconstrained, the City's reticulation system can manage up to 880 million m^3 of treated drinking water per day, distributed to 650 000 customers. Pump stations, reservoirs and pipelines form part of the urban reticulation system, transferring usually pressurised water to the relevant consumers. This reticulation system requires constant maintenance and development as the City grows to meet the required standards and demand. The loss of treated water attributed to faulty connections, meter inaccuracies and burst pipes are costly areas of waste for the urban water system, which result in a loss of up to 15% of otherwise usable drinking water. Subsequently, the water treatment process overview is illustrated in Figure 4.8 provide insight into the relationship among system variables.

The water treatment process depends on the capacity and condition of the reticulation system. Consequently, funding for maintenance, operation and upgrades are derived from water sale revenue and stakeholder contributions, which are dependent on the quantity of water sold, national objectives and the tariff charged per unit.

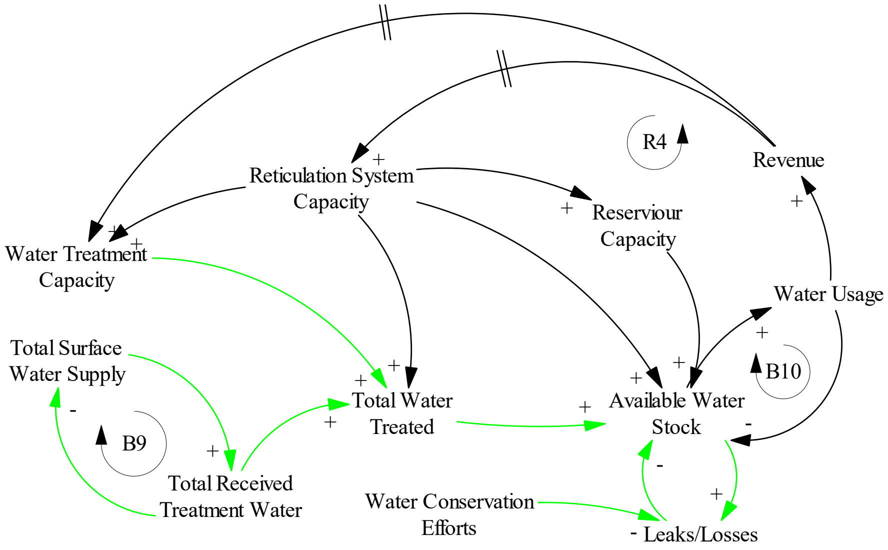


Figure 4.8: Treated Water CLD

The reinforcing loop R4 illustrates the increase in revenue and reticulation system capacity as a result of additional water stock and usage, which further promotes revenue return. Ecological and geographical limits are not included in the causal loop. However, capacity and stock cannot grow continuously as a result of various limiting factors. Finally, the influence of conservation management activities on reticulation losses serve to reduce waste in the system.

Water conservation initiatives aim to reduce losses within the reticulation system through smart metering, leak detection and pressure management (CoCT, 2018c). These actions result in a decline in losses which allow for the retention of available water stock for municipal consumption and revenue generation.

Rainwater Harvesting CLD

Rainwater harvesting is an alternate source of water that allows the City of Cape Town to become less reliant on conventional surface water resources (Fisher-Jeffes, Armitage, et al., 2017). Hence, the City of Cape Town is promoting several alternative sources of water as part of water conservation initiatives, of which rainwater harvesting in the domestic and industrial sector is promoted (Millson and Roux, 2015).

In February 2019, the City of Cape Town released a set of guidelines on the use of alternative water installations within the City. The guidelines provide consumers with essential information on how to correctly register and install alternative water systems to avoid contamination of municipal drinking water (CoCT, 2019b). Although rainwater harvesting systems do not require licensing from the Department of Water and Sanitation (DWS), approval from the City for plumbing installation and use of harvested rainwater is required. City building compliance approval is mandatory when rainwater storage tanks exceed 10 000 litres in capacity or are built on-site. The guidelines also address the route for overflow of harvested rainwater, which require chemical treatment to overflow into sewer. However, untreated rainwater overflow can be directed into the municipal stormwater system.

Rainwater harvested is dependent on several facets, which include the capacity of the rainwater collection/storage tank, the rainwater runoff area (rooftop) and the amount of rainfall (precipitation). Figure 4.9 shows that storage capacity is increased through investment, while runoff can be optimised by maximising the catchment area and runoff coefficient. Increased capacity and runoff translates to a rise in harvested rainwater and therefore, an increase in the total water supply as depicted by the balancing feedback loop B8*. However, precipitation is an exogenous parameter, with the City of Cape Town experiencing the majority of its rainfall during winter months, when the demand for non-potable water, used for irrigation and filling of swimming pools, is low.

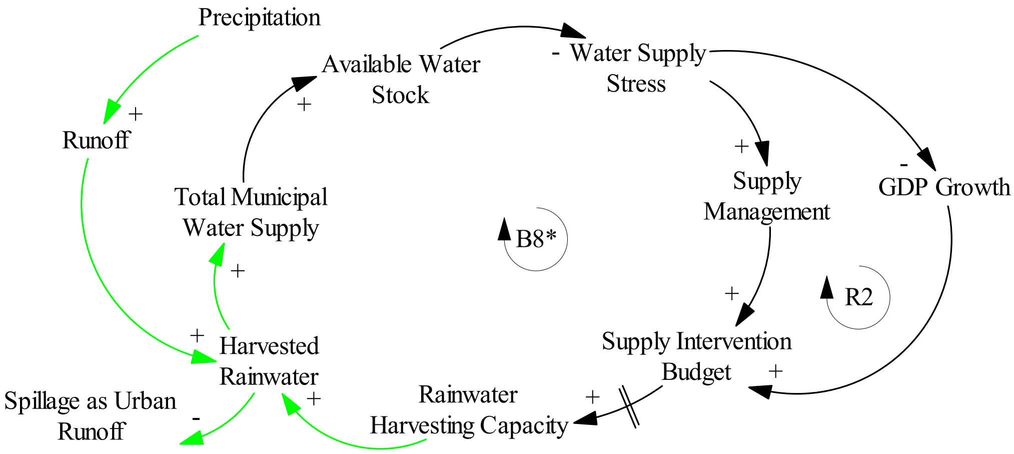


Figure 4.9: Rainwater Harvesting CLD

Treated Wastewater Supply

Treated effluent serves as an alternate source of water to offset the use of potable water. The target for wastewater treatment is set and measured as a percentage of potable water used. Figure 4.10 represents the potential supply that treated wastewater can add to the total water supply in the urban water system.

With a rise in available water stock, an increase in water usage is expected, which results in additional municipal wastewater. In the reinforcing causal loop R3 the increase in waterwaste received by the Waste Water Treatment Works (WWTW), adds to the total wastewater treated, therefore adding to the total water supply. The balancing loop B11, illustrates the rise in supply management with added water supply stress. Subsequently, leading to additional supply interventions and an increase in capacity and supply of treated wastewater, ultimately adding to the available water stock and reducing water supply stress as a result.

Further exploration of the reuse of treated effluent in the urban water system for the City is addressed in the *water as a waste stream* section (§4.3).

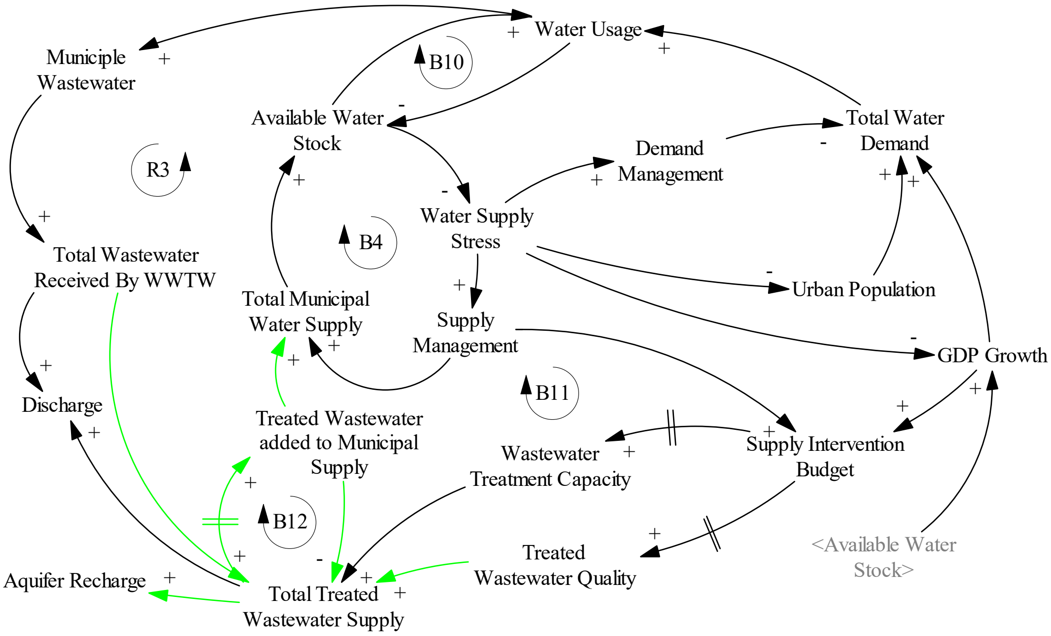


Figure 4.10: Treated Wastewater Supply CLD

Water as a Resource CLD

The entirety of the *water as a resource* subsystem for the urban water system is represented in Figure 4.11. This subsystem is a section of the urban water system that aims to provide context to the supply side of the water value chain for the City of Cape Town.

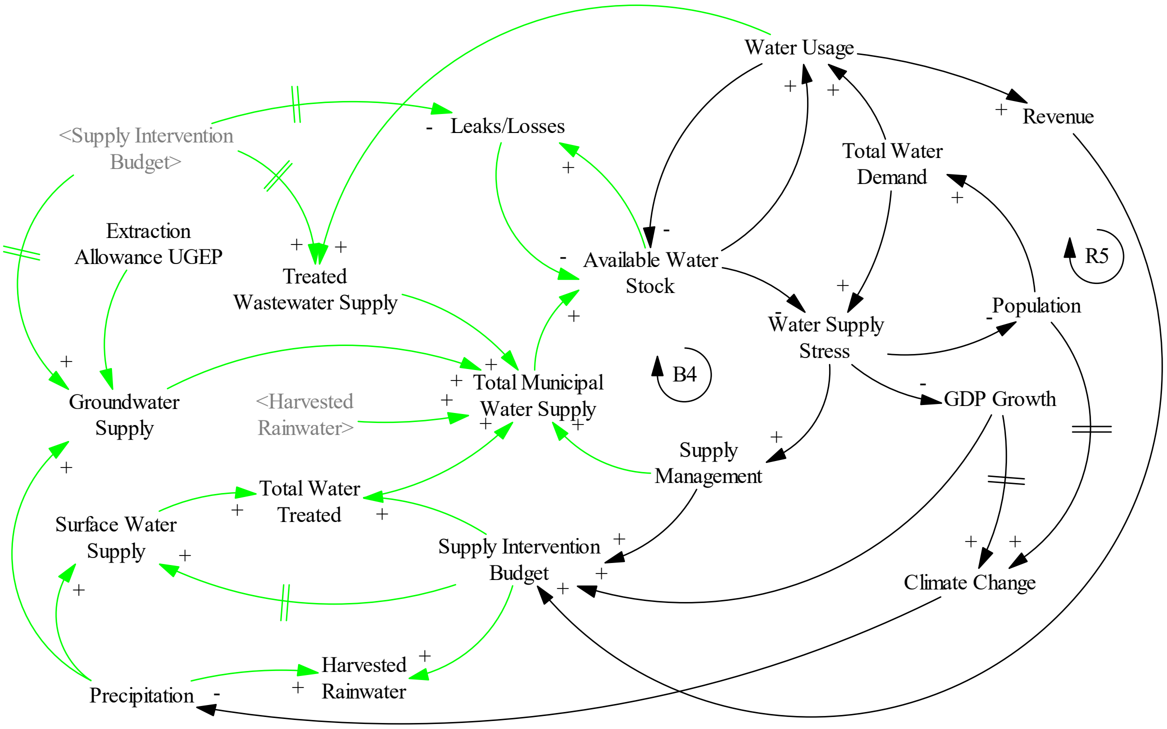


Figure 4.11: Water as a Resource CLD

As the total water supply increases, which results in more available water stock in the system, the usage of water increases. This leads to an increase in revenue generated by sales, allowing for an increase in supply intervention and therefore, additional capacity to generate water supply as per the reinforcing loop R5.

The variables with influence on the *water as a resource* subsystem in Figure 4.11 is connected with light green arrows. Additional sources can be added to expand the water system as required, subsequently the versatile model allows for the incorporation of changes and interventions alternatives. Furthermore, causal links are introduced in the combined *water as a resource* CLD to provide insight into supply network and the connecting water roles.

4.4.2 Water as a Product Input CLD

Water users in the City of Cape Town include domestic, education, health, industrial, institutional and commercial users. The revenue from these users are utilised for maintenance, repairs, infrastructure development and service provision. Thus, tariffs are increased to curb usage during drought seasons and to cover the deficit required for fixed costs as a result of decreased total usage and therefore, reduced revenue as per implemented water restrictions (Nzima and Sigenene, 2017).

Although, there are various consumers the majority of users are attributed to residential houses, flats and complexes. Consequently, water conservation through a reduction in per capital usage will significantly influence the total water demand, for both indoor and outdoor usage. Public awareness and educational programmes are some of the intervention actions implemented by the City of Cape Town to promote efficient water use and reuse within domestic residences.

To improve water management, the domestic water usage and consumption patterns are investigated, which found that the majority of potable water consumption can be attributed to personal cleaning and toilet flushing (Flower et al., 2015). Furthermore, the demand for water fluctuates with growth in both population and economy, however the domestic demand in the City of Cape town is significantly more than industry demand, thus the growth in population and urbanisation carry more influence in demand predictions.

National and regional technical reports in §4.1.1 and models explored in literature (Chapter 2.3.1) provide structure and input to the model development. Therefore, adjustments and key variables for the *water as a product input* subsystem are indicated by light blue arrows. These variables serve to influence the use of water resources in the City of Cape Town.

Urban Population

For the City of Cape Town, the growing population and the declining average household size, result in challenges associated with an increase in demand for housing and urbanisation as illustrated in Figure 4.12. This growing trend requires additional connections, services and consequently result in increasing the total water demand.

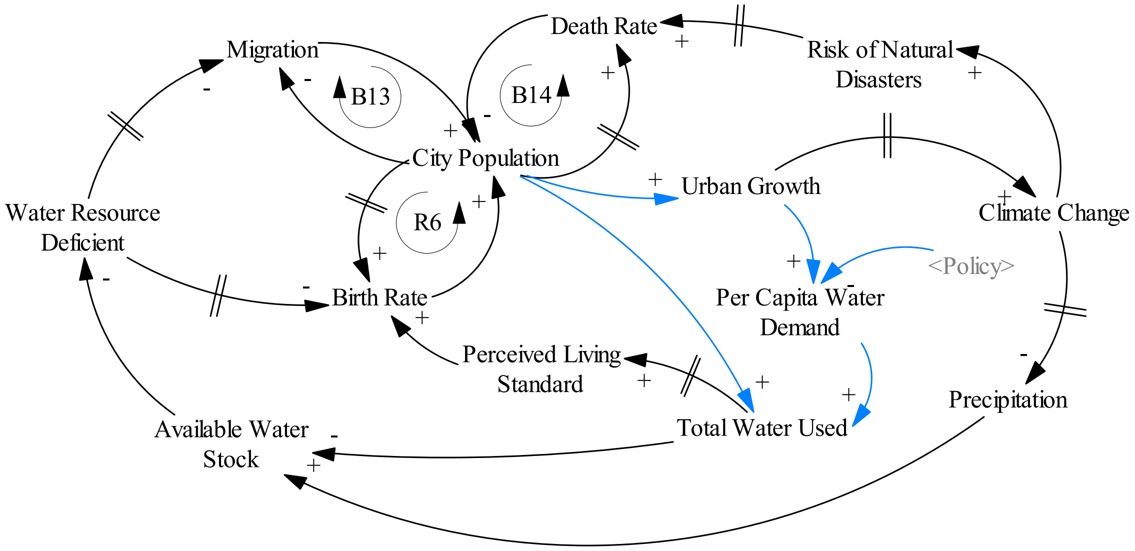


Figure 4.12: Urban Population CLD

The City population grows with the inflow of urban residence as a result of migration and an increase in birth rate as represented by the reinforcing loop R6. This inflow places further strain on the available water stock for the urban City. However, for the purpose of the research study, the *Urban Population* stock is simplified to increase with the rate of population growth in the City of Cape Town.

Water Demand

The urban water usage for the City of Cape Town in 2011 was estimated at a total of 332 million m^3 with a population of 3,68 million residents, which roughly estimated the per capita usage of 90.2 m^3 per annum (Pengelly et al., 2017). Pengelly et al. (2017) predicts that the demand will continue to grow in the future, resulting in a supply deficit with associated economic costs. Although the per capita demand has decreased since the implementation of regulatory demand management strategies and conservation programmes, the population in the urban City continues to grow, resulting in a continuous increase in total water demand.

Understanding population behaviour and usage patterns are beneficial to discerning the urban demand for water resources and the water waste generation for both indoor and outdoor purposes. Industrial water requirements differ from domestic or municipal needs in terms of quality and pressure requirements, thus the treatment and reuse of wastewater is popular in urban industries. Furthermore, cost incentives for treated wastewater usage in the industrial sector, attracts the usage of alternative water sources and therefore, reduces the demand placed on portable water sources.

The basic demand structure for *water as an input* in the urban City of Cape Town is illustrated in Figure 4.13. The total water demand is derived from the two major drivers of water use in the urban water system, domestic and industry consumption. Subsequently, the balancing loop B10 represents the impact of an increase in water usage on available stock and how the stock level in turn restricts the water usage in the system.

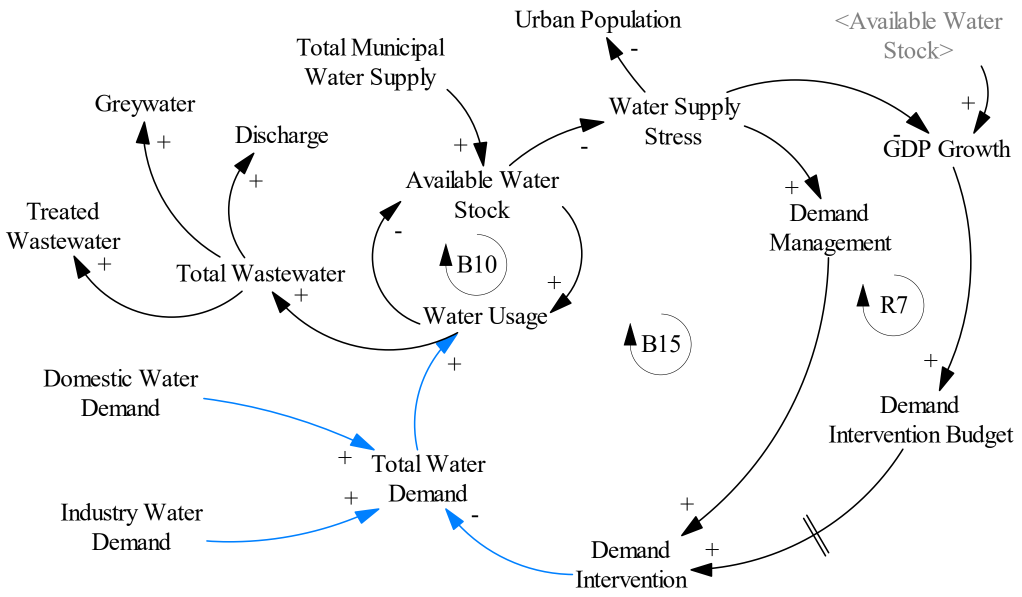


Figure 4.13: Urban Water Demand CLD

As water supply stress is experienced by the system increases, the demand management efforts and intervention actions are increased in the system, as per balanced loop B15. From which total demand for water is reduced to lower water usage, which improves the water supply stress as water stocks increases.

On the other hand, reinforcing loop R7 indicates the GDP Growth is lowered with higher water stress, thus leading to less allocated intervention funds, subsequently reducing the demand interventions. This leads to higher water demand and usage, ultimately heightening the water supply stress in the system. Therefore, the effect of water supply stress on the intervention actions should be considered as part of the holistic system.

Domestic users consume approximately 70% of total water supplied to the City of Cape Town, with the remainder allocated to the collective industry consumers. With commercial, industrial and municipal sectors categorised under the collective term, industry consumers. The water demand and consumption patterns differ for both industry and domestic users. Consequently, the distribution of demand for potable and non-potable quality water for industry and domestic use influence the demand management approach.

Cost Accounting

As urban users become reliant on incentive based and cost saving alternative water sources, the volume of potable water usage declines, leading to reduced revenue income. Furthermore, capital and fixed costs for centralised infrastructure and service delivery attributes to a significant fraction of the consumer bill. The decline in reliance on treated municipal supplies lead to higher tariffs to cover running and improvement costs. System losses and leaks place further strain on the costing of the central urban water system, as costly treated water is lost to the system without the benefit of revenue generation.

For this research study, the costs and incomes pertaining to tariff structures and water demand in the urban water system is not incorporated in the urban water system model. However, model expansion can easily accommodate cost structures to fit an evolved model purpose as illustrated in Figure 4.14.

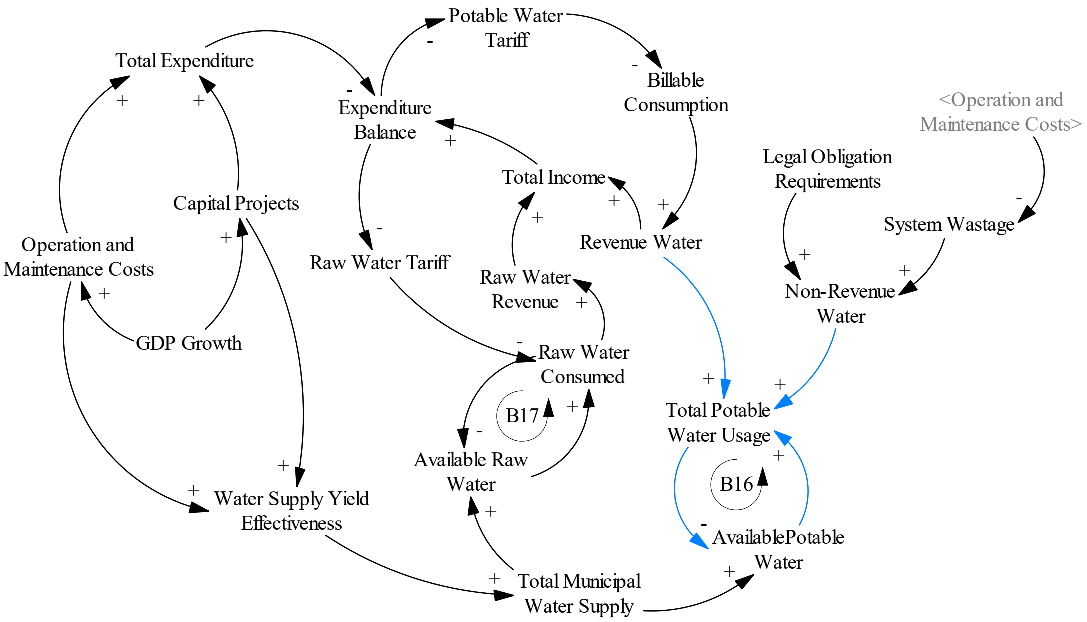


Figure 4.14: Urban Water System Cost Recovery CLD

Furthermore, *water as a product input* incorporates the consumption patterns and water demand in the urban City of Cape Town. For the purpose of the model the distinction is made between the quality of water demanded and the quantity demanded by both industry and domestic consumers. Subsequently, this leads to additional cost implications not included in the model evaluation, such as stepped water tariffs.

Water as a Product Input CLD

The National Water Act of 1998 emphasises that a shift from supply driven management of water resources is required to ensure the sustainable use of water sources, through efficient management and balancing of water reserves and accessibility to all South Africans. Industrialisation, urbanisation and population growth threatens the future of water supply in not only South Africa, but on a global scale. Thus, appropriate intervention and corrective actions are required to manage and regulate urban water usage in accordance with the available annual yield of water resources in the region.

Conservation and demand management initiatives are driven by local water demand management strategies responding to water supply stress experienced in the system. The relationship among water demand and management intervention is illustrated in Figure 4.15. The light blue arrows connect variables associated with the use and demand management of water resources that serve as an input to the urban water system.

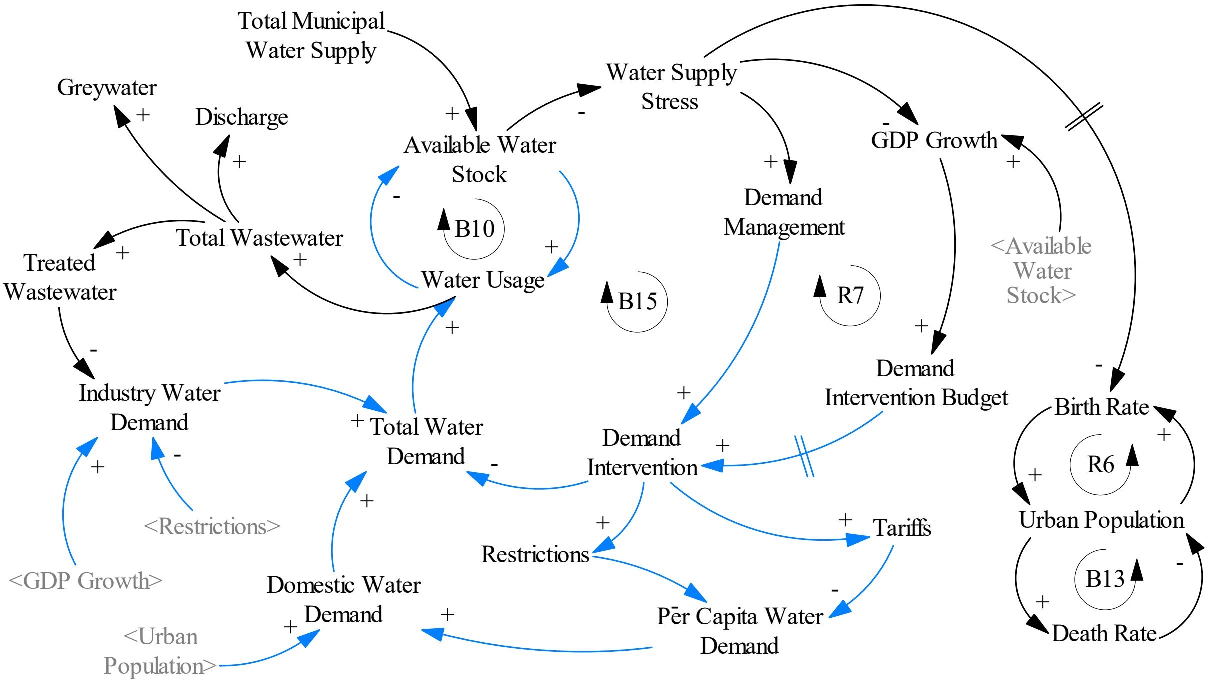


Figure 4.15: Water as an Product Input CLD

The consumption of water sources, as per urban demand, result in a decline in available water stock and the generation of total wastewater. While the increase in water supply stress initiates additional demand management intervention, restricting the total water demand. Furthermore, the potential value from wastewater sources produced by system users are evaluated for potential value extraction in the next subsection.

4.4.3 Water as a Waste Stream CLD

The City of Cape Town and surrounding regions are fast approaching the limit of economically feasible surface water augmentation, whilst the demand continuously increase with urbanisation and population growth in the urban City. The effects of climate change furthers the imbalance in the urban water system, with decreasing rainfall and more frequent drought years reducing the total water yield (DWS, 2017). This requires water management authorities to develop and implement new and more sustainable methods of reducing demand, conservation and extracting value from waste streams.

A mix of water sources aim to contribute to the reconciliation of water supply and demand. These include alternative sources such as wastewater reuse and rainwater and stormwater harvesting. While the total system input requirement can be reduced by limiting losses and leaks in the system. Therefore, alleviating the demand on natural resources needed for ecological and socio-economic sustainability. Several goals and strategies aimed at addressing the key issues related to ensuring a water future in South Africa, are addressed in national and regional legislation and strategies, including the Water Conservation and Water Demand Management Strategy (WCWDM).

To intensify efforts made to reduce losses in the water system, the understanding of water demand, usage and discharge patterns for water users becomes critical to developing and implementing appropriate governance and planning (Fu and Wu, 2014). The 2019

Cape Town Water Strategy commits the City to develop a mix of diverse water sources and promote the wise use of water to increase the resilience and sustainability of water supply for urban consumption (CoCT, 2019a). Furthermore, the 2015/2016 report on water demand management and strategy in the City of Cape Town provides long-term conservation efforts to ensure the balance between water demand and available water resources. The report emphasises the importance of reducing waste in the system, which aligns with the circular economy principle of zeroing waste streams.

Water Waste Streams

Domestic urban usage can be sectored into three major groupings, potable usage, non-potable usage and leaks. These usage patterns provide insight into the per household or per capita consumption and waste generation trends. This understanding allows for the identification of the quality and type of waste streams with potential value that can be extracted to add to the mineral, water and energy resources for the City. Wastewater generated from domestic water usage contributes to a large portion of input into the wastewater treatment plants, serving as a valuable alternative source of water for urban and industry usage.

The sources of input for the Waste Waster Treatment Works (WWTW) are predominantly derived from municipal discharge and industrial effluent. With indoor usage for domestic users estimated at 70% of total water consumption, an approximation of the discharge into the reticulation system can be derived from the estimated per capita consumption (Flower et al., 2015). According to the 2013 City of Cape Town Wastewater and Industrial Effluent By-law, all water with or without suspended or soluble particles derived from any industrial, mining, manufacturing or similar process is categorised as industrial effluent, which add to the inflow into wastewater treatment plants in the City.

Stormwater, on the other hand, is defined as the accumulation of groundwater, precipitation and spring water conveyed in the natural and constructed stormwater system, which serve as the management and flood prevention mechanism in urban cities. Stormwater harvesting has the potential to serve as an aquifer recharge source, however the process requires storing facilities, conveyance, quality monitoring and volume control.

The urban City serves as a catchment area, allowing for channelled water flows to be directed to natural floodplains and wetlands. Due to the lack of knowledge, information and data with regards to the stormwater system and behaviour in the City of Cape Town, this potential source of water has received limited attention as an alternative source to add to the constrained water supply and is mostly discharged into the ocean.

However, in recent years several studies have been done, predominantly by the University of Cape Town, which address the potential of improving water security in South Africa through the utilisation of stormwater harvesting and urban design. Stormwater harvesting (SWH) plays a significant role in the Atlantis Water Resource Management Scheme (AWRMS). Harvested stormwater, together with treated effluent, is used to recharge approximately 30% of the Atlantis aquifer system (Fisher-Jeffes, Carden, et al., 2017).

Generated greywater in industry and domestic facilities is another alternative source of non-potable water that serve to alleviate total water demand in the urban water system. Wastewater, as referred to in this report and in Figure 4.16, is the collective term for both domestic wastewater and industrial effluent. The variables associated with the reuse and retention of water waste streams are connected with orange arrows to represent the *water as a waste stream* sub-models.

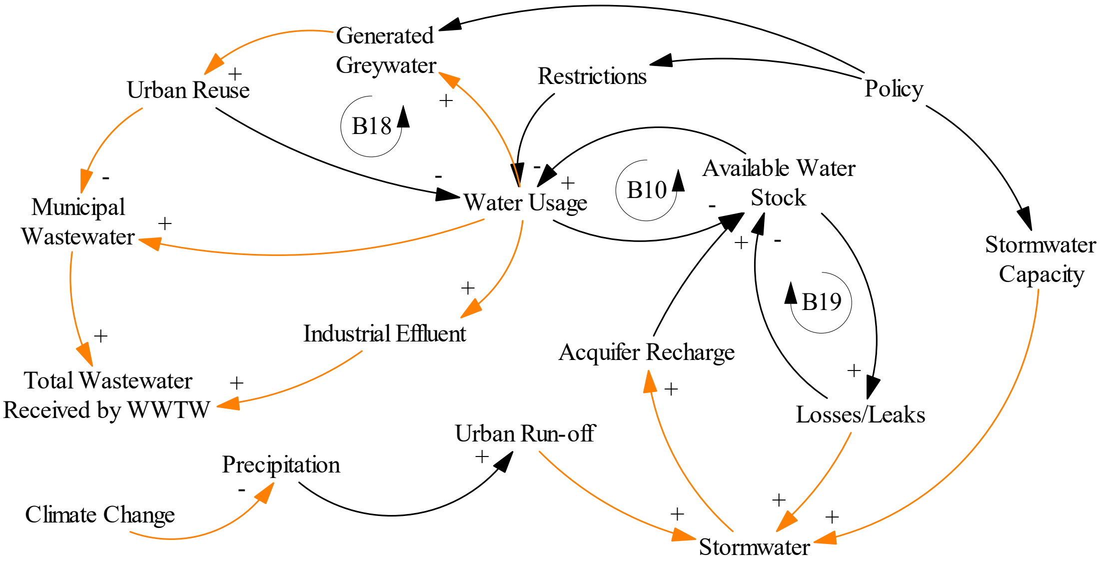


Figure 4.16: Wastewater Sources CLD

As water usage increase, the generated greywater increases, subsequently allowing for the rise in urban reuse, reducing water usage as per the balancing feedback loop B18. Furthermore, B19 illustrates the behaviour of the system indicating that as available water stock rises, there is an increase in the system losses in the reticulation system, ultimately reducing the available water stock.

The inflow of wastewater into the WWTW serve as the initiation point for alternative water source generation. Although application of this identified waste stream is limited, potential lie within the diversification of wastewater usage. Public resistance and quality control assurance are potential hurdles hindering the effectiveness of implementing potable reuse of wastewater.

Finally, demand conservation efforts aimed at curbing wasteful use of valuable water resources include the implementation of consumption restrictions. These restrictions serve to limit the usage and demand of water resources according to the prevailing water supply stress and available water stock in the urban water system.

Wastewater Treatment Works

The Green Drop Certification Programme initiative aims to ensure the quality of the facility's wastewater treatment procedures, management and operations associated with municipal wastewater discharge into water bodies and the reuse of treated effluent. With sewage disposal for the City of Cape Town being estimated at 70% of water consumption, high volumes of both domestic and industrial wastewater have to be introduced back into the environment (Nzima and Sigenene, 2017).

Various treatment processes and technologies are used to treat received wastewater at the WWTW in the City of Cape Town, each with an unique purpose and quality objective. The output product of these treatment plants depend on the intended use, which include the reuse in industrial processes, irrigation, recharge of aquifers, discharge or for potential potable usage. Treated wastewater for non-potable reuse is piped through a separate system of pipes and is currently only used for industrial, irrigation and toilet flushing purposes in the City of Cape Town.

Although limited treatment facilities are capable of treating effluent and domestic wastewater to a reusable standard, expansion of these facilities and capabilities are part of future strategies to further water conservation and prevent polluted water from entering the environment. Treated wastewater can be collected by organisations at draw-off points or receive treated wastewater through permanent distribution pipelines. Figure 4.10 in §4.4.1 and Figure 4.17 illustrate the causal links among variables in the WWTW in the City of Cape Town.

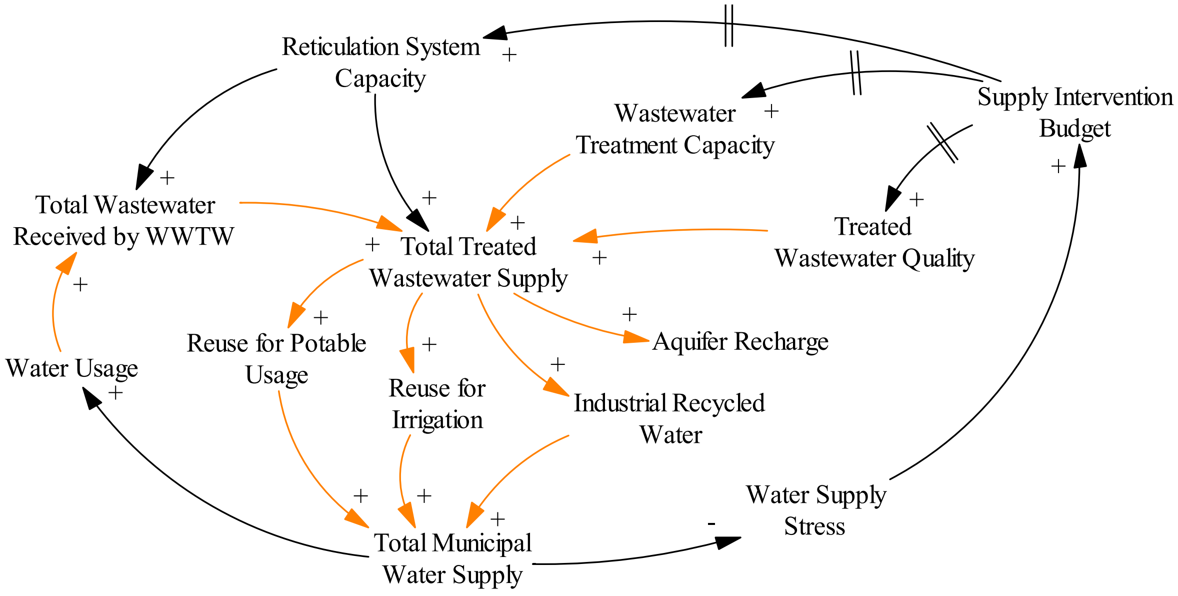


Figure 4.17: Wastewater Treatment Works CLD

The total municipal waste and industrial effluent in urban cities are received by wastewater treatment works through the wastewater reticulation system and treated for discharge or reuse. Thereafter, the recycled effluent is returned to the total water supply, however distinction in intended usage must be made. The recycled wastewater serves as a highly feasible alternative source of water supply and together with system loss and leakage reduction actions, provide alleviation of water supply stress experienced in the urban City.

Water as a Waste Stream CLD

The highest potential for reducing urban water supply stress lies within the final sector of the urban water system, which include the relevant waste streams. Waste can be reduced, retained or reused in the urban water system to avoid or limit raw resource extraction, thereby ensuring sustainable management of water resources and future availability. Figure 4.18 illustrates the concise representative structure of *water as a waste stream* in the urban water system.

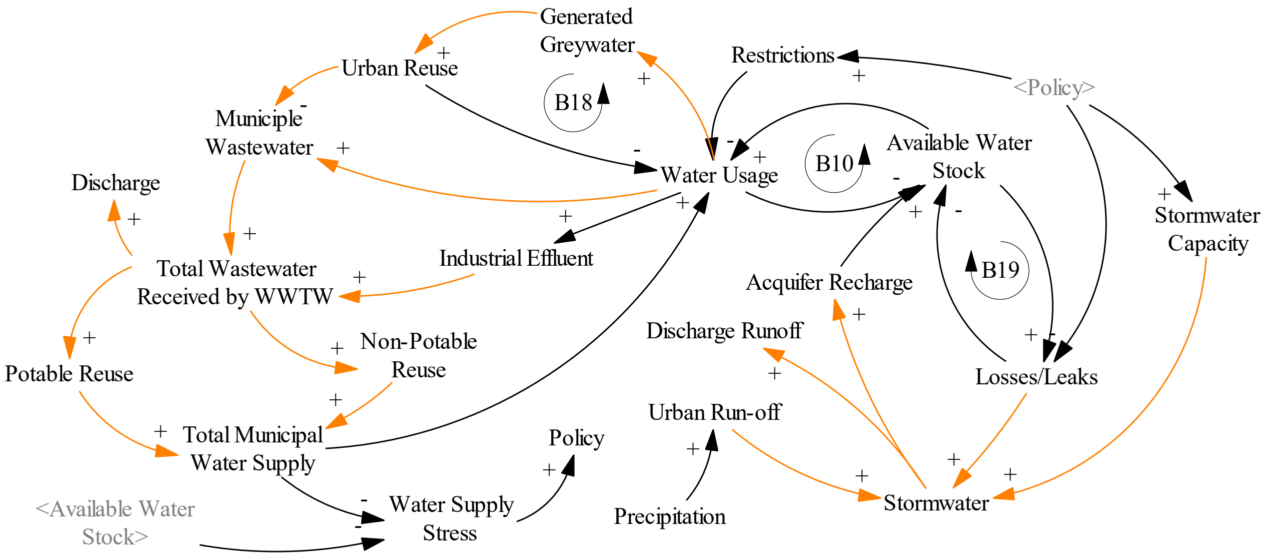


Figure 4.18: Water as a Waste Stream CLD

Management actions in the sector include the intervention actions aimed at addressing unaccounted for water, through leak detection, connection and meter repairs, pressure management and the installation of efficient water fitting. These actions are driven by national and regional strategies and policies to drive sustainability goals. Although rainwater collection, harvested stormwater and generated greywater serve as sources of water, these inflow streams are mostly limited to non-potable usage.

Thus, additional strategies and regulations serve to address potable usage through demand management and reuse motivation and education programmes, driven by restrictions and tariff steps. Consequently, funding and capital investment are required to drive these policy driven initiatives to address areas of waste. However, the implication of these actions may result in unexpected and unwanted outcomes, emphasising the need to evaluate the urban water system holistically.

4.5 Urban Water System CLD

Although agriculture in South Africa represents the majority of water demand, the urban City of Cape Town has a different water allocation weighting in relation to the Western Cape. Water demand is predominantly attributed to domestic and municipal demand for fresh water resources, which require water derived mostly from surface water resources.

The raw surface water is treated, stored in reservoirs and distributed through the reticulation system to consumers for consumption. However, the demand for water resources, when unrestricted, may result in a severe supply deficits with regards to the available water yield for the City. Hence, the importance of regulatory restriction aimed at curbing the usage of available water stock.

Although greywater reuse within domestic residence are encouraged, the reduced amount of sewage may become cumbersome to the infrastructure and required sewage flow. These interconnected influence among system parameters and the effects of intervention alternatives are to be considered throughout the urban water system. Figure 4.19 illustrates the concise causal loop diagram for the City of Cape Town urban water system. The three water roles, depicted by different colours, interconnect to provide an integrated model representing the urban water system. Black arrows are used to represent the link connecting water supply stress to policy initiation, urban population and fluctuations in GDP growth.

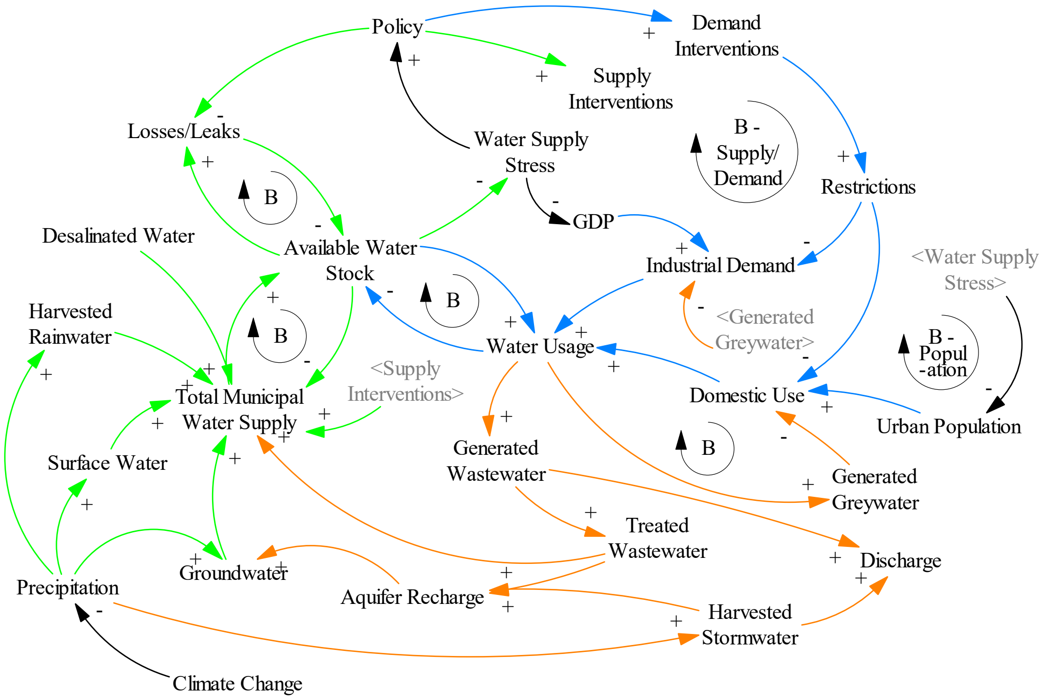


Figure 4.19: Urban Water System CLD

Wastewater is generated by both municipal and industry consumers, which is received by the WWTW through the sanitation distribution network. The capacity, treatment quality and reticulation system are dependent on funding and environmental limitations. Thus, understanding the interactions and behaviour of these system elements as a whole allows for the evaluation of variable changes to provide insight and understanding of the system behaviour and not just the behaviour of parts. The causal loop diagrams, although not populated with the entirety of influencing variables, provide the visual representation of qualitative information as derived from publicly available literature, regulations and technical reports.

The conceptual model for the urban water system in the City of Cape Town allows for the identification of likely primary influencing feedback loops. Consequently, urban water use is identified as a potential primary feedback loop, influencing the available water stock and water supply stress directly. However, to support the identification of the most influential feedback loops affecting the model behaviour, dynamic evaluation of the system response is required.

4.6 Conclusion

The initial phase of the model development lie in the qualitative domain, which include the formulation of the problem and the construction of the conceptual model using system dynamics as the appropriate modelling method. To provide clear guidance for the construction of the model the problem formulation phase serves to clearly define the purpose and boundaries for the model. The urban water system model for the City of Cape Town aim to evaluate and test the legislative decision alternatives aimed at addressing the retention and reuse of water streams in the urban water system for the City of Cape Town, to ensure a sustainable economic, social and environmental future.

The objective for the decision support model is to provide decision-makers with insight into the behavioural patterns and shortcomings of the urban water system. The model is constructed using causal loop diagrams that serve as a visual language to describe the interdependencies and directional feedback loops among system variables. These diagrams ultimately aim to describe the effects of policy intervention on the performance and sustainability of the system as a whole, using suitable model indices as performance measurements.

The deficit between required water demand for urban usage and available water supply is a suitable index for determining the benefit intervention actions may return, in relation to the associated cost. The model is constructed in accordance with the three water roles derived from the circular economy principles that strive for zero system wastage. These sectors can be categorised as *water as a resource*, *water as a product input* and *water as a waste stream.*

Several causal loop diagrams represent various elements of the system to visually describe the relationship and interaction among the urban water system variables. However, to address the growing demand for limited water resources the drivers of demand and potential water supply alternatives are highlighted. Although certain policies and directed strategies have utilised both supply and demand strategies and interventions, the highest potential still lie in the uncapped waste value sector. The reduction, reuse and retention of water in the system serve as highly feasible actions aimed at reducing the supply deficit in the urban water system.

The evaluation and prediction of the effects and outcomes of intervention actions on the urban water system, as prescribed by regulation and strategies, is a costly and time consuming process. Thus, the constructed model, based on the qualitative conceptual model, ultimately serves as support to decision-makers that aim to provide insight into the behaviour and responsiveness of the system to changes in variables.

Chapter 5

Development of the Decision Support Model

> *"There are no separate systems. The world is a continuum. Where to draw a boundary around a system depends on the purpose of the discussion."* –
> Donella H. Meadows, Thinking in Systems: A Primer

The aim of this chapter is to develop the second phase of the decision support model that primarily lie in the quantitative domain. The development of the dynamic model for the urban water system in the City of Cape Town is categorised in two main steps, namely dynamic modelling and model validation. System dynamics models are used to represent the real-world urban water system for the City of Cape Town, for the purpose of providing insight and understanding into the behaviour of the urban water system for policy evaluation and decision making.

5.1 Dynamic Modelling

Mathematical equations are constructed to represent relational behaviour among system variables in accordance with rates and values found in data sources (Simonovic and Rajasekaram, 2004). The transition from causal loop diagrams to dynamic modelling techniques such as stock-and-flow diagrams, require that the distinction be made between variables, as either stocks, connectors or flows in context to the system. In the modelling environment, variables are defined as the qualitative or quantitative measurements for the system parts and can be categorised as stocks, flows, sources, sinks, converters and connectors (Simonovic and Rajasekaram, 2004). The refinement of variables and the addition of descriptive equations, transforms the qualitative conceptual model constructed in the first phase, to a dynamic model capable of representing the dynamic system behaviour of the urban water system, using quantitative data and analysis techniques.

Data is collected and extracted from various sources, including modelling principles and theory from several studies aimed at addressing water resource management problems, variable calibration and evaluating policy implementation (Simonovic and Rajasekaram, 2004). Technical reports, legislative documentation, available statistics and public information and data are used to identify system variables and relational links for the development of the system model.

The causal loop diagrams serve as the qualitative mental maps which are especially valuable for generating system feedback structures and behaviour patterns. However, policy evaluation generally requires a more reliable approach, such as quantitative simulations, to generate dynamic results based on the system structure maps produced by using quantitative means (Kunc, 2016; Tulinayo et al., 2012).

The dynamic computer system model consist of more variables than the causal loop diagrams for the system, requiring checks such as relational direction and dimensional accuracy during the validation process. As stock-and-flow diagrams are involved in explaining variable relationships and assumptions, all data and information used should be referenced for transparency and validity.

5.2 Quantitative Data Extraction

The National Water Act of 1998 requires the establishment of a National Water Resource Strategy (NWRS) to facilitate the appropriate management and allocation of water resources, to ensure sustainable and equitable water for now and in the future. The distribution obligations are set out in Figure 5.1, as per the Guide to the National Water Act, with additional reference to water users in the City of Cape Town (Harpe and Ramsden, 2000).

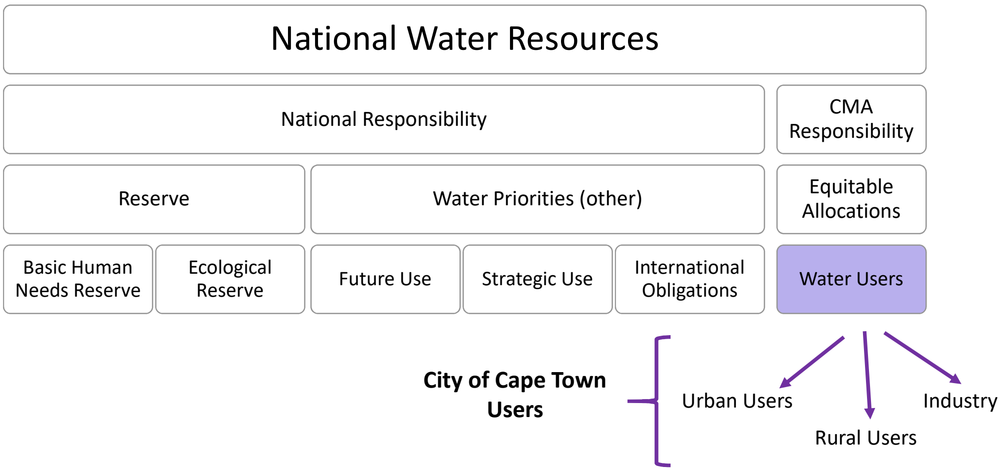


Figure 5.1: National Water Resource Allocation in South Africa

The national water resources are managed, distributed and allocated in accordance with strategic objectives aimed at achieving socio-economic and environmental sustainability. The 2013 National Water Resource Strategy (NWRS2) document serves as the second edition of the regulatory requirement for periodic National Water Resource Strategies. This report provides strategic sustainability objectives and developmental goals for the next five to ten year period, establishing the document's relevance to the research study for data extraction.

The Western Cape Water Supply System (WCWSS) is an important water system, responsible for the supply of water to the City of Cape Town and surrounding regions. The six major WCWSS dams have a combined capacity of approximately 900 Million m^3, yielding between 248-570 million m^3 per annum (CoCT, 2018a). In 2015, 358 million m^3 of water was allocated to the urban City of Cape Town, which accounts for 58% of the total allocated supply, seconded by the capped agricultural allocation of 216 million m^3, with the remainder distributed to other urban areas (Bronkhorst, Pengelly, et al., 2017).

The City of Cape Town is responsible for the management and servicing of three of the major dams in the WCWSS, the Wemmerhoek, Steenbras Upper and Steenbras Lower dams. Furthermore, primary source documents, from which the quantitative data is extracted for modelling the urban water system for the City of Cape Town, include the 2007 Western Cape Water Supply System: Reconciliation Strategy Study, the Water Outlook 2018 Report, Annual Water and Sanitation Reports for the City of Cape Town, Census statistics from Statistics SA and the GreenCape Market Intelligence Reports.

What is more, consistent units and time intervals are essential to the successful modelling and evaluation of the urban water system model. Costing, measurements and results must comply with standardised units. Subsequently, conversion units and variables assist the stock-and-flow diagrams in the simulation model to ensure the consistency of units. Water sources and usage can be measured in litres, m^3 or kg with rainfall in mm. Thus, conversions must be done accurately from one measuring unit to the next as seen in Equations 5.2.1 and 5.2.2. Water measurement for this model is presented in m^3, in order for the model to remain consistent with the majority of water measurements and costing in the available public documentation.

$$1\ m^3 = 1\ kL = 1000\ l = 1000\ kg \tag{5.2.1}$$

$$1\ m^3 \text{ Runoff} = 1\ mm \text{ Rain } \cdot\ 1\ m^2 \text{ Roof Area } \cdot\ 0.001 \tag{5.2.2}$$

Furthermore, the time horizon over which the model is simulated, to test and evaluate policy implementation, runs between 2001 and 2040, with annual time steps. Available forecasts and statistical data has refined the time period for testing to provide relevant information and data against which the model should be validated. Consequently, time conversion variables, for example *1/year*, are used to convert units for per annual measurements and values in the model.

5.3 Stock-and-Flow Diagrams

Although, causal loop diagrams allow for the visualisation and analysis of system feedback structures, a more quantitative approach is required to incorporate the quantitative modelling aspects. Stock-and-flow models transforms causal loop diagrams for quantitative analysis by specifying the mathematical relationship between system variables and defining system parameters (Tulinayo et al., 2012).

The stock-and-flow diagrams consist of six main parameters, that allow for the visual representation and analysis of a complex system, in a quantitative manner. The six elements are: stocks, flows, converters, connectors, sources and sinks (Albin, 1997; Simonovic and Rajasekaram, 2004).

Stocks represents the accumulation of system variables at any given time, based on past behaviour of the system and are mathematically represented by integrals. Stocks indicate the state of the system at a specific point in time, while acting as a buffer for changing flows within the chosen time horizon $[t_i, t_n]$ (Simonovic and Rajasekaram, 2004).

$$\int_{t_i}^{t_n} f(t)\,\mathrm{d}x = F(t_n) - F(t_i) \tag{5.3.1}$$

As stocks serve as a reservoir, it cannot hold a negative quantity and the initial value t_i can only change with system inflows and outflows, initiating delays in the system (Forrester, 1961). As stocks represent the current state of the system, it often provides the basis for decision making (Sweeney and Sterman, 2000).

The rate at which the stock changes at any given point in time is known as the flow, which can either be flow into or out of a stock, expressed as an unit per time or rate. Flows, which are mathematically represented as differential equations, describe the process or rate of change and can be described by a verb, for example "*Births*".

$$\frac{du}{dt} = f(t) \tag{5.3.2}$$

Although, stocks can only be influenced by flows, the system flow can be changed by other flows, stocks and converters. Converters represent parts of the system that are not determined by the system behaviour, such as system boundaries and system influence, where the value of the converter can be derived from other system parts. Figure 5.2 illustrates the connection of stock-and-flow elements for mapping the system structure.

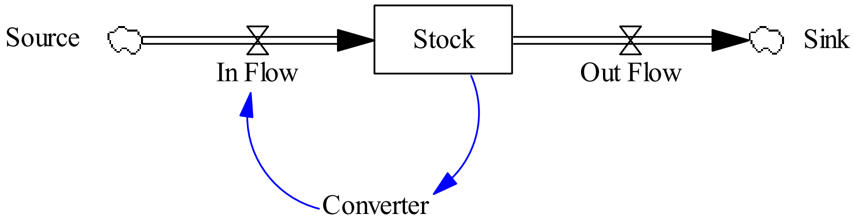


Figure 5.2: Stock-and-Flow Diagram Elements

Input data is converted to output data to explain system flows through a computational procedure. Therefore, converters can either be affected by stocks, flows and other converters, or in the case of representing system boundaries, not at all. The information contained by converters, ultimately affect the flow of stocks in the system.

The connectors indicate how the system parts influence one another by moving information from one element to map another in the system. Furthermore, both sources and sinks are stocks that lie outside the boundary of the system model. Represented as stock flowing into a *sink* and flow from a *source* that exists outside the boundary into a stock of the model. For the stock-and-flow diagrams, the sink and source stocks are represented by small clouds and lie outside the model boundary as seen in Figure 5.2.

The exogenous drivers, are external constants that influences endogenous variables, known as auxiliary variables. These auxiliary variables serve as a modus of simplification and clarity, by dividing the complex equations into manageable and more understandable parts, making the influence polarity clear. Auxiliary variables can also be described as the adverb or adjectives of the system, present between the source of action and the decision, serving as the connection (Hillman, n.d.; Wan and Li, 2014).

The advantage of using stock-and-flow diagrams is that important system details such as unit and magnitude of variables must be specified, which required detailed investigation into system variables and their relationships among others. Once the stock-and-flow diagrams are constructed, the mathematical relationship among system variables are defined for simulation (Tulinayo, 2009). However, it must be noted that stock-and-flow diagrams are more complex with extensive data requirements and are more time consuming than causal loop diagrams to construct (Albin, 1997). Subsequently, causal loop diagrams can more easily represent and describe the local reality, while dynamic modelling may become more linear, with limited feedback loops as a result of time and data constraints.

The causal loops constructed in Chapter 4 are used as the basis on which the stock-and-flow diagrams for the urban water system are built, using the software VENSIM® PLE for simulating the behavioural responses. The quantitative data extracted from technical reports and publicly available data sources are used to quantify the conceptual model to support decision making. Consequently, the stock-and-flow diagrams, for the City of Cape Town urban water system are developed per water role to align with and transfer information from the qualitative conceptual models in Chapter 4.

5.4 Water as a Resource

Water resources for the City of Cape Town refer to the collection of surface water, groundwater and treated wastewater supplies, with limited alternative sources adding to the total supply. Although desalinated seawater prior to 2017 added an insignificant amount to the water supply for the City, the potential for adding additional yield to the supply capacity for the City of Cape Town is incorporated in the model. The available supply serves as the water stock, which rise as a result of inflows based on secondary variables such as inflow of runoff into dams and fall as a result of demand outflows. These secondary variables serve as time varying constants that affect the rate of flows into and out of the available water stock or reservoir.

Although the capacity of the Western Cape Water Supply System's (WCWSS) major surface supply dams is approximately 900 million m^3, the stock varies greatly in accordance with annual rainfall and demand. The 2018 Water Outlook Report provides the unconstrained and restricted allocation and demand values for the City of Cape Town. These restrictions serve as intervention actions to ensure available water resources for ecological reserves, legislative agreements and urban users during droughts, when the water stock dwindles with decreasing dam levels.

The climate in the City of Cape Town is characterised by high variability in rainfall from one year to another, or between groupings of years. Wet years are exchanged for dry years, with a gradual decline in average annual precipitation from 1960 to 2017 (Wolski, 2017). Consequently, the Western Cape's high dependency on surface water supplies make the province vulnerable to water shortages as a result of low annual rainfall and periods of drought. Subsequently, the distinction must be made between drought years and non-drought years, as this affects the allowable usage of groundwater resources, the potable usage restrictions and ecological reserves.

To further the understanding of variable interaction, the first water role is divided into four sub-models, that serve as sections of the urban water system model. The water as a resource input sub-models are:

1. Surface Water Supply Sub-Model
2. Groundwater Supply Sub-Model
3. Alternative Water Supply Sub-Model
4. Total Water Supply Sub-Model

5.4.1 Surface Water Supply

The City of Cape Town lies in the amalgamated Berg-Olifants Water Management Area (WMA), the boundaries of which align with river drainage areas and not provincial boundaries (Adams et al., 2017). The current water usage in this WMA outweighs the water supply, resulting in a negative water balance, however the demand in the Berg region include groundwater consumption. The City of Cape Town relies on the WCWSS for approximately 98% of its water demand, which is predominantly derived from surface water resources. Furthermore, the WCWSS network contributed 65% of the total system allocation in 2015 to urban areas, while irrigation allocation were set at 35%. This is a slight decrease in urban usage from 67% in 2006 (Reddick and Fundikwa, 2018).

As surface water rely on rainfall and dam capacity, the precipitation conversion from mm rainfall to litre per m^2 in Equation 5.4.1 is used.

$$1\ mm = 1\ l/m^2 \tag{5.4.1}$$

Raw surface water is stored in dams, from where water is transferred to be treated at water treatment works that are limited by transfer, storage and treatment capacity. The WCWSS dam capacity can be increased through augmentation programmes, however the capacity cannot increase indefinitely, regardless of available funding. Interbasin transfers and runoff can increase the raw water to capacity. Hence, additional inflow is diverted among the network of dams or as spillage into rivers and streams and as infiltration to groundwater reserves. The fraction of runoff entering dams, depend on the size and type of the catchment area and the precipitation over the catchment area and dam. Furthermore, raw water losses are attributed to the rate of evaporation, which is dependent on the temperature, exposed area and air movement over the dams, as well as leaks and groundwater infiltration. However, these variables are difficult to quantify and are generally taken as an approximation for simulation.

Although the distribution percentages vary slightly per year, the 2017/2018 WCWSS release of raw water were distributed to three major user sectors, namely agriculture (29%), the City of Cape Town (64%) and other urban towns (7%) in the Western Cape (CoCT, 2018a; CoCT, 2018e). Water for urban consumption is treated at water treatment works. The City of Cape Town has twelve water treatment facilities with a total capacity of 1600 million litres per day (580 million m^3 per annum). These facilities aim to produce high quality potable water for consumption by adhering to strict guidelines and incentive based programmes, such as the DWS Blue Drop measurements and awards. Thereafter, treated water is transferred through a network of reticulation pipelines to bulk and smaller reservoirs.

The volume of *WCWSS Raw Water* stored in the dams serve as the stock limited by the collective capacity of the WCWSS dams. The stock is influenced by both flows into and out of the dams. The volume of water in the dams serve as an indication of the level of water availability or raw water stock in the surface supply dams. At the end of the hydrological year, the water level is used to determine the extent of water shortages in the region and initiates water use restriction as part of water demand management.

The surface water stocks for the urban water system model are:

1. WCWSS Dam Capacity
2. WCWSS Raw Water
3. Potable Surface Water

This model is an adaptation of several water system models, however the model allows for the predetermined system allocation of other urban and irrigation consumers. This allows the model to provide insight into the urban consumption and how supplemented water resources impact the total demand for surface water resources under constrained and unconstrained conditions.

Raw Water

Raw surface water in the WCWSS is limited by the collective capacity of the network of WCWSS dams. The assumption is made that the six major dams in the supply system, that accounts for 99.6% of total surface water capacity, is representative of the total surface water system. Thus, changes in variables only relate to these major dams. The *WCWSS Dam Capacity* increase as a result of planned augmentation through investment. The annual depreciation and maintenance is not considered in the simplified model as it does not serve the purpose of the research study, however further elaboration on such aspects can be found in studies conducted by Musango et al. (2015), Pienaar et al. (2017) and Swart (2017).

The *WCWSS Dam Capacity* (DC) stock is a function of the integral of *Increase Dam Capacity* (r_{DI}) in Equation 5.4.2, which is influenced by augmentation over the simulated period, both historical and planned. Lookup tables are used to initiate capacity increase according to the year of implementation. These equations and data sources are elaborated on in Appendix B.4.1.

$$DC(t) = DC(0) \; + \; \int_{t_{2001}}^{t_{2040}} [r_{DI}] \, \mathrm{d}t \tag{5.4.2}$$

The *Initial Dam Capacity* DC(0) is equated to the 2001 total major dam capacity of 770 million m^3, with a yield of 440 million m^3 per annum. In 2009 the Berg River System added 130 million m^3 to the total capacity, adding a yield of 80 million m^3 per year. Additional augmentation projects planned to address water shortages include the Voëlvlei dam diversion, adding 23 million m^3 in yield per annum in 2021 (Bronkhorst, Pengelly, et al., 2017). However, according to the augmentation programme stipulated in the 2019 City of Cape Town Water Strategy, the Berg River is planned to undergo augmentation in 2022 to effectively yield 15 million m^3 of surface water per annum (CoCT, 2019a).

The volume of *WCWSS Raw Water* (RW) increases through annual inflows from interbasin transfers (r_{IBT}) into the system and inflow of rainwater runoff and filtration from groundwater resources (r_{IRW}). Water volume is decreased by water transferred to water treatment works (r_{WT}) for consumption, other allocation and evaporation (r_{RWD}). Equation 5.4.3 represents the change in stock in the system for raw surface water.

$$RW(t) = RW(0) \;+\; \int_{t_{2001}}^{t_{2040}} [r_{IBT} \;+\; r_{IRW} \;-\; r_{WT} - \; r_{RWD}]\,\mathrm{d}t \tag{5.4.3}$$

The dam level in November 2000, at the beginning of the hydrological cycle, was approximately 71% of the total capacity of 770 million m^3. Thus, the initial raw water for the simulation model is estimated as 547 million m^3 (CoCT, 2018a). Annual rainfall in the catchment areas result in runoff flowing into the dams however, the volume of water entering these dams vary with annual precipitation. Precipitation in the Western Cape is below the national and global average, with the South African average annual rainfall set at 490 mm per year (Colvin and Muruven, 2017).

The fraction of runoff is equated based on the size and terrain of the catchment area however, the runoff volumes entering the WCWSS dams are provided in the 2018 Water Outlook report from 1928 to 2017. For modulation purposes, the runoff volumes per annum for the period 2018-2040 are based on the closely resembled data pattern over the period 1978-2000 (CoCT, 2018a). These values are approximates as they are based on bar-chart data provided in the report. Furthermore, the runoff fraction of water that flows into the major dam system, is estimated at 0.88 in the 2018 Water Outlook report. Furthermore, a small fraction of groundwater filtrates into the major dams however, the amount is negligible for the purpose of this study.

Alternatively, the model is constructed using precipitation data, catchment area and conversion variables to quantify the volume of raw water entering the dams. The six major dams' catchment area encompass a sum of 173 500 km^2, allowing rainfall runoff to enter the surface water dams (DWA, 2006b). It was found that for this model the precipitation data represented the system inflow better than the runoff values extracted from the 2018 Water Outlook report. For the model, the volume of water in the WCWSS dam system serves as the trigger for the implementation of demand restrictions to reduce the outflow of water and ensure sustainable water storage for critical purposes.

Water is lost to the system as a result of bulk losses, leaks and evaporation. To reduce evaporation losses, water is withdrawn from the larger dams first, such as Theewaterskloof and Voëlvlei dams. The annual evaporation is a product of the supply area (km^2) and the annual evaporation rate (m^3/annum), which lead to the relative evaporation as a percentage of the dam capacity (%). Table 5.1 is an adaptation of dam evaporation stipulated in the Department of Water and Sanitation Guidelines for the Western Cape Water Supply System report of 2006 (DWA, 2006a).

Table 5.1: WCWSS Annual Evaporation

Dam	**Capacity** Mm^3	**Yield** Mm^3	**Area** km^2 (Mm^3/a)	**Annual Evaporation** (Mm^3/a)	**WRYM Evaporation** (Mm^3/a)
Steenbras Dams	66	40	6.3	7.1	5.5
Wemmershoek	59	54	3	3	2.5
Voëlvlei	165	105	15.2	28	25.5
Theewaterskloof	480	219	50.8	63	28
Berg River	127	80	5.2	7	6
Total	897	498	80.5	108.1	67.5

The simulated gross annual evaporation as per the Water Resource Yield Model (WRYM) is used to assist the decision making process for restriction implementation. These restrictions ensure that adequate water resources are available to meet basic requirements in the next hydrological year based on reasonable demand and water inflow predictions (DWA, 2006a).

The volume of raw water declines as water is allocated to irrigation and other urban areas. During drought periods, irrigation allocations are restricted and capped in accordance with available water resources, to ensure a suitable quantity of water for urban consumption and environmental flows. The WCWSS raw water allocation for the model is based on the relevant scenario, both constrained and unconstrained as per Table 5.2 (CoCT, 2018a).

Table 5.2: WCWSS Allocation of Raw Water

Allocation Scenario	**City of Cape Town** (Mm^3/a)	**Irrigation** (Mm^3/a)	**Other Urban** (Mm^3/a)	**Total** (Mm^3/a)
Unconstrained	324	144	23	570
Constrained	178	58	13	248

The total water allocation for the WCWSS is capped at 609 Mm^3/a, with the 2014/2015 total consumption estimated at 547 Mm^3 for the year. The agricultural allocation is capped at 216 Mm^3/a (35%), with the City of Cape Town receiving an allocation of 358 Mm^3/a (59%). The remaining 36 Mm^3/a (6%) is distributed among other urban areas (Reddick and Fundikwa, 2018). However, the more realistic unconstrained system allocation per year is approximately 570 Mm^3/a (CoCT, 2018a). With 45% restriction on consumption translated to the constrained water allocations estimated in Table 5.2.

These allocations and restrictions are managed by the Department of Water and Sanitation, in partnership with inputs from the City of Cape Town Municipality (CoCT, 2019a). Initially, the model's water allocation towards agricultural irrigation and other urban areas are fixed, whereas urban water usage in the City of Cape Town is based on per capita consumption of surface water resources influenced by restriction levels based on the average WCWSS dam level. However, to better represent the allocation of water for irrigation, the consumption of surface water for irrigation is alternatively modelled to be constrained by several water restriction levels as stipulated in Table 5.3.

Table 5.3: WCWSS Irrigation Water Restriction Levels according to Dam Levels

Level	**Dam Level**	**Restrictions**
Water Wise	Above 81%	No restriction
Level 1	66-80%	10% Saving
Level 2	61-65%	20% Saving
Level 3	56-60%	30% Saving
Level 4	46-55%	40% Saving
Level 5	36-45%	50% Saving
Level 6	26-35%	60% Saving
Level 7	Below 26%	65% Saving

Raw Water Treatment

The total capacity of the water treatment plants in the City of Cape Town amount to 1600 million litres per day (MLD), equating to a capacity of 580 million m^3 per annum (CoCT, 2019a). The current capacity is sufficient to meet urban demand, with demand estimated at 1100 MLD during unconstrained conditions, however restrictions reduced the daily consumption for the City of Cape Town well below capacity (CoCT, 2018a).

Losses in the reticulation system have been addressed through conservation initiatives, including pressure management, leak detection and system upgrades. These losses are presented as a fraction of water treated, *Fraction of Reticulation Losses*, to be adjusted with further system intervention and management. Furthermore, the capacity of the City of Cape Town water treatment works allow for the minimisation of spillage from major dams during periods of high rainfall and to ultimately ensure higher system yield through retention of runoff (DWA, 2006a). A simplified stock-and-flow representation of the surface water sub-model in Figure 5.3 encompasses the information and data extracted from publicly available documents to form part of the *water as a resource* subsystem for the City of Cape Town.

5.4.2 Groundwater Supply

Groundwater resources in the City of Cape Town provide approximately 2% of urban drinking water, supplied mostly to Atlantis and the surrounding area by the Atlantis Aquifer System. Other groundwater projects include the Table Mountain Group aquifers and the Cape Flats aquifer. Currently, the Cape Flats aquifer serves as a water source for irrigation in the Philippi farming area (CoCT, 2018e). Due to the drought experienced, especially in the City of Cape Town and surrounding regions, the abstraction from aquifers are being investigated to increase the per annum groundwater yield to effectively reduce the demand on stressed surface water resources.

The groundwater resources are not inexhaustible and require a balance between abstraction and recharge to ensure the sustainability of the underground water bodies. In light

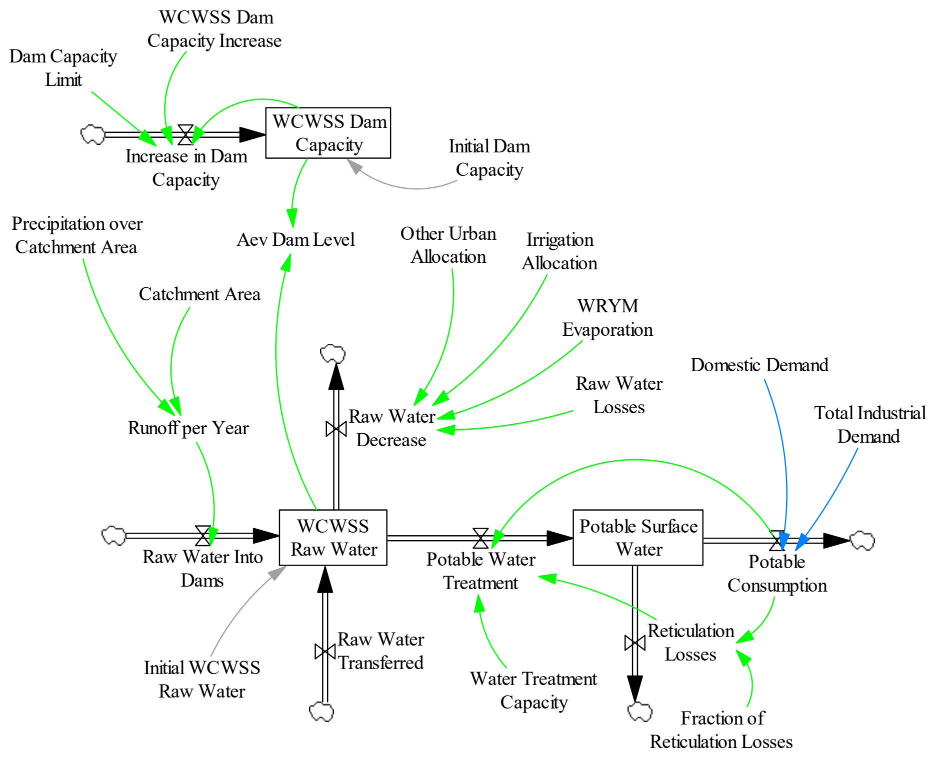


Figure 5.3: Stock-and-Flow Diagram: Surface Water

of this, the aquifers have usable storage capacity limits, that restrict the annual yield in comparison to the recharge rate of these water bodies. Recharge of the aquifers occur naturally, as a result of water infiltration or can be artificially recharged by pumping treated effluent and stormwater runoff into these aquifers or wetlands.

From 1998 groundwater has been considered a national asset. However, legislation and control processes relevant to private borehole usage are limited. In January 2018, the City of Cape Town implemented the requirement for groundwater monitoring devices for individual households, utilising groundwater through a privately owned boreholes. These instructions are stipulated in the Government Gazette No. 41381 (Vol. 631), dated 12 January 2018, that provide borehole and wellpoint guidelines. At present the implementation, costs and consequence for failure to comply with these instructions are unclear.

In 2018, with the implementation of Level 6b water restrictions, it was strongly encouraged that the usage of groundwater in the City of Cape Town be limited to indoor usage only. Whereas under normal circumstances, groundwater is used for basic irrigation, cleaning and non-potable household purposes. Furthermore, groundwater abstraction from private boreholes may not be used for commercial usage or offered for sale as per Section 22 of the National Water Service Act. Subsequently, the City of Cape Town's regulations limit the extraction of groundwater to 400 m^3 per year per hectare, which is equivalent to approximately 100 litres a day on a 1000 m^2 stand.

A small fraction of households in the City have access to groundwater through privately owned boreholes, as the cost of installation range anywhere from R60 000 to R150 000, depending on the level of plumbing and operating purpose. This fraction is based on the estimated 22 000 registered borehole users in 2018, which is approximately 2% of formal households in the City (Nel et al., 2018). Thus, assuming the average household stand equates to 1000 m^2, consuming a maximum of 40 m^3 of groundwater a year, the total domestic extraction can be determined for the domestic usage as an alternative source for municipal water, aimed at supplementing non-potable requirements.

The impact of drought periods in the region is muted in groundwater resources in comparison to the evident impact on surface water supplies. This is due to slow groundwater movement. However, the decentralisation of groundwater abstraction challenges the management and monitoring of groundwater usage, making it difficult to regulate and enforce restrictions. To address this challenge, the recharge of aquifers have become a requirement to influence the available groundwater yield, reducing the stress experienced based on the abstract-recharge ratio.

The centralised capacity for ground water extraction and the Utilisable Groundwater Exploitation Potential (UGEP) for the Water Management Area (WMA) limit the annual yield from groundwater resources. Thus, for this model the groundwater stock for the urban water system is the *Groundwater Abstraction Capacity*.

The *Groundwater Abstraction Capacity* (GAC) in Equation 5.4.4 increases with additional project intervention. While the capacity is limited by the WMA's Utilisable Groundwater Exploitation Potential (UGEP). The initial capacity of groundwater abstraction is based on the estimated groundwater yield, taken as a fraction (0.26) of the regional UGEP in m^3 per year, under normal rainfall conditions (Adams et al., 2017).

$$GAC(t) = GAC(0) \; + \int_{t_{2001}}^{t_{2040}} [r_{WI}] \, \mathrm{d}t \tag{5.4.4}$$

To ensure sustainable groundwater resources, a rise in the abstraction of groundwater requires emphasis on the balanced recharge of these aquifers. According to Woodford et al. (2005) the mean annual recharge volume for South Africa was estimated at 30520 million m^3.

The State of Environment Outlook Report for the Western Cape tabled the UGEP for the Western Cape WMA's per year at 1049,3 million m^3 during normal rainfall periods and 659 million m^3 during drought periods (Adams et al., 2017). However, the majority of the City of Cape Town fall within the Berg-Olifants WMA, with a UGEP per annum for the region estimated at 406 million m^3 during normal rainfall periods and 256 million m^3 during drought periods, which serve as the estimation of initial yield (Adams et al., 2017). Thus, future augmentation projects and artificial recharge initiatives have to adhere to the environmental restriction to ensure a sustainable water future. Future augmentation yield projects plan to increase groundwater abstraction, projecting an additional yield between 38 and 45.6 million m^3 per annum in total (CoCT, 2018a; CoCT, 2019a).

Abstraction from groundwater resources are monitored and regulated by a licensing system, with additional recharge management requirements aimed at addressing the underground water body balance, to avoid the degradation of these resources. The underground storage systems have the additional advantage of reduced evaporation losses and reacting less dramatically to periods of drought. The current and planned groundwater resource yields in Table 5.4 are based on the augmentation summary in the 2018 Water Outlook Report and the 2019 Cape Town Water Strategy (CoCT, 2018a; CoCT, 2019a).

Table 5.4: CoCT Groundwater Resources

Aquifer	**Current Yield** (MLD)	**Planned** (MLD)	**Year**	**Total** (Mm^3/a)	**Unit Capex** (Rm/MLD)
Cape Flats Aquifer P1	10	20	2019	11	31
Table Mountain Group P1	-	15	2019	5.5	25
Cape Flats Aquifer P2	30	25	2020	20	18
Altantis Aquifer P2	12	10	2021	8	29
Table Mountain Group P2	15	15	2021	11	23
Table Mountain Group P3	30	20	2021	18	16
Total Future Yield		105	> 2019	38	

The Atlantis and Silverstroom aquifer schemes currently yield 12 MLD. Due to the insufficient natural recharge rate of the Altantis aquifer an approximate 30% artificial recharge is required to meet the demand requirements (Bronkhorst, Pengelly, et al., 2017). Thus, additional yield from the aquifer will require the recharge rate through stormwater runoff and treated effluent water to be increased accordingly.

Recharge of the Atlantis aquifer is supplemented by artificial inflow into the groundwater body of approximately 7500 m^3 per day, resulting in a total of 2.7 million m^3 artificial recharge per annum (Tredoux and Cain, 2010). In 2010, the two infiltration basins recharged the aquifer storage with 2 million m^3 treated effluent per year, that serve as an indirect source of potable water for Atlantis (Bugan, Jovanovic, Israel, et al., 2016; Milkwood Communications, 2010).

The Cape Flats aquifer is licensed to abstract a total of 20 million m^3, with an annual recharge requirement set at 12 million m^3 (CoCT, 2018a). No artificial recharge is required to balance the Table Mountain Group aquifers due to the nature of its environment. However, the abstraction licence allows a maximum of 42.2 million m^3 per annum, with a planned annual yield for the future of 18 million m^3 per annum. For the purpose of this study the *Fraction Groundwater Recharge* required is set at 0.3 of *Available Groundwater Supply*.

Although the Newlands, Albion Spring water is pumped directly into the drinking water network system, the assumption is made that groundwater abstracted by households in the City of Cape Town is mostly used for irrigation purposes and non-potable domestic use, both indoor and outdoor (T. Wright and Jacobs, 2016). Brackish (salt) groundwater require reverse osmosis treatment before potable use. The process produces the by-product brine, that should not be disposed of in the municipal wastewater system.

Groundwater resources are extracted to add to the total potable and non-potable yield. Although the majority of groundwater yield is currently used for non-potable usage, the reconciliation plan aims to add the Table Mountain Group Aquifer (TMGA) abstraction to the potable yield for the City of Cape Town. The first TMGA phase is set to add 10 MLD to the Steenbras dams to increase the potable surface water yield. Based on the extracted data, the stock-and-flow diagram in Figure 5.4 illustrates the dynamic model for the groundwater sub-model, taking into account the UGEP limits and recharge requirements for utilising groundwater to supplement the WCWSS surface water resources.

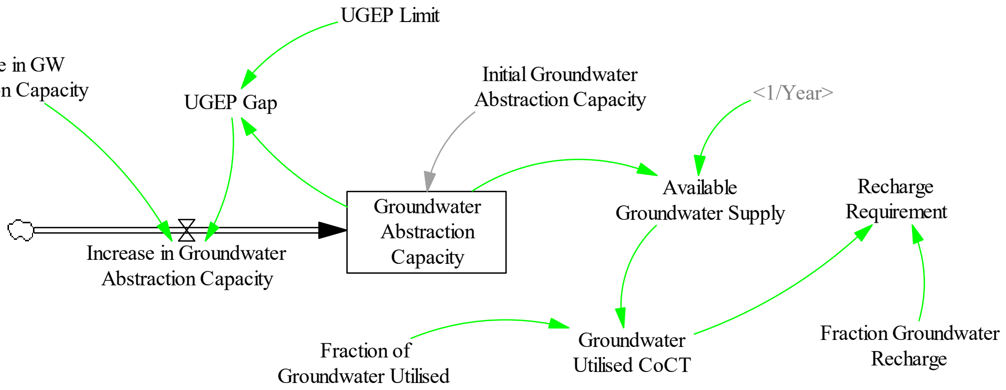


Figure 5.4: Stock-and-Flow Diagram: Groundwater

5.4.3 Alternative Water Supply

As surface and groundwater resources become more constrained with rising demand, zero water waste principles offer an alternative approach to addressing water shortages experienced in densely populated urban cities. The circular economy approach strive to reduce water demand and raw resource extraction, by reusing and retaining water within the system. To address the supply deficit, alternative sources should be developed to meet user demands, both potable and non-potable, as opposed to extracting more water from finite resources such as groundwater and surface water.

Alternative sources include harvested rainwater and stormwater, desalinated seawater, greywater and reclaimed wastewater for potable reuse. These alternatives pose various advantages and disadvantages aimed at ensuring a sustainable environment, capable of supporting the growth of both the economy and society. There are several policies and regulations that aim to support the diversification of water sources in the urban City. An example of legislative support in this regard is the City of Cape Town's Water By-laws (2010 and 2018). These by-laws provide requirements and guidelines for households within the City of Cape Town in relation to water usage and plumbing installations, aimed at reducing wastage and demand.

Domestic household may resort to alternative water supplies to mitigate the impacts of water restrictions or water rationing. These alternatives include the installation of rainwater collection systems, or for the higher income households, greywater systems are installed or boreholes are drilled. However, the price comparison of these decentralised systems are vast, varying from R2000 to R150 000. A Water Harvesting Tool was developed by the University of Cape Town (UCT) Climate System Analysis Group (CSAG), which intend to assist the design of household water retaining systems. The tool calculates the potential volume of water captured from the runoff on a particular rooftop area. This free tool, funded by the Water Resource Council (WRC), is available for use from *http://cip.csag.uct.ac.za/waterharvest/*.

Alternative water supply sources include rainwater and stormwater harvesting, desalinated seawater and treated wastewater. The stock and flows for the alternative water sub-model are elaborated on per source category. These sections are closely related to the final water role, *water as a waste stream*, which serve to identify alternative water resources from system waste to supplement scarce water resources.

Rainwater Harvesting

Rainwater and stormwater harvesting in urban areas serve as alternatives to municipal water from the central supply system. Rainwater harvesting is defined as the water captured from runoff, typically off rooftops and stored in external on-site tanks. Whereas stormwater harvesting refers to the capturing of stormwater from impervious urban surface areas, then treated and stored. These urban surface areas may include pathways, parking areas and roads. However, contaminants and pollution means that the water must be treated before storage and use. Although collected rainwater can be used for indoor and outdoor usage, it is predominantly limited to outdoor usage or for non-potable uses, such as toilet flushing.

Fisher-Jeffes, Armitage, et al. (2017) and Viljoen (2014) investigated the feasibility of rainwater harvesting in both the domestic and commercial setting in South Africa. Viljoen (2014) found that harvested rainwater served to supplement municipal water by substituting potable quality water for toilet flushing in commercial buildings with harvested rainwater. Whereas, the financial viability of rainwater harvesting systems in domestic households in Cape Town, evaluated by Fisher-Jeffes, Armitage, et al. (2017), found that for the majority of households the cost of installation and maintenance of rainwater harvesting systems outweighs the savings achieved on water bills. Although the alternative is not yet economically attractive for the majority of residence in the City of Cape Town, water assurance and municipal water savings can be achieved.

Subsequently, the volume of stored decentralised rainwater serve as alternative water stocks for the urban water system model:

1. Volume of Stored Rainwater
2. Volume of Industrial Stored Rainwater

The number of households with access to decentralised rainwater tanks are predominantly dependent on the income bracket of households. However the model allows for the scenario evaluation of the impact of increasing and decreasing the fraction of households with access to utilising rainwater tanks, through policy and government incentive schemes. The scenario evaluation is elaborated on in Chapter 7.3.2.

The average roof size for the model is set at 50 m^2, with a roof runoff coefficient of 0.9, while the precipitation is measured in *mm* (Bronkhorst, Pengelly, et al., 2017). The *Volume of Stored Rainwater* (SRW) increase with *Rainwater Entering the Tanks* (r_{RE}) and decrease with the *Rainwater Consumption* (r_{RC}) as per Equation 5.4.5.

$$SRW(t) = SRW(0) \; + \; \int_{t_{2001}}^{t_{2040}} [r_{RE} \; - \; r_{RC}] \, \mathrm{d}t \tag{5.4.5}$$

The initial assumption is made that the average capacity of decentralised rainwater tanks at residential households are 5000 *l* (Reddick and Fundikwa, 2018; Viljoen, 2014). While industrial users with large warehouse and factory structure are capable of generating larger quantities of harvested rainwater to supplement non-potable demand, subsequently the capacity of storage tanks should increase equivalently.

Although not all households benefit from the installation of rainwater harvesting systems, the model aims to determine the per capita saving. Hence, the model estimates the available non-potable water generated by a fraction of households and industries harvesting rainwater, taking into account the runoff captured based on the storage capacity and rooftop area. Appendix B.4.3 capture the model structures the equations for rainwater reuse in both the domestic and industrial sectors.

The model stocks for rainwater harvesting are *Volume of Stored Rainwater* (RD) for domestic use and *Volume of Industrial Stored Rainwater* (RI). Both stocks increase with runoff from precipitation off rooftops and decrease with annual consumption. For the purpose of the model, no seasonal usage or refill of rainwater tanks are included in the modelling. However, the assumption is made that the minimum non-potable water supply is the total stored volume per annum. The model can be adjusted to allow for the scenario where the refill of tanks and subsequent consumption is incorporated. Equation 5.4.6 and 5.4.7 represent the stocks for rainwater harvesting in both domestic and industry sectors.

$$RD(t) \; = \int_{2001}^{2040} [r_{RDI} \; - \; r_{RDD}] \, \mathrm{d}t \; + \; RD(0) \tag{5.4.6}$$

$$RI(t) \; = \int_{2001}^{2040} [r_{RII} \; - \; r_{RID}] \, \mathrm{d}t \; + \; RI(0) \tag{5.4.7}$$

Precipitation is a key parameter in the rainwater harvesting sub-model. The historical and predicted precipitation values are used to serve as the quantitative input for rainwater harvesting inflow calculations. The use of actual variable data provide the model with non-linear input, subsequently allowing for the dynamic behaviour and storage capacity evaluation, similar to real-world performance.

Furthermore, the capacity of the decentralised rainwater tanks and the total runoff, limits the amount of rainwater harvested However, spillage can be translated into stormwater harvesting for aquifer recharge. What is more, Fisher-Jeffes, Armitage, et al. (2017) found that although rainwater harvesting attenuates the impact of high volume rainfall, due to the constrained capacity of rainwater storage tanks, little damping of stormwater overflow is achieved during peak flow events.

Figure 5.5 represents the dynamic sub-model for rainwater harvesting, linking primary influencing parameters to both industrial and domestic rainwater stock for the City of Cape Town.

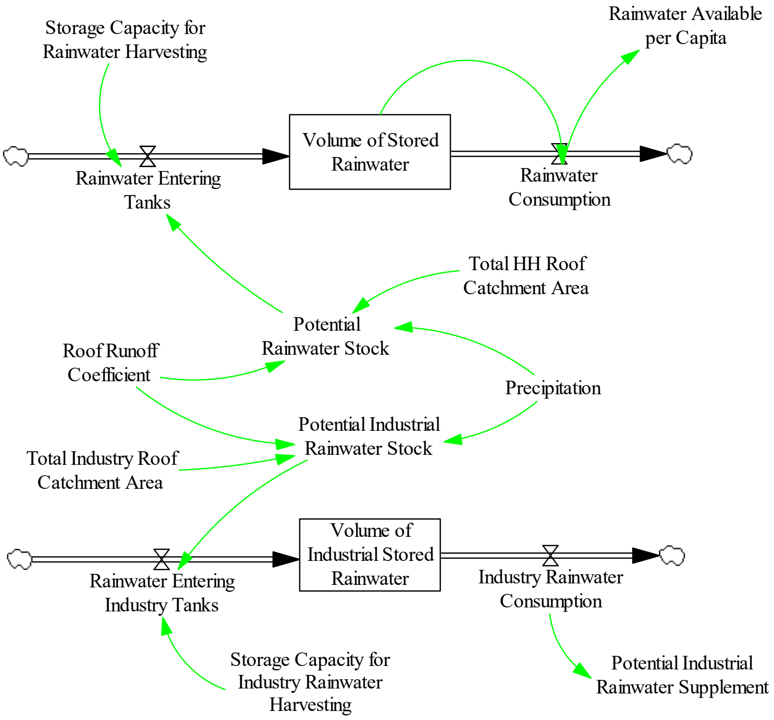


Figure 5.5: Stock-and-Flow Diagram: Domestic and Industrial Rainwater Harvesting

Desalinated Seawater

Desalinated seawater is the only alternative water resource not dependent on rainfall capable of assuring water supply. Unfortunately, the associated capital investment, energy requirement and environmental risks must be adequately addressed. The energy and operating requirements for both permanent and temporary desalination plants are extremely high and should not be considered as an emergency drought response, but should be used as a permanent source of supply (Lam et al., 2017). Several global examples indicate that the high cost of establishing desalination plants during periods of drought, which are not being used optimally, leads to difficulties in the financial and political sectors (Reddick and Fundikwa, 2018; Reddick and Kruger, 2019).

The high operational and recovery costs associated with seawater desalination plants, hinder the implementation and preference of this alternative. Several less expensive options are considered prior to establishing high cost and energy alternatives, as the cost is ultimately carried by the user. According to the 2018 GreenCape Market Intelligence Report, a large scale permanent seawater desalination plant aimed at adding 100-150 MLD will increase water cost to between R12-R18 per m^3 with an energy requirement of 3-3.5 kWh per m^3 (Reddick and Fundikwa, 2018). Another barrier include the safe disposal of waste products, such as brine, to ensure the sustainability of the environment.

Future augmentation projects for the City of Cape Town include the limited desalination of seawater to add to the water supply. The V&A Waterfront is in the process of establishing a temporary supply of two million litres daily in 2018, which will potentially convert to a permanent yield of five MLD. Other projects include the Strandfontein and Monwabisi temporary desalination plants, adding a further seven million litres per day each (Reddick and Fundikwa, 2018). The site for a large permanent seawater desalination plant needs to be confirmed with feasibility investigations to be completed. This site aims to add 120-150 MLD by 2030 according to the WCWSS Reconciliation Strategy. Furthermore, the committed programme set out in the 2019 City of Cape Town Water Strategy, stipulates how the first desalination phase over the next ten years is planned to effectively yield 50 MLD by 2026 at an operating cost of approximately R9/kl, with further phases adding an additional 100 MLD in the future (CoCT, 2019a).

The volume of desalinated seawater produced per annum is dependent on the capacity of the City's desalination plants. The *Capacity of Desalinated Water* (DWC) serves as the stock for the urban water system model. The capacity is increased (r_{IDWC}) with the addition of permanent and temporary desalination facilities as per Equation 5.4.8 and Figure 5.6.

$$DWC(t) = DWC(0) \ + \int_{t_{2001}}^{t_{2040}} [r_{IDWC}] \, \mathrm{d}t \tag{5.4.8}$$

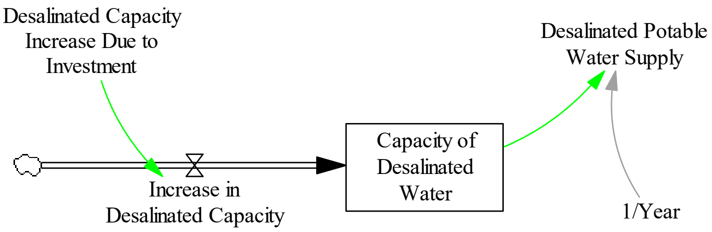


Figure 5.6: Stock-and-Flow Diagram: Desalinated Seawater

For the purpose of this model, the depreciation and decommissioning of desalination facilities are not accounted for. The initial value of the desalination capacity for 2001 is set at zero, with increases in capacity occurring per lookup table in relation to the year of initiated water production. For modelling purposes the capacity increase, as planned and reported by the 2018 and 2019 GreenCape Market Intelligence Report and the 2019 City of Cape Town Water Strategy, is combined and summarised in Table 5.5.

The 2018 Water Outlook report found that desalination plants should not be designed to produce more than 200 million litres of water per day on a permanent basis. Also, smaller or temporary plants are to be avoided, as they are inefficient, extremely expensive and logistically complex. Investigation found that private sector involvement and purchase agreements may yield desalinated water at a reduced cost to the municipality and end users. Therefore, an alternative to desalinated water production, may be the cheaper process of treating wastewater to potable quality. However, desalinated seawater is the only alternative water source not dependent on rainfall, therefore assuring water supply.

Table 5.5: CoCT Desalination Capacity

Desalination Project	Year of Production	Planned (MLD)	Planned (Mm^3)
Strandfontein	2018	7	2.55
Monwasnisi	2018	7	2.55
V&A Waterfront	2018	2	0.73
Permanent Plant I	2026	50	18
Permanent Plant II	>2030	100	36.5
Total Future Yield		>160	> 60

Wastewater Treatment Works

Water management extends further than ensuring sufficient water supply but includes the management of wastewater removal, treatment and disposal. The importance of well managed and maintained Wastewater Treatment Works (WWTW) in urban cities cannot be underestimated. These facilities aim to remove and treat water waste produced by households and industry, for reuse or discharge in a safe and environmentally friendly manner.

The City of Cape Town's wastewater network consists of a network of pipelines, pump stations and wastewater treatment plants. The sewer pipeline is approximately $9300km$ long, with a larger diameter than that of potable water pipes. These pipes usually allow for gravity flow, unless the wastewater must be pumped uphill. The City's WWTW has a total capacity of 740 MLD, licensed to a production capacity of 700 MLD by the Department of Water and Sanitation (DWS). Furthermore, thirteen of the City of Cape Town's wastewater treatment plants can treat wastewater to non-potable reuse quality for industrial or irrigation purposes, up to a capacity of 164 MLD.

These wastewater treatment plants are continuously refurbished, upgraded and expanded to maintain or increase effluent treatment capacity, for reuse, aquifer recharge and discharge into marine outfalls. Approximately 50 000 m^3 of treated effluent for reuse is piped via a separate pipeline network, 230 km long, to industrial and irrigation users per day. Effectively reducing the demand for surface water resources, supplementing 18.25 million m^3 of non-potable industrial demand per year.

Further investigation into the reuse of treated effluent, as a source derived from the urban water waste stream, is elaborated on in the *water as a waste stream* section (§5.6).

5.4.4 Total Water Supply

For the purpose of the research study, the differentiation between potable and non-potable supply sources are made. The study investigate the supply deficit associated with demand for municipal potable water, while allowing for non-potable demands to be supplemented by non-potable sources.

Surface water supply is dependent on the capacity of the WCWSS dams, the annual water yields and the water treatment facilities. The following stocks and flows in Table 5.6 are linked as urban water supply sources.

Table 5.6: Stock, Flows and Auxiliary Variables for Water as a Resource Sub-models

Stock	Flow	Auxiliary Variables
Surface Water Supply		
WCWSS Dam Capacity	Increase Dam Capacity	Lookup Dam Capacity Increase
WCWSS Raw Water	Raw Water Into Dams	Annual Runoff
	Raw Water Decrease	Evaporation
		Irrigation Allocation
		Other Urban Allocation
Potable Surface Water	Potable Water Treatment	Water Treatment Capacity
	Potable Consumption	Domestic Demand
		Total Industrial Demand
	Reticulation Losses	Fraction of Reticulation Losses
Groundwater Supply		
Groundwater Abstraction Capacity	Increase in Groundwater Abstraction Capacity	UEGP Limit Groundwater Recharge
Rainwater Harvesting		
Volume of Stored Rainwater	Rainwater Entering Tanks	Storage Capacity Increase
	Rainwater Consumption	Fraction of Non-Potable Demand
Volume of Industrial Stored Rainwater	Industrial Rainwater Consumption	Total Industry Roof Catchment Area
	Rainwater Entering Industry Tanks	Storage Capacity of Industrial Rainwater Harvesting
Desalinated Seawater Supply		
Capacity of Desalinated Water	Increase in Desalination Capacity	Increase due to Investment

Thus, the distinction is made between both potable and non-potable water supply, to provide better insight into the behaviour among system elements. For potable water supply, the 2007 WCWSS Reconciliation Strategy, the 2018 GreenCape Market Intelligence Report and the 2019 City of Cape Town Water Strategy presented the planned augmentation projects and yields to increase the total potable water supply for the WCWSS.

Figure 5.7 compares the updated WCWSS reconciliation graphs with the simulated augmentation of the new water programme for the City of Cape Town yield (red line) and the simulated results for the updated WCWSS reconciliation strategy yield (blue line) (Van der Berg et al., 2007; Reddick and Fundikwa, 2018; CoCT, 2019a).

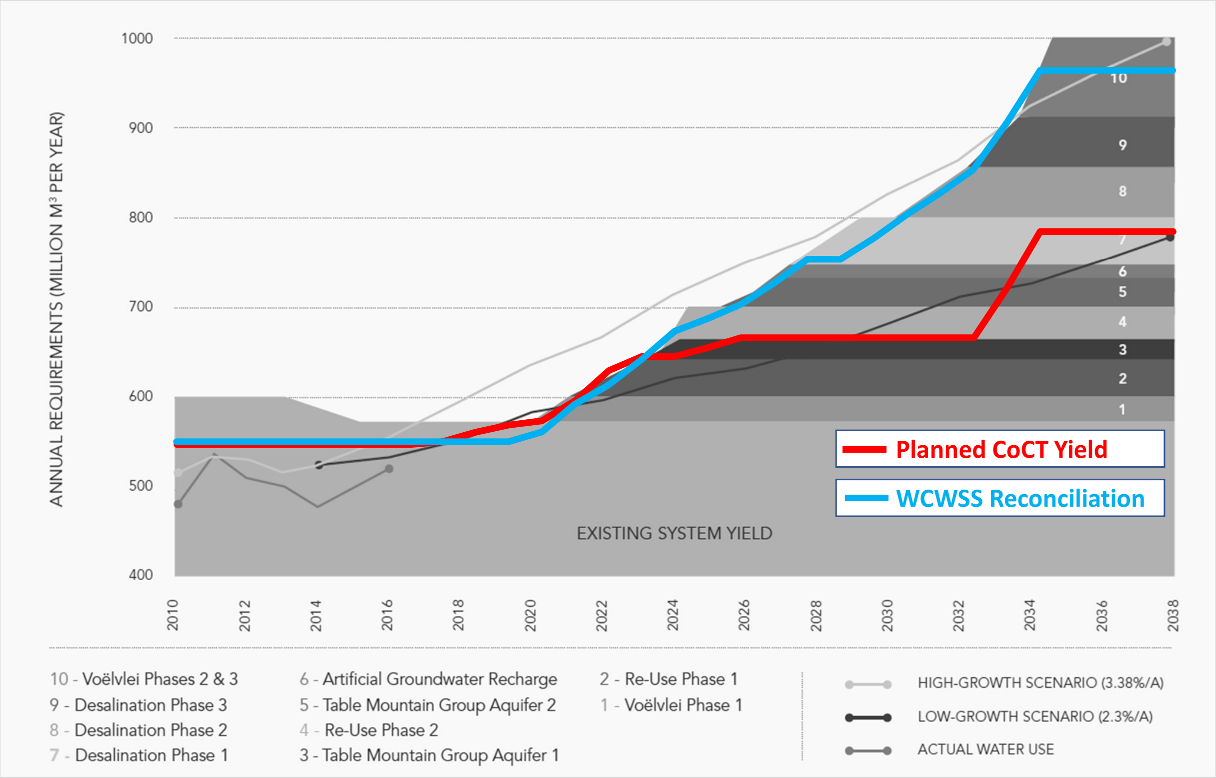


Figure 5.7: The Updated Reconciliation Strategy for the WCWSS with Modelled Data

Due to the drought, several projects have been fast-tracked to ensure sufficient water supply for the region, hence the *Total Water Supply* sub-model generates the planned augmentation over the period 2001 to 2040, not taking into account impacts associated with climate change and environmental reserves. The committed programme, as set out in the 2019 City of Cape Town Water Strategy, aim to augment water supply sources by 110 million m^3 per annum over the next ten years, with plans to increase the capacity by 2040 with a further 90 million m^3 per annum (CoCT, 2019a). Therefore, the diversification of water supply sources in the region aims to mitigate the risk of water shortages for essential purposes and socio-economic development, while ensuring a sustainable future for the City of Cape Town.

5.5 Water as a Product Input

The Western Cape's fresh water is predominantly used in the agricultural and domestic sector, with small portion of usage allocated to the industrial and commercial sectors. The agricultural sector accounts for a large portion of the province employment and Gross Domestic Product (GDP), making the sustainability of this sector essential to the socio-economic well-being of the region. Risk associated with water shortages include loss of jobs, health problems and environmental decline. However, the majority of the usage of water from the WCWSS's major dams are allocated to the City of Cape Town (64% allocation). Therefore, the urban region with its dense population, consumes a significant portion of the available water supplies in the province.

Water usage in the City of Cape Town is predominantly distributed among urban housing and industry or municipal owned facilities. Domestic users are composed of housing, both formal and informal, while industry users include retail, commercial and manufacturing. Municipal and government owned institutions are included in industry, as these entities serve as employment centres. Subsequently, the drinking water distribution is based on data extracted from the 2018 Water Services and the Cape Town Urban Water Cycle report as per Table 5.7 (CoCT, 2018e).

Table 5.7: Drinking Water Consumption per Category

Year	**Domestic**	**Industry**
2014/2015	72.5%	27.5%
2015/2016	71.3%	28.7%
2016/2017	69.9%	30.1%
2017/2018	70%	30%
Average	71%	29%

The City of Cape Town receives an unconstrained allocation of 324 million m^3 per annum from the WCWSS, which is further supplemented by privately or municipally owned resources, such as smaller dams, treated effluent and aquifers. The 2018 GreenCape Market Intelligence Report found that the distribution for potable water consumption was 70% for domestic usage and 30% for industry and municipal, supporting the data in Table 5.7 (Reddick and Fundikwa, 2018).

The industrial, commercial and municipal consumers in the City of Cape Town contributes to approximately 30% of water consumed in the urban City (CoCT, 2018a). These entities are combined for analysis under *Industry Users*, as their consumption patterns are corresponding. The industrial and commercial sector in the City of Cape Town contributes approximately 70% to the Western Cape's GDP, hence the availability of suitable water resources are essential for the economic well-being of the City and the province (Provincial-Treasury, 2017).

The residential users are combined under *Domestic Users*, with the small portion of urban farms falling under *Agricultural Users*. However, *Agricultural Users* within the urban City of Cape Town is negligible for the purpose of the research study. Furthermore, the water usage habits of consumers, for both potable and non-potable water resources, are essential to understanding the behavioural patterns for forecasting and estimated predictions for the achievement of water objectives, as prescribed by the National Water Act of 1998 (Viljoen, 2014; T. Wright and Jacobs, 2016).

The *water as a product input* sub-model for the urban water system in the City of Cape Town is built on the combination of connecting main system elements. These elements and corresponding equations for the *water as a product input* stock-and-flow diagrams are discussed in the sub-models. The model units, equations and supporting information for further insight, are provided in Appendix B.5.

The *water as a product input* sub-models are:

1. Domestic User Sub-Model
2. Industry Users Sub-Model
3. Consumption Patterns Sub-Model
4. Water Demand Management Sub-Model
5. Total Water Demand Sub-Model

5.5.1 Domestic Users

Statistics South Africa was used as a primary source of data for the population analysis of the City of Cape Town. This data collection entity serves as part of the Government-Wide Monitoring and Evaluation (GWM&E) framework for evaluating and monitoring policies in South Africa investigated in Chapter 2.6.1. Based on the system's data evaluation categories, the distribution of housing and the connection to water services in the City of Cape Town data is extracted for the quantitative modelling approach.

The majority of the water demand in the urban City is based on the consumption patterns and requirements of residents, thus the urban population and household growth and consumption patterns strongly influence the total demand for water resources in the City of Cape Town.

Urban Population

The population sub-model is a central point for water serving as an input into the urban water system and represents the relational link between water demand and urban population in the City of Cape Town. The sub-model consists of one stock, *Urban Population* (UP), with unit *People*, which increase with *Population Growth* (r_{PG}) and declines with *Population Decline* (r_{PD}) in Equation 5.5.1 at time t.

$$UP(t) \;=\; UP(0) \;+\; \int \left[r_{PG} - \; r_{PD}\right] \mathrm{d}t \tag{5.5.1}$$

Population, specifically the fraction of the population residing in households connected to the central supply network, demands the bulk of potable water in the urban water system. Thus, the importance of incorporating the total dependent households in the urban water model is highlighted.

Business as Usual (BAU) growth rate of population within the City of Cape Town is based on the historical growth rates experienced between national census data in 2001 and 2011. However, the community survey in 2016 indicates a significant change in population growth rates from 2011 to 2016 (Pengelly et al., 2017). As growth rates compound, the simulation model uses a lookup table in Appendix B.5.1 to determine the rate of growth to estimate the total population over the simulation period.

Urban Households

Urban housing consist mainly of formal housing (80.2%) and informal housing in the City of Cape Town only accounts for 4% of water consumption (CoCT, 2018a). Furthermore, the connected households are supplied with potable water sources from a centralised supply system with limited available water stock for urban usage. The fraction of households types are distributed as per Table 5.8.

Table 5.8: City of Cape Town Households Fractions

Year	Total HH	Formal HH	Informal HH	BY Dwellers
2001	759485	-	-	-
2011	1068572	-	-	-
2012	1106000	887219	143823	74958
2016	1272160	1036436	154901	80823
Fraction	100%	80.2%	13%	6.8%

The household sub-model in the K-DEM municipal model served as a basis on which the simplified urban water system model for the City of Cape Town is built (Holmes et al., 2014). The K-DEM model consisted of two stocks, households with basic supply and connected households. Subsequently, the model for the research study uses similar variables to represent the distribution of households in the City of Cape Town. The population sub-model is connected to the urban household variables, *Total No. Households* using the data extracted on the *Avg People per Household* from public sources.

For the purpose of the urban water system model, in comparison to the K-DEM model, the research does not focus on the transition from informal to formal households through specific household stocks and sub-models, although this functionality can be added to serve future requirements. The distinction is however made among formal housing, informal housing and backyard dwellers for the research model.

Domestic Users

Approximately, 66% of potable water consumption is attributed to formal households, whereas an estimated 4% is allocated to informal housing. Retail and industry usage makes up around 16%, leaving 14% to government and City owned users. Although, agriculture on a national scale demands the majority of water resources (67%), the WCWSS predominantly supply to urban communities (65%). These urban areas drive the economic growth of the region, therefore it is important to secure water supply to these domestic and municipal users.

Several South African research reports based the water requirements and patterns on 2011 records, as these records are deemed accurate and correlate with census data. Consequently, 2011 serve as a baseline year, indicating that the total urban usage amounted to 326,3 million m^3 for the year, with a population of 3,68 million people, resulting in the per capita usage per annum equating to 88.6 m^3 (Pengelly et al., 2017). This equates to 242 *litres/day* per person, which is well above the national average of 208 *litres/day* per person.

Furthermore, the dam level at the end of the hydrological year for 2011 fell to between 80% and 90%, indicating an unconstrained allocation year (CoCT, 2018a). Based on the available information, the assumption is made that unconstrained, non restricted usage per person is estimated at 242 l/day.

Unconstrained conditions fall within the range of no water usage restrictions up to and including Level 3b water restrictions, thereafter the consumption is restricted to daily allowances and is categorised as constrained conditions. The consumption patterns for potable and non-potable water usage aligns with these conditions to provide a more realistic representation of domestic user habits.

To identify where waste products can be reused in the urban water system, the distinction between non-potable and potable domestic usage patterns must be made. Potable Demand (PD) is the portion of domestic water demand used for essential purposes, such as drinking, cooking and hygiene, whereas Non-Potable Demand (NPD) accounts for laundry, toilet flushing and outdoor purposes. A fraction of potable water used can be reused in households as domestic greywater for toilet flushing and laundry.

Equation 5.5.2 represents the total domestic demand as the sum of non-potable and potable demand for domestic use. The stock-and-flow diagram in Figure 5.8 represents the total domestic water demand as influenced by population growth and the sum of potable and non-potable water demand per capita.

$$Domestic\ Demand = PD + NPD \tag{5.5.2}$$

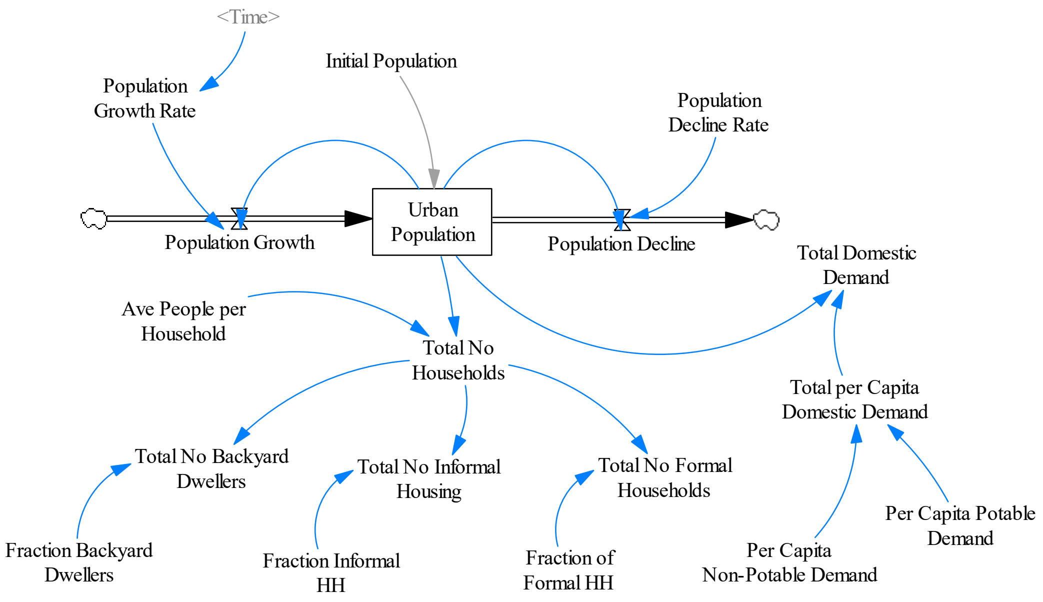


Figure 5.8: Stock-and-Flow Diagram: Domestic Demand and Population Growth

Non-potable demand can be met by various alternative sources, each of which depend on demand management interventions implemented to reduce the demand for potable water. Decentralised (household) greywater systems, groundwater resources, treated effluent from the centralised (municipal) WWTW and rainwater or stormwater harvesting are non-potable alternatives that serve to meet the demand for outdoor and other uses that do not require potable quality water.

The quantity of alternative sources depend on the availability of each resource, which in turn depend on domestic and industrial usage, produced wastewater, legislative restrictions, investments into alternative resources, resource availability and associated costs. The model developed by Ghasemi et al. (2017), although based on preserving groundwater resources in urban water systems, provided insight into making the distinction between water sources.

Urbanisation

Land transform is the process of changing the utilisation of land from natural and agricultural land, to urban settlements. Population growth, urbanisation and economic growth influence the rate at which the process occurs. The City of Cape Town is predominantly urbanised, in comparison to the rest of the Western Cape, thus the emphasis of evaluating urban water management for the study.

In addition, households are becoming smaller, while the population continues to increase, thus leading to the extensive urbanisation of the City of Cape Town with a decline in average household size. This decline is reflected in the lookup table for *Avg People per Household* model variable in Appendix B.5.1.

The City of Cape Town covers an area of 2408 km^2, of which 30.1% of the areas is covered by urban built-up, with agricultural land accounting for 23.5% in 2010. The continual growth in urbanisation will result in further loss in agriculture and natural land. Whereas, water bodies only amount to a small percentage of the total City of Cape Town area, 1.9% (van Weele and Maree, 2013).

The data is sourced from the Western Cape State of Environment Report for 2013. The City of Cape Town has the highest percentage of already transformed landscape, almost 60% in 2009, indicating its high fraction of urbanised areas in comparison to natural landscape.

Although land transformation influence several variables in the urban water system, such as the usage patterns, urban runoff and groundwater filtration, the focus of the study allows for the approximation of wastewater and waste stream collection, using population and household variables.

5.5.2 Industry Users

The industrial sector in this study refers to the formal sector in the City of Cape Town, including the commercial and municipal sector, which accounts for the majority of employment in the City. The 2017 Economic Performance Indicators for Cape Town for the first quarter serves as a source for data extraction.

Water usage in industry indicates over 30% of potable water usage, in businesses and municipal institutions, are for restroom usage. While landscaping range from 5% to 20% of total usage. Water restriction level 5 requires commercial businesses to reduce consumption by 20%. Whereas, at level 6 restrictions, the consumption for industry is required to be reduced by 45% (Reddick and Fundikwa, 2018).

Thus, 30% of industrial water demand can be mitigated with alternative non-potable water resources. The 2018 Cape Town Water Outlook report found that 30% of the total urban water demand in the City is consumed by the collective industrial sector (CoCT, 2018a). Subsequently, approximately 30% of total system input equates to the industrial demand, of which a fraction of 0.3 is allocated to non-potable requirements.

The economic growth for the City of Cape Town has varied since 2001, with an average growth in GDP of 3.2% over the period 2005 to 2015. This includes a decline in growth to an annual 2.5% observed from 2010-2015 (Provincial-Treasury, 2017). However, the GDP growth over a recession period is estimated at 1.5%, compared to a high growth trend at 3.9%, while recovery growth rate is set at 2.7%. Subsequently, the annual growth in water demand for industrial users is assumed to be proportional to the annual economic growth for this model. The model equations and parameters for the Industry Users sub-model are expanded on in Appendix B.5.2, while the stock-and-flow diagram in Figure 5.9 represents the model structure.

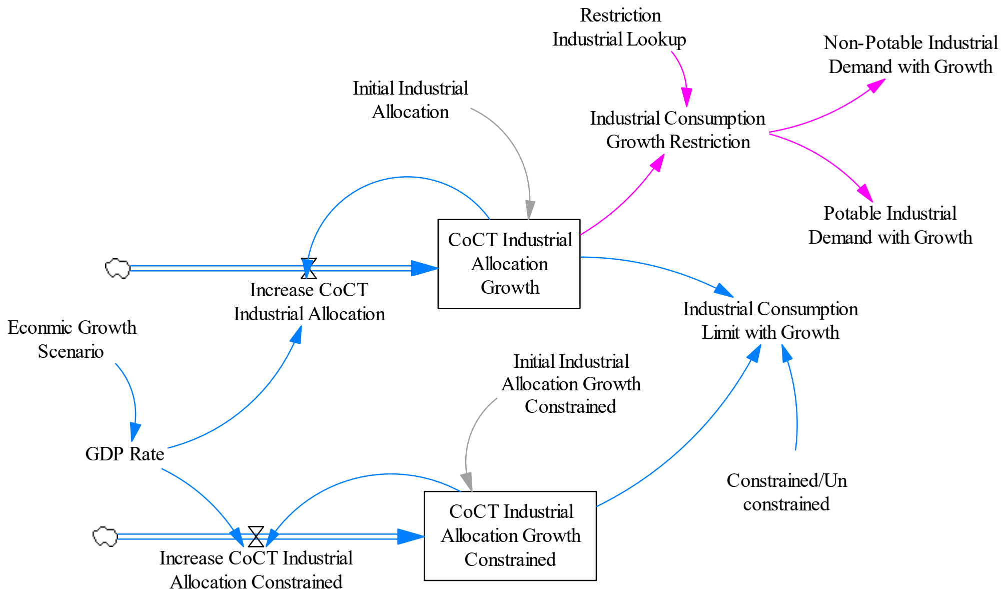


Figure 5.9: Stock-and-Flow Diagram: Industry Demand and Growth

The three growth rates are modelled in comparison to provide insight into the consumption patterns and behaviour of a growing industry and the impact it has on the water available in the urban City. Using the 2017 WCWSS unconstrained and constrained allocations for the City of Cape, the approximated 30% consumption allocation is used as reference for growth in the economy over the period 2018-2040. However, to refine the model behaviour, water savings based on restriction levels for industrial consumption is structured into the sub-model (pink arrows).

5.5.3 Consumption Patterns

Conservation policies were evaluated by Ahmad and Prashar (2010) to identify the performance and success of intervention aimed at addressing consumption behaviour within the South Florida municipality. This study distinguished between domestic and non-domestic demand with simplified models to determine the efficiency of policy interventions. On the basis of this distinction, the quality of water required is used as the dividing principle for different water type requirements in both industry and domestic sectors. However, this research study goes further than differentiating between water consumers to include the categorisation of water quality type, namely potable and non-potable requirements.

According to the 2017 World Wide Fund (WWF) report on scenarios for the future of water in South Africa, the distribution between domestic water use activities are predominantly for gardening, toilet flushing and personal hygiene. However, water restrictions has limited the outdoor usage of potable water, thus altering the usage patterns of consumers, as restrictions usually limit potable water usage to indoor application only. Freshwater withdrawals for domestic (D) and industry (I) use must be consolidated to determine the total water demand (WD), where water serves as input to the urban system.

$$WD = WD_D + WD_I \tag{5.5.3}$$

The research study aims to identify the impact of utilising various waste streams in the urban water system to address water demand for both industry and domestic consumption. However, the quality of water demand influence the decision for identifying suitable water resource to address the demand. Thus, the model makes a distinction between potable quality water demand and non-potable quality water demand. Table 5.9 summarises the municipal consumption patterns for domestic indoor usage prior to restriction constraints (Reddick and Fundikwa, 2018).

Table 5.9: Unconstrained Per Capita Consumption Behaviour

Usage	**Contribution**	**Water Quality**
Laundry	17%	Non-Potable
Toilet Flushing	37%	Non-Potable
Personal Cleaning	32%	Potable
Cooking, Dish-washing and Drinking	14%	Potable

The predominant usage of potable water for consumption activities that require lower quality water, indicates the potential of reducing the demand for municipal (potable) water through the reuse of greywater or the retention and use of rainwater. Furthermore, the usage of potable water for outdoor purposes are prohibited under several restriction levels, however alternative non-potable sources are used as substitutes.

According to the City of Cape Town's recommended usage during level 6b restrictions, the potable to non-potable ratio is suggested as $31l$:$19l$. Using the typical Cape Town household water uses, the distribution of potable to non-potable demand for constrained and unconstrained scenarios are approximated in Table 5.10 for the urban water system model (Reddick and Fundikwa, 2018).

Table 5.10: BAU Per Capita Consumption Behaviour

Supply Scenario	Potable	Non-Potable
Constrained	62%	38%
Unconstrained	46%	54%

Consumption Efficiency serves as an adjustment variable, which function as a calibration parameter to align the model and real life consumption behaviour. Demand restrictions targets are exceeded, indicating the adherence to restrictions are not efficiently met by consumers. Using the public Water Dashboard's average daily consumption of approximately 500 MLD in February 2018 and comparing the value to the targeted 450 MLD the *Consumption Efficiency* is set at 0.9. The equations supporting the assumptions and mathematical structure for the consumption model is documented in Appendix B.5.1

The City of Cape Town's municipal domestic sewage tariff structure rates 70% of metered municipal (potable) water as effluent, regardless of irrigation allowance. Hence, the assumption is made that 70% of consumed potable water will serve as input to wastewater treatment plants. In addition, the fraction of generated greywater in domestic households is based on this assumption, thus *Fraction of Indoor Greywater Generated* is initially set at 0.7.

The constrained and unconstrained allocations to the City of Cape Town allow for the approximation of industry allocation. The usage patterns, along with estimated allocations can be used to identify potential mitigation actions to reduce the total industrial demand on the municipal system. The model allows for the investigations into the effects of implementing alternative water source systems in the industrial and commercial sector.

5.5.4 Water Demand Management

The national Water Conservation and Water Demand Management (WCWDM) programme address the consumption and protection of scarce water resources in South Africa to ensure a sustainable environment, society and economy. Several initiatives and programmes have been implemented as part of the water services provided by the responsible municipalities or water authorities. These demand management actions include the implementation of water restrictions, pressure management and the installation of efficient water appliances, metering and fittings (DWAF, 2004).

In the 2014/2015 financial year, system water losses amounted to 15.8% of total system input (Flower, 2017). These losses are attributed to metering inaccuracies, unauthorised usage and real losses. Real losses (9%) include burst mains, leaks and connection faults which are being addressed through several demand and conservation intervention actions.

Actions include meter replacement, leak detection, reticulation system upgrades, maintenance and pressure reduction. In Appendix B.4.1 the parameter *Reticulation Losses*, incorporates the loss of potable water in the model.

Water Restrictions

Water restriction serves as a major contributor to the management of water demand. Consumption patterns and total water demand in the urban City change as a result of implemented restriction, subsequently influencing the behaviour of the system. Various exogenous and endogenous variables impact the implementation of water restrictions in the City of Cape Town. Therefore, a thorough investigation into the causal relationships between applicable parameters are conducted.

The WCWSS dams are generally replenished during the winter months, with rainfall and associated water runoff from catchment areas flowing into the network of dams and river systems. Water consumption is at the lower end of the scale during these winter months, with high demand and evaporation causing an increase in outflows during the hot summer months. Consequently, the storage in the Western Cape dams, that serve the City of Cape Town, varies with the seasons. To ensure that basic water requirements are met, interventions such as demand management through usage restrictions and irrigation allocations are implemented to mitigate the impact of climate variations and drought periods.

Water restrictions are imposed through a process of evaluating results obtained from the Water Resource Yield Model (WRYM) and the enhanced Water Resources Planning Model (WRPM), in addition to a formal forum with the Minister of Water and Sanitation at the end of the hydrological cycle before 1 November (DWA, 2006b).

Furthermore, water restrictions serve as a demand and conservation management approach to reduce the potable and groundwater consumption in the applicable region. The City of Cape Town has imposed several levels of water restrictions aimed at curbing demand and educating residence on the efficient and effective use of scarce water sources in the City. Levels of restriction include the allowable usage, restrictions on usage habits and tariff structures. Table 5.11 serves as a summary of restrictions introduced in the City of Cape Town since 2001 (CoCT, 2018a). However, restriction tariffs and limitations can be adjusted as new information and innovations are acquired. These adjustments include changes in water allowance, for which the model allows modifications to be made in the lookup tables in Appendix B.5.4.

Contingency measures for dam storage are mainly implemented in the introduction and enforcement of water restrictions and pressure management. As dam storage drops, the restrictions increase and water pressure is reduced, or in cases where dam levels reach 15% or lower, supply may become intermittent. Level 5 water restrictions include the commercial reduction in consumption by 20%. In October 2017, domestic and industrial potable water supply was limited by 40% and agricultural supply by 50% against the 5 year baseline. With level 6 restrictions, instituted in January 2018, heavy fines were implemented for high consumers with an increase in commercial reduction to 45% and agriculture to a 60% reduction.

Table 5.11: City of Cape Town Water Restriction Levels

Level Restriction	Date Imposed	Portable Usage Restrictions	Groundwater Restrictions	Additional Information
Level 1	Nov 2001 and 2005	Irrigation in time allowable brackets	No Restriction	10% Saving
Level 2	Jan 2016	Outdoor usage limitations	Usage Restrictions	20% Saving
Level 3	Nov 2016	Outdoor usage: no hosepipe and limits	Outdoor usage: no hosepipe and limits	30% Saving
Level 3b	Jan 2017	Outdoor usage: no hosepipe and limits	Outdoor usage: no hosepipe and limits	Urban -20% Agriculture -30%
Level 4	June 2017	100 l/day per capita	Discouraged No pool usage	Target: 600 million litres/day
Level 4b	July 2017	87 l/day per capita	Restrictions: Discouraged	Target: 500 million litres/day
Level 5	Sep 2017	87 l/day per capita	Restrictions: Discouraged	Target: 500 million litres/day
Level 5b	Nov 2017	87 l/day per capita	Restrictions: Discouraged	Target: 500 million litres/day
Level 6	Jan 2018	87 l/day per capita	Restrictions: Indoor use only	Target: 450 million litres/day
Level 6b	Feb 2018	50 l/day per per capita	Restriction: Indoor use only	Target: 450 million litres/day
Level 7	N/A	25 l/day per per capita	Restriction: Indoor use only	Target: 350 million litres/day

The dynamic behaviour of water restrictions in response to changes in the dam level and the resulting change in consumption patterns, for both industrial and domestic, are captured in model equations documented in Appendix B.5.4.

However, as new information from continuous research are brought to light, changes to water conservation and demand management strategies may occur. The 2019 City of Cape Town Water Strategy redefine the associated water restrictions, which are implemented in-line with the percentage of water available in the WCWSS dams. Table 5.12 summarise the new planned restriction levels with associated dam levels for the City of Cape Town (CoCT, 2019a). As the planned restriction levels are not yet implemented, the constructed model continues to utilise restriction levels as set out in Table 5.11.

Educational and Communication Campaigns

Although water restrictions are enforced with higher tariffs and penalties, several campaigns have been conducted to create greater awareness and ownership with regards to the water shortages experienced in the City of Cape Town. These include numerous advertisements, public dashboards and pamphlets, which are easily accessible on the upgraded

Table 5.12: City of Cape Town Water Restriction Levels according to Dam Levels

Level	Dam Level	Restrictions
Water Wise	> 81%	No restriction
Level 1	71-80%	10% Saving
Level 2	61-70%	20% Saving
Level 3	46-60%	30% Saving
Level 4 >	Below 45%	Strict consumption limits

City of Cape Town website. Consumption and water use information is readily available to promote the demand management and improve water saving efforts in households to meet daily target consumption.

To intensify the effort towards water saving, the City of Cape Town launched a "live water usage map" to provide information to the public with regards to treated effluent collection points, household water usage and water pressure management areas (A. Walker, 2018). Colour coded dots are used to plot water usage on a map of the City of Cape Town as seen in Figure 5.10. Dark green dots represent households consuming less than 6 *kl* of water a month, whereas bright green dots indicate households using less than 10,5 *kl* per month. Those households utilising more than 10,5 *kl* a month are not displayed. However, with the recovery of the dam levels, the City Water Map has been discontinued since January 2019.

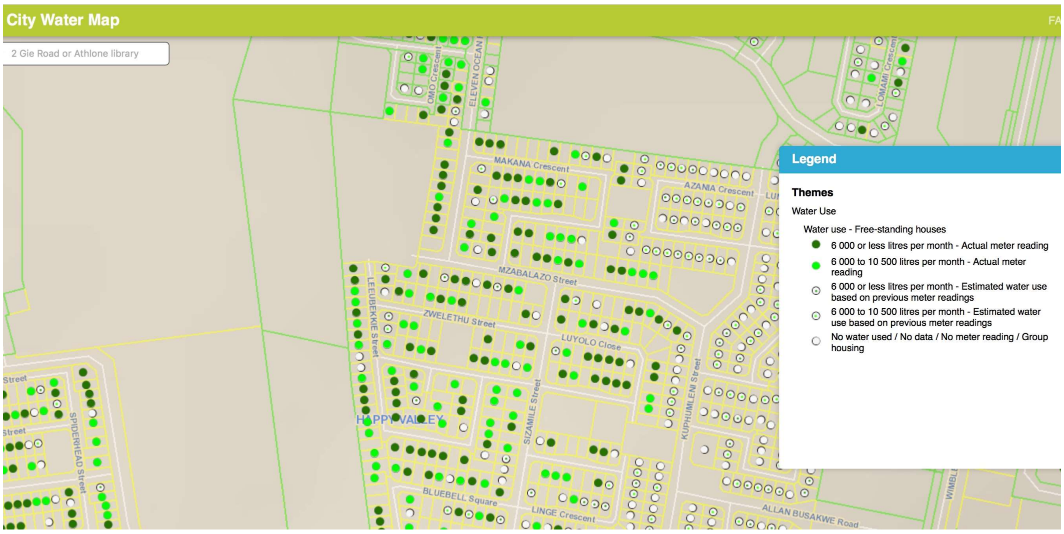


Figure 5.10: City of Cape Town Water Map

Regulating Household Flows

Pressure reduction and water management devices serve to manage and reduce daily household consumption and limit the impact of reticulation leaks in the City. Households consuming more water than the implemented restriction level allocates, are fitted with water flow regulators that allow for the provision of water to be halted once the daily limit per household is reached. The system opens the following day to resume usage up to the restricted daily allowance (CoCT, 2018a).

The model does not account for the influence of eduction campaigns or flow regulations on the consumption of municipal water resources, however the expansion of the model can accommodate additional parameters.

5.5.5 Total Water Demand

Restrictions on water use influence the total demand on the WCWSS and the City water resources,. Thus, the allocation and urban water usage are regulated by implementing restrictions in the City of Cape Town. The *Per Capita Consumption Limit* is the allocated allowance for domestic users in the City, which is based on the restriction level, ranging from 242 to 25 l/day per capita.

Water restriction level 4 and upwards constrain the usage of potable use per capita, thus the constrained scenario and allocation of water resources are aligned with water restriction 4 and higher. For water restriction level 3 and lower, water consumption is categorised as the unconstrained scenario. Subsequently, the total demand for potable water is the combined demand from both industry (30% of allocation) and domestic demand.

The non-potable requirements for both industry and domestic users are based on the relevant fraction of non-potable demand. However, several intervention actions serve to integrate supplementary non-potable supply sources for industry and domestic usage. Hence, non-potable demand can be significantly reduced by adding non-potable water resources, from retained and reused water streams, to the total non-potable supply.

The following stocks and flows in Table 5.13 form part of the *water as a product input* subsystem. While supporting equations for the domestic and industry demand parameters are captured in Appendix B.5.

Table 5.13: Stock, Flows and Auxiliary Variables for Water as a Input Product Sub-models

Stock	Flow	Auxiliary Variables
Domestic Demand		
Urban Population	Population Decline	Population Growth Rate
Industrial Allocation Growth		
CoCT Industrial Allocation Growth	Increase CoCT Industrial Allocation	Economic Growth Scenario GDP Rate
CoCT Industrial Allocation Growth Constrained	Increase CoCT Industrial Allocation Constrained	

Interventions are predominantly implemented through national or regional policies and regulations, including water restrictions, pressure management, flow regulation and installation requirements of alternative water sources in households and industries. Consequently, a reduction in non-potable demand can result in significant savings on the municipal water resources, ultimately reducing water supply stress in the region. However, the reduction in water supply stress may result in lowered restrictions and heightened consumption patterns.

5.6 Water as a Waste Stream

As a result of the continuous growth in demand for finite fresh water supplies, the 2007 Water Conservation and Water Demand Management (WCWDM) strategy became an integrated part of the water services provided by the City of Cape Town Municipality. Several interventions are set out in the policy to reduce the urban and agricultural demand, whilst other actions set out to conserve the City's water resources. However, the demand continues to grow, while resources are further constrained by the prevailing drought periods and pollution. Consequently, additional actions must be taken to provide urban users with the necessary affordable water resources to ensure the well-being and development of the economy and society in a sustainable manner.

These intervention actions must adhere to the Constitution. Hence, the environmental impacts of potential supply schemes must be considered for appropriateness of use and whether the actions are sustainable. The retaining of decentralised and centralised waste streams serve as potential solutions to address water shortages at the route of the cause, the users. The scientific findings in the 2007 Intergovernmental Panel on Climate Change (IPCC) report indicate, with a high level of certainty, that human involvement has resulted in changes in climate, resulting in more extreme temperatures and weather patterns (Viljoen, 2014). Therefore, it is reasonable to expect a further reduction in precipitation or more frequent drought periods, followed by periods of extreme rainfall, with higher temperatures. This further emphasises the importance of reusing and retaining available resources sustainably.

Conventional water management is no longer a feasible option in rapidly urbanising regions, as resources are constrained while the demand continues to grow (Carden and Armitage, 2013). Alternative management approaches, such as circular economy principles, facilitates the change towards a zero water waste system. By retaining water and reusing waste streams within the urban water system, whilst conserving and reducing demand for the raw water resources. Regulations and governing strategies are drivers of establishing the conservation and sustainable approach towards alternative water management.

The urban water system model incorporates the potential sources of water for urban usage from the reuse of waste streams and retention of resource within the system. The *water as a waste stream* sub-models are:

1. Wastewater Treatment Works Sub-Model
2. Retain, Reuse and Reduce Sub-Model
3. Total Water Waste Management Sub-Model

5.6.1 Wastewater Treatment Works

There are 17 wastewater treatment works (WWTW) operated by the City of Cape Town, with an additional 6 minor facilities. The total WWTW system capacity at present is 746 MLD, however only thirteen of the plants are equipped to produce reusable effluent. Several of these wastewater treatment plants produce treated effluent for reuse in industry and for irrigation within the City. Moreover, the treated effluent quality is monitored for compliance with national standards.

The use of treated effluent is influenced by seasonal changes, with warm summer months increasing the demand for alternative irrigation sources. Thus, winter months are predicted to result in surplus treated effluent of up to 200 million m^3 by 2020 (Milkwood Communications, 2010). In 2018, thirteen of the City of Cape Town's 23 wastewater treatment plants were equipped to produce reusable treated effluent, with a combined capacity of 164.5 MLD. Industries, municipal institutions and recreational areas use on average 50 000 m^3 treated effluent per day, which is a relatively small fraction of the total daily water consumption in the City (CoCT, 2018e).

The *Wastewater Treatment Works Capacity* (WWTWC) is increased by added capacity through upgrades and additional facilities as per planned investment. The *Increase in WWTW Capacity* (r_{IWWTW}) is a function of added capacity based on past and future projects as per strategic planning documentation. According to the State of Cape Town Report for 2001, the *Initial WWTW Capacity* is set at the 2001 capacity of 205 million m^3 per annum in Equation 5.6.1.

$$WWTWC(t) = WWTWC(0) \;+\; \int_{t_{2001}}^{t_{2040}} [r_{IWWTW}]\; \mathrm{d}t \tag{5.6.1}$$

Wastewater from domestic and industry users are received by the various treatment plants in the City. The model monitors the sufficiency of the total WWTW capacity to accept and treat the growing production of water waste from urban users. The quantification of model variables and causal behaviour in Figure 5.11 is expanded on for model development in Appendix B.6.1.

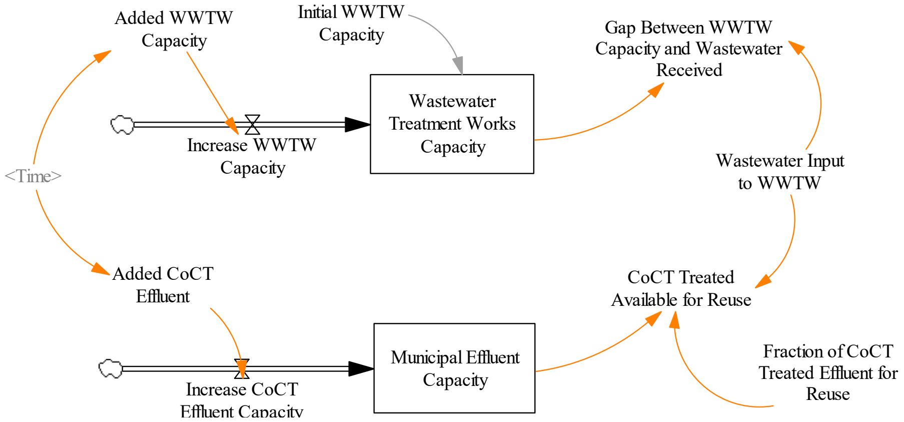


Figure 5.11: Stock-and-Flow Diagram: Centralised WWTW

In 2012, the Fisantekraal effluent plant was added to the City sewage network, adding an additional capacity of 24 MLD, treating water for irrigation purposes. However, this plant is licensed by the DWS to treat up to 58 MLD of wastewater. Furthermore, an extensive upgrade on the Bellville and Athlone WWTW is in progress to increase the quality and capacity of the current system (CoCT, 2018e).

Additional projects to expand and upgrade current WWTW form part of the future scheduled projects with added capital expenditure planned at a total of R761 million

(CoCT, 2018a). The energy cost per m^3 is estimated at 2 kWh, almost half the requirement for desalinated water. As wastewater is primarily treated for reuse as irrigation and industrial consumption, less aquifer recharge water will be available. However, this can be mitigated through stormwater and rainwater recharge.

Future augmentation programmes for reuse include the 70 MLD facility at the Faure water treatment works, with potential to scale to 90 MLD, processing wastewater from Zandvliet and Macassar. Additional concept designs for the Athlone water reuse facility of 75 MLD may take affect in the medium term. Furthermore, potable reuse schemes are being investigated and feasibility studies are in process, with an investment cost of R4.5 billion to become available in 2025, potentially adding 100 MLD to the potable network in the future (Bronkhorst, Pengelly, et al., 2017).

The capacity of both total wastewater treatment works and effluent reuse is captured in Table 5.14. This table serves as an approximation, based on data extracted from several sources.

Table 5.14: CoCT Wastewater Treatment Works Capacity

Year	**Capacity** (Mm^3/a)	**Licensed** (Mm^3/a)	**Reuse Capacity** (Mm^3/a)	**Actual Reuse** (Mm^3/a or %)
2001	205	-	-	9%
2002	215	-	-	-
2003	242.8	-	22	11.6
2007	221.3	-	-	10%
2018	270	255	60	18
Future	+25.55		124.7	

Estimation of potential yield from wastewater treatment works are based on findings in the 2007 WCWSS Overview of Water Re-use potential from Wastewater Treatment Plants (Ketteringham, 2007). The report based the total future reuse yield on 74.4% of inflow into the wastewater works.

The WCWSS report further found that the reuse prior to 2007 was estimated at 11.6 million m^3 per annum in the City of Cape Town for irrigation and industrial purposes (Ketteringham, 2007). However, the feasible potential for potable and non-potable reuse was estimated at 76.6 million m^3 and 50.2 million m^3 per annum respectively.

However, the reuse of treated effluent as a potable source, both direct or indirect, experience several barriers, including, the perception of the public, health risk due to poor management and design, disposal of brine and reduced discharge to downstream users. The process is thus lengthy and costly, resulting in alternative interventions being favoured.

The 2007 WWTW capacity is based on the eight largest effluent treatment plants, indicating a slightly lower total capacity. What is more, the inflow and discharge of effluent is highest during winter months, when stormwater runoff ingress into the sewer network (Milkwood Communications, 2010). However, the fluctuation in flows are not considered for the purpose of this study, thus annual average values are used.

Education on the disposal of household and industrial waste in the sewage system aim to reduce the amount of foreign matter and toxins that pollute and block the sewage system. Guidelines, tips in public documentation and City by-laws serve as educational and regulatory guidance to reduce sewer blockages and disruption to the biological treatment process as a result of toxins and solid waste in the wastewater reticulation system (CoCT, 2018e).

Furthermore, the wastewater treatment works in the City is under pressure from excessive stormwater directed into the sewer systems during high rainfall periods, referred to as *stormwater ingress* (van Weele and Maree, 2013). The system capacity is limited to a certain wastewater volume. Consequently, the overload caused by the additional stormwater, results in untreated effluent being released or overflows (sewer surcharge) in the reticulation system, which pose health and environmental risks.

Water for discharge through marine outfalls receives limited treatment, however the outfalls are carefully designed to disperse wastewater deep into the ocean, where ocean currents serve to disperse the effluent further. The total discharge licence allows for a total of 60 million litres of mostly untreated effluent to be discharged into the ocean per day. However, the design capacity of 55 million litres per day (20.075 Mm^3/a) limits the marine outfall discharge (CoCT, 2018e). The remainder of wastewater is discharges into surrounding natural water bodies.

5.6.2 Retain, Reuse and Reduce

To reduce waste in the system, behavioural alterations are necessary, which include actions towards retaining water within the system, reusing water and reducing the demand for water resources. These actions are central to minimising system wastage in a circular water economy. Interventions include the retention of rainwater and the reuse of greywater for non-potable purposes. These waste stream reuse actions are applicable to both the domestic and industry sectors in the City of Cape Town.

Addressing the non-potable demand entity in the urban water demand, allows for saving in the abstraction of groundwater and surface water from natural resources. These alternative sources of non-potable water supply can be decentralised from the water supply system, reducing the socio-economic risk associated with water rationing and shortages.

Stormwater Harvesting

The City of Cape Town is committed to its transformation into a water sensitive city as part of the City's water strategy. Using the water sensitive urban design (WSUD) approach the City aims to optimally utilise water supply, sanitation and stormwater management and planning in an integrated manner to improve system resilience (CoCT, 2019a). One of the challenges identified is the problems associated with stormwater and urban water ways, which include the impairment of water quality and structural damage during peak flows (Malaviya and Singh, 2012). Therefore, the City of Cape Town aims to integrate the natural and constructed networks of stormwater conveyance and treatment to protect the receiving environment and the citizens by optimising the use and management of stormwater.

Urban structures and stormwater systems should be constructed with extreme weather changes in mind. As urbanisation has replaced natural water cycles, additional variables such as wastewater discharge, poor quality runoff and a reduction in infiltration and evaporation has become part of the urban water cycle. To address this, urbanisation should aim to become more sustainable, by reducing potable water demand and allowing for groundwater infiltration and the harvesting of surface runoff. Urban areas result in impervious cover, which severely limits the shallow and deep filtration of water to underground water reservoirs. The impervious cover results in up to 55% precipitation to become runoff, compared to 10% runoff in natural water systems (Viljoen, 2014).

Evapotranspiration is the collective term used to account for the sum of transpiration and evaporation, which forms part of the natural water balance. Precipitation in natural ground cover and urban impervious cover regions are distributed differently, resulting in higher runoff rates in urban areas opposed to higher infiltration portions in natural regions as per Equation 5.6.2 and Equation 5.6.3 (Viljoen, 2014).

$$\begin{aligned}\text{Precipitation (Natural)} &= 0.4\ \text{Evapotranspiration} + 0.1 \cdot \text{Runoff} + 0.25 \cdot \text{Shallow} \\ &\quad \text{Infiltration} \ + 0.25 \cdot \text{Deep Infiltration}\end{aligned} \tag{5.6.2}$$

$$\begin{aligned}\text{Precipitation (Urban)} &= 0.3 \cdot \text{Evapotranspiration} + 0.55 \cdot \text{Runoff} + 0.1 \cdot \text{Shallow} \\ &\quad \text{Infiltration} \ + 0.05 \cdot \text{Deep Infiltration}\end{aligned} \tag{5.6.3}$$

Rainwater collection further serve as a source of pressure reduction of stormwater inflows, allowing for more efficient treatment of stormwater, while reducing ingress into the sewage system. Harvesting stormwater reduces the excessive runoff from urban areas into natural rivers and ecosystems. Thus, reducing the damage and allowing for improved water quality through the re-establishment of natural ecosystems. Additional benefits pertaining to the harvesting of rainwater and stormwater, is the reduced energy requirement and extensive infrastructure required to capture non-potable water sources, resulting in cost savings. What is more, to restrict the saline water intrusion from the ocean into the groundwater aquifers, treated wastewater and stormwater runoff can be used as a source of artificial recharge (Fisher-Jeffes, Carden, et al., 2017).

High quality municipal treated effluent and stormwater is used to artificially recharge approximately 30% of groundwater supplied to the town of Atlantis (Bugan, Jovanovic, Israel, et al., 2016; Fisher-Jeffes, Carden, et al., 2017). Research conducted by Fisher-Jeffes (2017) found that stormwater harvesting has significant potential in reducing potable municipal water in residential areas, by substituting water consumed for irrigation and toilet flushing.

However, the yield is dependent on the implementation and application of stormwater harvesting systems. In the City of Cape Town, the majority of rainfall and therefore, peak stormwater flow, is in winter when irrigation requirements are low and surface water reservoirs are receiving inflows from rainwater runoff (Fisher-Jeffes, Carden, et al., 2017).

Subsequently, the research reports that the capturing, storage, treatment and reuse of stormwater serves to reduce flooding during peak flows, reduce potable water demand and promote the enhancement of natural water systems.

Viljoen (2014) studied the feasibility of stormwater harvesting for commercial sites with winter rainfall in Cape Town. The study reports that the cost estimation and potential saving for a stormwater system is estimated at R95 000 with an annual saving of approximately 2000 m^3. Therefore, the return on investment is found to be 3.5 years based on commercial water tariffs, if the totality of water captured is used to substitute municipal water (Viljoen, 2014). The University of Cape Town is directing several studies investigating the viability and application of stormwater harvesting in Cape Town, case studies conducted include Diep River, Cape Flats and Liesbeek River catchment areas (Fisher-Jeffes, Carden, et al., 2017; Rohrer and Armitage, 2017; Gobin, 2018).

The model structure allows for the overflow from rainwater harvesting systems to be translated to stormwater, which can be captured and stored for reuse. Harvested stormwater can then serve to recharge groundwater resources or supplement non-potable water requirements such as toilet flushing in both industry and domestic sectors. Unfortunately, limited data and results are available to validate a stormwater harvesting sub-model.

Greywater Reuse

The volume of greywater generated per capita is based on the fraction of household water usage that produce reusable greywater for non-potable requirements. Although individual usage patterns differ, a standard of usage fractions for both potable and non-potable water consumption is assumed for the urban water system model. These fractions are based on documented usage suggestions by the City of Cape Town and similar documents. The end-user consumption based on the constrained and unconstrained water supply scenario can be distributed as per Table 5.15.

Table 5.15: Per Capita Consumption Behaviour

Supply Scenario	Potable	Non-Potable
Constrained	62%	38%
Unconstrained	46%	54%

The assumption is made that under normal or unconstrained circumstances, when water levels are sufficient to allocate water resources during non drought years, the distribution of potable to non-potable water requirements is 46% and 54% respectively for daily per capita consumption of 242 l/day.

The per capita consumption of potable water is limited by the implemented water restrictions. However, the efficiency with which users adhere to these restrictions are calibrated to represent real life system performance. Consequently, the *Per Capita Consumption Limit* is indicative of the total water demanded from the municipal water system (potable water) without any decentralised water supplementation.

The assumption is made that 70% of water used for potable purposes is suitable for reuse as greywater to supplement non-potable requirements in domestic households. The fraction aligns with the sewage generation fraction as per water billing. This fraction depends on the reuse habits of domestic households, which can be guided by public water education and regulation. Potential greywater should be used for indoor non-potable purposes preferably, to ensure that wastewater reach downstream wastewater treatment processes.

The generated greywater can be used to supplement the non-potable requirements, consequently reducing the total demand on the municipal water supply system. The applicable equations for domestic greywater generation and the industrial greywater generation in Appendix B.6.2 support the quantification of the sub-model in Figure 5.12.

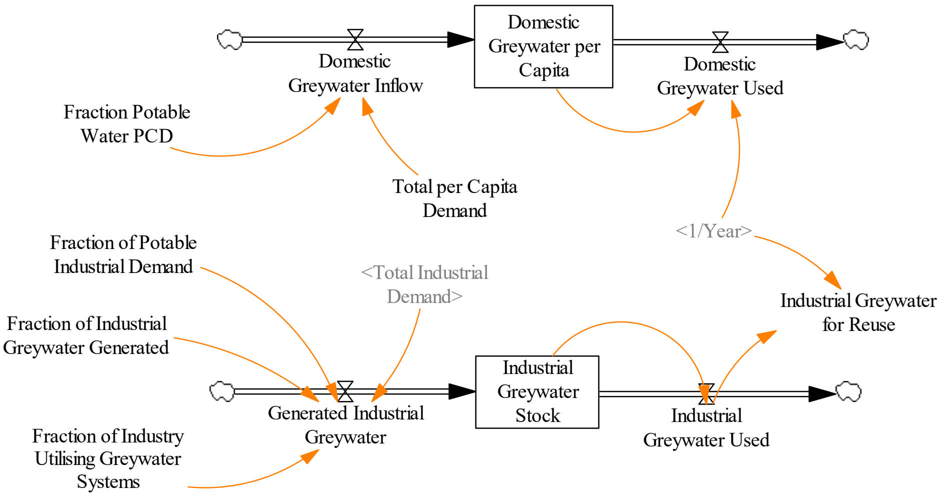


Figure 5.12: Stock-and-Flow Diagram: Domestic and Industrial Greywater

Furthermore, industrial greywater systems generate non-potable water in a similar fashion. However, information in this regard is not as thorough, thus estimated fractions of greywater generation is used. For modelling purposes, the same billable fraction of 70% is used to estimate the portion of greywater generated in industry. For industry, the demand for non-potable usage is estimated at 30% for toilet flushing. Therefore, alternative source of water should serves to supplement the minimum of 30% of total industrial water usage.

The model aims to test several potential policy actions to address the shortage of suitable water sources for the assurance of a sustainable socio-economic and environmental future. An example of legislative support, include the amendments to the City's water by-laws, which require new developments to include the installation of alternative water systems and water saving fixtures for non-potable uses such as laundry, irrigation and toilet flushing (Reddick and Fundikwa, 2018). However, the largest contributor to municipal demand is potable quality water requirements, which can be supplemented by alternative sources of potable water such as desalinated seawater and high quality treated wastewater.

Decentralised Industrial Reuse Plant

The industrial sector may invest in more expensive supplementary water alternatives such as decentralised wastewater treatment plants for reuse. The advantages of these systems are the assurance of water for economic use and the municipal water bill savings. The 2017 GreenCape Market Intelligence Report for Water presented an illustration of financial savings high water users can obtain by investing in sophisticated decentralised wastewater treatment systems. The saving were estimated at up to R8 million, resulting in a five year system pay-off (Bronkhorst, Pengelly, et al., 2017).

The *Industrial Reuse Plant Capacity* (IRC) stock in Equation 5.6.4 is increased with additional industries adding decentralised treatment systems (r_{IRCI}) in the industrial sector. The generated water serves as a substitute to municipal potable water, reducing the total industry demand on the City's urban water system. The sub-model for the decentralised wastewater generated by industrial facilities is illustrated in Figure 5.13.

$$IRC(t) = \int_{2001}^{2040} [r_{IRCI}]\,\mathrm{d}t + IRC(0) \tag{5.6.4}$$

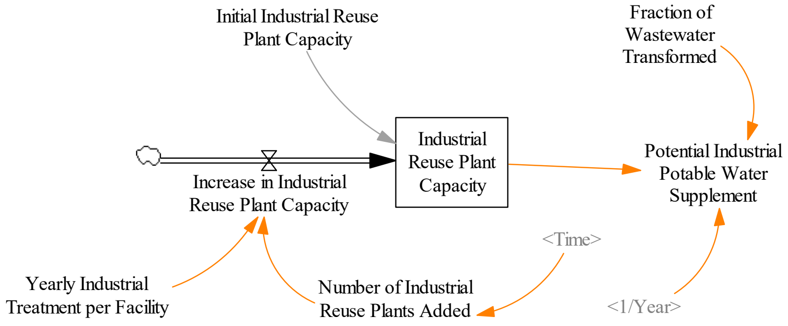


Figure 5.13: Stock-and-Flow Diagram: Decentralised Wastewater Treatment Plant

However, there is insufficient information and data available to validate the constructed sub-model to assure accurate representation and insight of the real-world system. To investigate the potential and challenges associated with implementing decentralised wastewater treatment facilities in the urban setting, an in-depth investigation into real-world application of decentralised wastewater systems for potable reuse needs to be conducted. Results obtained from suitable case studies will provide clear structure and operational feasibility to refine the conceptual and dynamic model based on current publicly available information and data.

Chapter 6 investigates the singular case of a decentralised wastewater treatment facility installed at Old Mutual's Pinelands campus in Cape Town. The case study findings are used to refine the decentralised industrial reuse plant sub-model, to better depict real-world application and behaviour.

5.6.3 Total Water Waste Management

The waste stream sub-models aim to identify areas of waste and the potential to utilise these waste streams as an alternative to WCWSS potable water yield. The independence from centralised systems not only mitigate the risk of unavailable water sources, but also reduce the associated cost of municipal water usage, especially for industrial purposes.

The following stocks and flows in Table 5.16 are linked as urban water waste streams.

Table 5.16: Stock, Flows and Auxiliary Variables for Water as a Waste Stream Sub-models

Stock	Flow	Auxiliary Variables
Treated Wastewater Supply		
Wastewater Treatment Works Capacity	Increase WWTW Capacity	Added WWTW Capacity
Municipal Effluent Capacity	Increase Reuse Capacity	Added Reuse Capacity
Greywater Reuse		
Domestic Greywater per Capita	Domestic Greywater Inflow	Fraction Potable Water PCD
	Domestic Greywater Used	Total per Capita Demand
Industrial Greywater Stock	Generated Industrial Greywater	Fraction of Potable Industrial Demand
	Industrial Greywater Used	Fraction of Industrial Greywater Generated
Decentralised Reuse Plant		
Industrial Reuse Plant Capacity	Increase in Industrial Reuse Plant Capacity	Potential Industrial Potable Water

The model aims to investigate the potential reduction in water supply stress in the urban water system through the implementation of waste reduction principles, driven by regulation and water management strategies. Scenarios are tested through a process of simulation to determine the behaviour of the system in response to parameter changes, providing insight and understanding to decision-makers.

5.7 Simulation Model

Model simulation allows for the visualisation and behavioural prediction in accordance with input variables for scenario testing, using VENSIM® PLE software. The sub-models for the water roles interact through a network of causal links to provide model behaviour outputs.

Simulation output can be displayed and checked using display graphs and tables built into the software. SyntheSim is a VENSIM® capability that allows for interactive representation of outputs in custom graphs and tables, using adjusting variable bars, control panels and graph design options (Hillman, n.d.). The value and usability of a simulation model, is determined through the establishment of model accuracy and credibility. Thus, the analyst is required to validate the proposed model to confirm the appropriateness of model implementation and use (Qudrat-Ullah, 2010). The suitability and accuracy of the conceptual model will not be evident until the model is simulated and validated. Therefore, the validation and calibration of the model is a crucial step in the dynamic modelling process (Albin, 1997).

System dynamics place emphasis on the characteristics of the system through pattern identification. These patterns may be present in various modes such as linear, exponential, s-shaped or oscillatory. The patterns allow for comparative evaluation of interventions to determine the growth, decline, consistency or oscillatory behaviour of the system. Several comparison tools and techniques are available for analysing simulation results over the modelled time scale. However, the validity of the model must be established before interpretation of outputs can be conducted with a realistic level of confidence.

The use of measuring indices allow for the investigation of the performance of potential system interventions. These interventions include the installation of rainwater harvesting and greywater systems in urban households and industry. The impact of such actions are tested through a process of testing measurement sets with parameter variation during simulation runs.

5.7.1 Measurement Indices

The shortage of water in the urban region can be simplified to the ratio of available water supply and water consumption in the City of Cape Town. To reduce the water shortage, both the demand and supply side of the ratio can be addressed. Alternatively, the the water supply stress index in Equation 5.7.1 can be used as a basis for measuring the water shortfall in the urban region. The available water supply (S) and estimated water demand (D) is used to equate the water supply stress index ($WaSS_I$) as a fraction deficit or excess over the total supply.

$$WaSS_I = \frac{D}{S} \tag{5.7.1}$$

The available traditional yield allocated to the City of Cape Town and the total demand for municipal water resources are compared in Equation 5.7.2. This formula is based on the water supply stress index explored in Chapter 4.1.3 to indicate the performance of the water system.

$$\text{Water Supply Stress} \;=\; \frac{\text{Municipal Demand}}{\text{Available Yield}} \tag{5.7.2}$$

Water Supply Stress values less than 1 indicate a sufficient supply of water to meet user requirements, however values higher than 0.4 do indicate water stress in the region (Wada et al., 2011). Values above 1 indicate the inability of system yield to meet the water demand. Subsequently, the fraction of *Water Supply Stress* shows to what degree the system meets the demand, or to what extent the yield of the system is insufficient to meet the demand.

However some water stress indices aims to determine the per capita availability of water resources, using thresholds to indicate the level of water stress experienced. Taking availability below 1000 m^3/capita/year as an indication of a water stressed region. This water stress index does not take the actual consumption of water sources into account and only serve as an indication of water stress within a populated region.

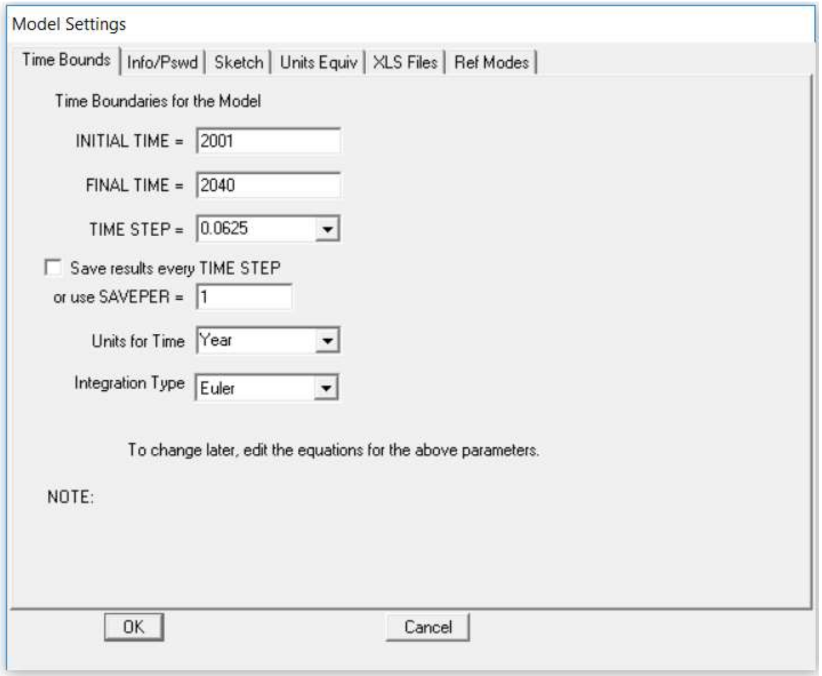
Chapter 2.2 introduced the Falkenmark Index as a water stress indicator. The index compared the fraction of runoff available for human consumption to predefined categories of water stress indicators. For example, the available water per capita below 1000 m^3 indicates that the region is water stressed. Subsequently, the Falkenmark Index in Equation 5.7.3 aims to identify the measure of water stress in the City of Cape Town.

$$\text{Falkenmark Index} = \frac{\text{Runoff per Year}}{\text{Urban Population}} \tag{5.7.3}$$

Several measurements are available to provide information and insight into the performance of the urban water system. However, the fraction of water stress and water scarcity indices only serve as an comparative measurement tool for the research study. It is important that the benefit and performance of alternative water interventions be evaluated against a set baseline, using the water supply stress index and cost as performance references.

5.7.2 VENSIM® Model Settings

The VENSIM® model settings is illustrated in Figure 5.14, which shows that the model is simulated over the fixed time period from 2001 to 2040, with the time step recorder per year, thus using the time set unit as *Year*. The Euler integration method was selected due to its ability to provide the approximate values of a solution for first order differential equations using time steps. Furthermore, the Time Step of 0.0625 serves as the delay fraction between iterations, which is slightly less than a month.



Time Boundaries for the Model

INITIAL TIME = 2001

FINAL TIME = 2040

TIME STEP = 0.0625

☐ Save results every TIME STEP

or use SAVEPER = 1

Units for Time Year

Integration Type Euler

To change later, edit the equations for the above parameters.

NOTE:

Figure 5.14: VENSIM® Model Settings

The system model serves the intended purpose of providing decision support to policy makers for evaluating the impact and behaviour of the urban water system in relation to implemented policies and to determine the viability of policy actions in light of sustainability objectives. Consequently, the constructed model must be an accurate representation of the real-world urban water system, which require the model to be validated to ensure that it is fit for purpose.

5.8 Model Validation

Models aim to represent reality, albeit imperfectly and can be judged as valid if they serve as useful tools for decision making (Barlas, 1996). The process of validation is an ongoing mix of activities, conducted throughout the modelling process. This process aims to establish confidence in the accurate representation and usefulness of the model.

The purpose and application of the system dynamics model, determines the validation approach (Brzezina et al., 2015). This means that there are many validation and verification tests for determining which models are useful and which are unhelpful. Although model validation aim to ensure the representation of all aspects of the model, to replicate real-world behaviour, validation does not imply that models are completely accurate (R. Walker and Wakeland, 2011).

Chapter 3.7 introduced the system dynamics model validation theory, which emphasised three main validation tests, namely: model structure, model behaviour and policy implication tests. Initially the accuracy and detail sufficiency with which the model represents the real world, is tested. The appropriateness and accuracy of data used is also tested. Thereafter, the correctness of the model's transfer to computerised modelling is verified and the real-world representation of the computerised simulated model is tested for accuracy to establish the usefulness of the constructed model for decision support (Lemke and Katuszynska, 2013).

Qudrat-Ullah (2010) agrees that the identification of model purpose is crucial to the validation process, with equal emphasis on the correct construction of causal relationships during model development. Subsequently, validation in practice, should be conducted throughout the modelling process, although formal model validation is typically conducted after model construction and before model evaluation (Barlas, 1996).

5.8.1 Structural Validation

Structural validation is technically difficult as both philosophical and technical aspects are required to validate the internal system structure for ensuring an accurate representation of a real-world structure (Barlas, 1996). With most structural validation techniques based in the qualitative domain, reliant on expertise, inspection, consistency checks and data flow analysis. Furthermore, structure tests aim to identify structural flaws in the model. Whereas, extreme value testing involves assigning extreme values to selected parameters and comparing simulated behaviour to anticipated or observed real system behaviour in light of these changes (Forrester, 1996).

For the verification of the model structure, techniques for testing model fitness include: structural verification test, extreme condition test and dimensional consistency test. Furthermore, the process of structure validation requires the trend per unit of time and the input of parameters to be identified and captured for evaluation.

For structural validation, the causal diagram structures are compared with actual real system structures and available knowledge (Qudrat-Ullah, 2010). Subsequently, the direction of parameter relationships in the causal loop diagrams should also match the direction of the dynamic computerised model (Qudrat-Ullah, 2005).

Structural Verification Test

The main structure and model elements required for the configuration of urban water system models include water resources, water users and recipients (Margeta et al., 2015). Each of these main model elements are influenced by several variables that serve as the directional connectors between main model elements. The constructed research model in this chapter should adhere to the key variables identified by Margeta et al. (2015) in Table 5.17 for urban water systems.

Table 5.17: Structural Validation: Urban Water System Variables

Required Urban Water System Variables	**Constructed Urban Water System Variables**	**Included Yes/No**
Water Supply Capacity	*Total WC Potable Supply Yield*	✓
Water Supply Inflow	*Potable Water Treatment*	✓
Water Supply Losses	*Reticulation Losses*	✓
Industry Consumption	*Total Industrial Demand*	✓
Domestic Consumption	*Domestic Demand*	✓
Total Water Consumption	*Total Municipal Resource Demand*	✓
Wastewater Quantity	*Municipal Effluent Capacity*	✓
Other Water	*Non-Potable Domestic Demand Supplement per Capita*	✓
Other Water	*Non-Potable Industrial Demand Supplemented*	✓
Sewage System Capacity	*Wastewater Treatment Works Capacity*	✓
Sewage System Loss	Not Applicable	No
Sewage System Inflow	*Wastewater Input to WWTW*	✓
Wastewater Reuse Treatment Plants	*Municipal Effluent Capacity*	✓

The model structure is based on insight gained from several sources, including water management models built for similar studies conducted in the Western Cape and the 2018 Water Services and the Cape Town Urban Water Cycle report, which describe the structure of the City's urban water system.

The parameter verification aims to compare real-world and modelled systems. These include numerical values from data sources in the quantitative model construction. For improved transparency and parameter verification, variables or parameters are summarised for each water role in Table 5.18, indicating the corresponding variable name, initial value (2001), unit and the data source.

Table 5.18: Key Parameters for the City of Cape Town Urban Water System

Parameter	**Initial Value**	**Unit**	**Data Source**
Urban Population	2 892 243	People	StatsSA Census 2001
Total Households	759 485	Household	StatsSA Census 2001
WCWSS Dam Capacity	768.3	Mm^3	WCWSS Reconciliation Strategy
WCWSS Dam Capacity Yield	440	Mm^3	WCWSS Reconciliation Strategy
WRYM Evaporation	61,5	Mm^3	WCWSS Reconciliation Strategy
Avg Size of HH Roof	50	m^2	Market Intelligence Report: 2017
Avg Capacity of Rainwater Tank	5000	*litres*	Market Intelligence Report: 2018
Groundwater Abstraction Capacity	105.56	Mm^3	State of Environment Outlook Report 2017
UGEP (Berg-Olifants WMA)	Constrained: 256 Unconstrained: 406	Mm^3/annum Mm^3/annum	State of Environment Outlook Report 2017
WWTW Capacity	205	Mm^3	Water Services and the Cape Town Urban Water Cycle: 2018
Precipitation	Average: 490/ Time Varying	mm/annum	Assumption based on average rainfall

Parameter verification serve as an alternative test for structural validation. Subsequently, the model parameters and source documents provide support to the accurate representation of the real-world urban water system. Therefore, the model structure is found to sufficiently represent the City of Cape Town's urban water system for the purpose of the research study.

Extreme Conditions Test

The plausibility of the model is tested through a process of extreme condition testing, which subjects the model to significantly high or low variable values to determine the model behaviour in comparison to normal conditions. These values can be selected outside historical highs and lows to test the usefulness of the model's ability to evaluate policies outside these limits.

Changing the capacity of decentralised household rainwater tanks can result in large water storage volume changes as illustrated in Figure 5.15. The model responds as expected, limiting the harvested capacity to rooftop runoff from precipitation as indicated by the orange line.

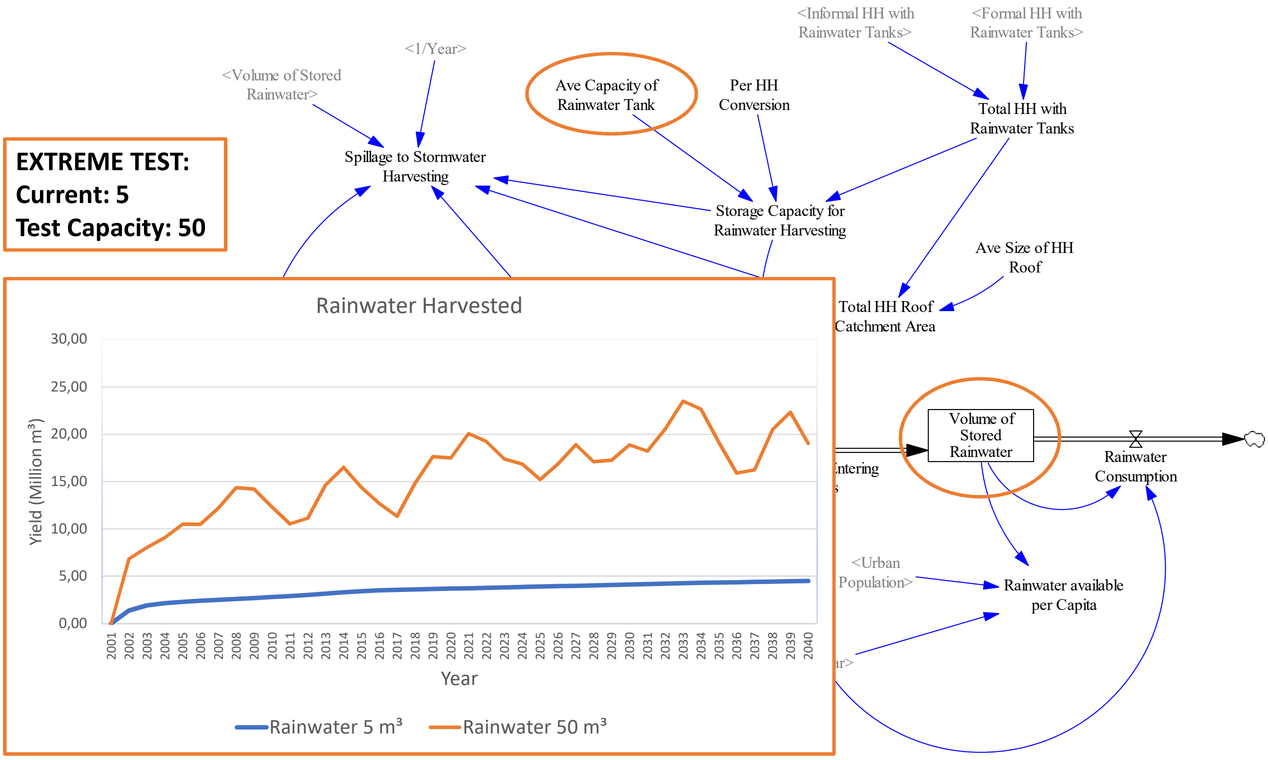


Figure 5.15: Extreme Condition Testing: Rainwater Harvesting Tank Capacity

The *Consumption Efficiency* parameter influence the manner in which domestic water consumption adheres to the implemented water restriction. Consequently, the extreme condition testing allows for the behavioural evaluation of the urban water system in light of changes made to the *Consumption Efficiency* parameter. Figure 5.16 indicates the changes in *Restriction Level* as a result of changes in consumption patterns. The changes range from zero to one, of which the test evaluated the response at 0.9 (Good adherence to restriction levels) down to 0.1 (Lack of adherence to restriction levels).

The causal variables affected by the *Consumption Efficiency* include the *Per Capita Consumption Limit* and subsequently the total domestic demand on the Western Cape Water Supply System. Therefore, the dam level is affected, influencing the level of water restriction implemented. This water consumption feedback loop results in the oscillating behaviour of water restrictions depicted during the good adherence scenario in Figure 5.16.

The requirement for non-potable water in industry is limited to 30% of total industrial consumption, therefore it is expected that alternative sources can only substitute total municipal water demand to an extent. Extreme condition testing is used to evaluate the model's response to an excess amount of non-potable water from alternative sources.

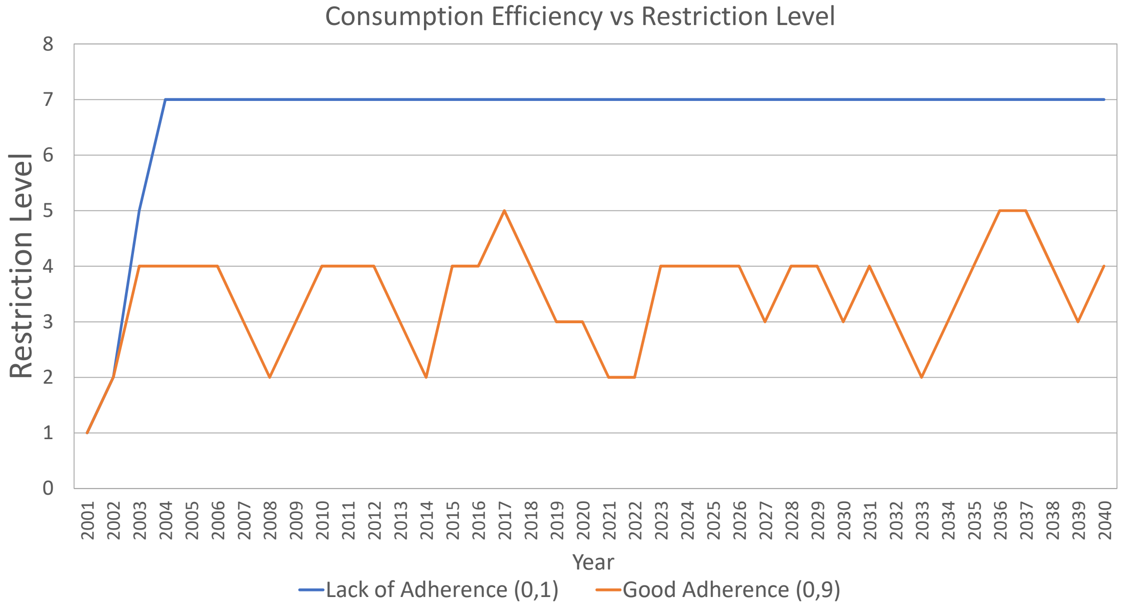


Figure 5.16: Extreme Condition Testing: Consumption Efficiency

Figure 5.17 compares the industrial non-potable water requirement with available non-potable water from alternative sources. The extreme case multiplied the amount of municipal treated effluent, supplementing the industrial non-potable water demand, by five. The simulation results found that the model structure does not allow surplus alternative water to influence the total municipal demand further than warranted, limiting the impact to the maximum non-potable water requirement. Subsequently, during the extreme case, total industrial municipal demand equals potable water demand.

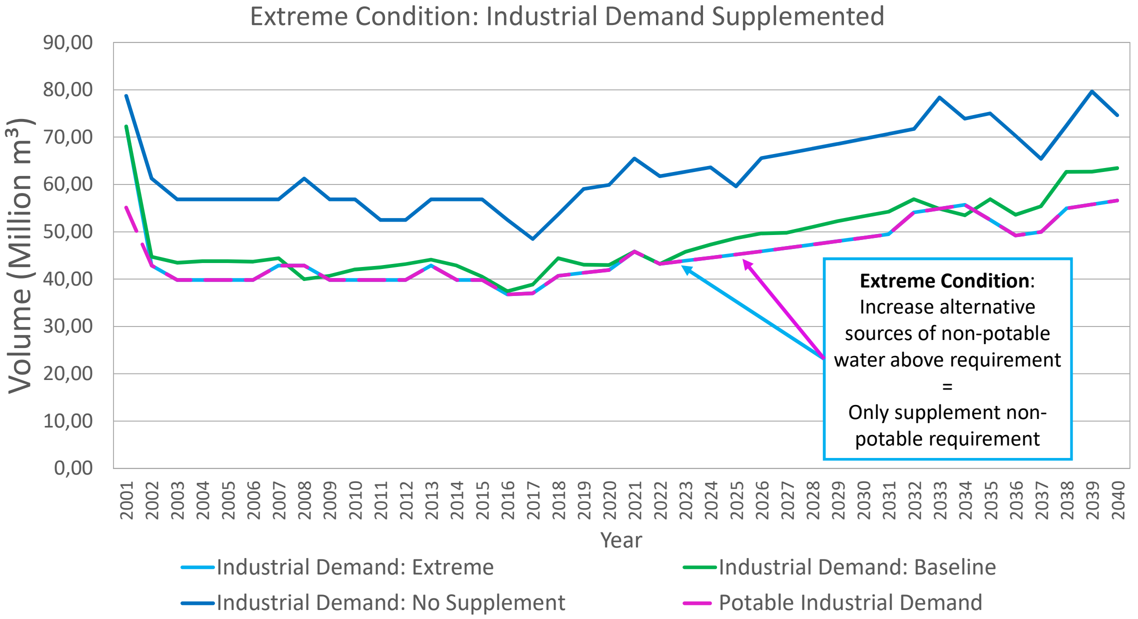


Figure 5.17: Extreme Condition Testing: Non-Potable Water Requirements (Industry)

The model is found to act in a plausible manner, responding to extreme changes in usage patterns, by implementing more severe consumption restrictions. Whereas, the increase in rainwater harvesting capacity in extreme cases are limited to the total runoff as shown in Figure 5.15. The model also proved to limit the amount of influence alternative water supply sources can have on the total water system, based on specific water requirements (quality and quantity of water demand). Hence, it is found that the model structure is capable of addressing extreme conditions outside normal operating standards.

Dimensional Consistency Test

During the construction of the model, VENSIM® provides the capability of checking variable units and equation syntax during function set-up. This process allows for continuous structure testing of the model, to ensure the direction, syntax and units of the model is set out in a logical manner. The dimensional consistency test was performed and the result was that no unit errors were found in the constructed model.

5.8.2 Behavioural Validation

Model behaviour, on the other hand, is tested for fitness and consistency by validation techniques such as parameter sensitivity test, statistical test, resilience test and symptoms generation test (Lemke and Katuszynska, 2013). Behavioural validation compares the performance of the real system with the simulated system, by comparing data generated by the simulated system with real system historical data (Barlas, 1996; Qudrat-Ullah, 2010). Once the context of the model has been considered reliable and parameter values are compared to real system values, the behaviour can be tested.

The statistics convey the measure of discrepancy of model behaviour, such as the determination of percentage error in variations over time, or the variation in phase lags and delays (Qudrat-Ullah, 2010). The model fit and overall model discrepancies can be evaluated using statistical elements, to ultimately test the accuracy of model behaviour.

Once the model structure is validated and the model confidence is set, the accuracy of model behaviour and patterns can be compared and measured against the expected real system behaviour (Barlas, 1996). System dynamics models are not useful for accurate point predictions, but rather for the identification of the system's behavioural patterns as a result of policy actions over a long period of time. Emphasis is once again placed on the importance of a clear understanding and definition of the model purpose in the problem formulation phase (Barlas, 1996).

Domestic water consumption is directly influenced by *Urban Population* and *Total No Households* in the City, establishing the importance of ensuring the model's ability to represent the real-world behaviour accurately. The parameters tested for behavioural accuracy in Table 5.19 is found to be an accurate representation of the observed reality.

The error fraction is estimated using the absolute difference between the actual and experimental value, divided by the actual value, which is stated as a percentage by multiplying the fraction with 100. The *Urban Population* and *Total No Household* parameters are tested for accurate representation, as the variables are critical to the determination of domestic consumption and rainwater harvesting output in the model.

Table 5.19: Behavioural Test: Error Analysis

Variable	**Observed**	**Simulated**	**Error**
Urban Population (2001)	2892243	2892243	0%
Urban Population (2011)	3740026	3744980	0.1%
Urban Population (2016)	3972237	4042680	0.9%
Total No Household (2001)	759485	741600	2.4%
Total No Household (2011)	1068572	1069990	0.1%
Total No Household (2016)	1272160	1268090	0.3%

Industrial parameters are difficult to test statistically, due to the limited available data. Therefore, assumptions for industrial consumption is based and aligned with domestic behaviour, consequently limited error analysis can be conducted and compared to real data.

Precipitation and runoff rates are modelled based on historical data and documented catchment areas to match the observed behaviour of the real-world system, as seen in Figure 5.18. What is more, the sharp decline in water levels in the major WCWSS dams correspond with the simulated volume of raw water in the modelled system.

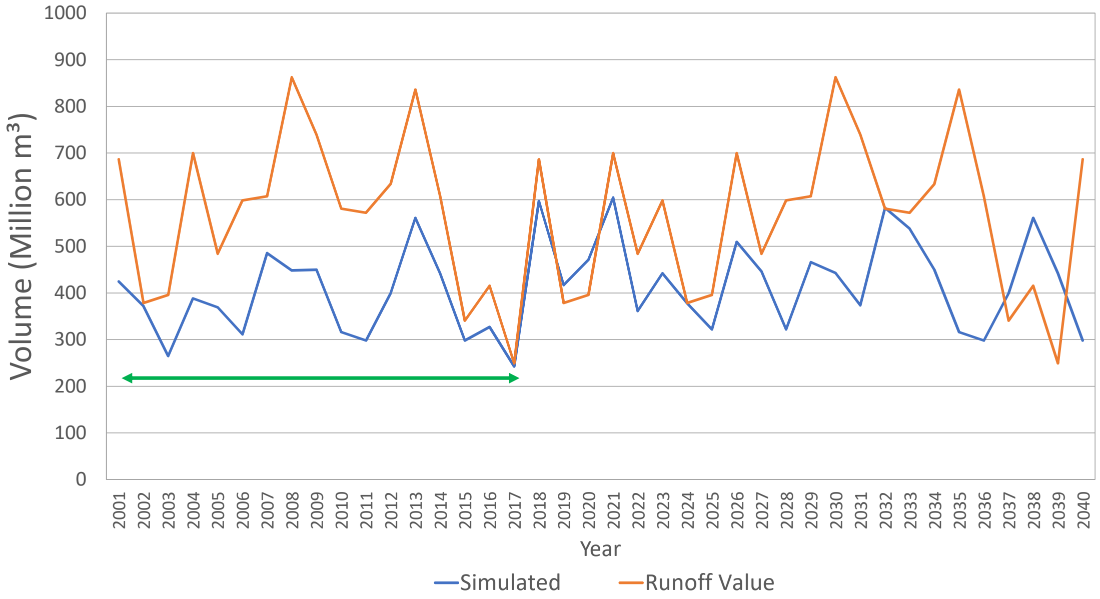


Figure 5.18: Behavioural Validation: WCWSS Runoff Simulation Comparison

The simulated runoff accounts only for the runoff to major WCWSS dams, therefore the quantity is lower than captured data from the 2018 Water Outlook report. However, the replicated pattern over the 2001-2018 period confirms the model behaviour is representative of the real-world system. Subsequently, the generated model behaviour is found to accurately match the real-world behaviour. It is important to note that the model's response to water restrictions are strict and responsive in comparison to real-world behaviour.

Finally, the sensitivity in model behaviour is evaluated in §5.8.5, to determine if model behaviour fails with shifts in model parameters, specifically the behavioural response to changes in external model parameters.

5.8.3 Policy Implication Test

To test policy implementation, the test referred to as legitimisation test, aims to determine whether the model accurately predicts the behaviour of the system in relation to the change in policy. The sensitivity to policy changes is another test, evaluating the extent of change in recommendation, as a result of changes in policy outcome based on parameter variations (Maani and Cavana, 2007). Barlas (1996) recommends that model validation should be an iterative process that is continuously implemented to improve the accuracy and usability of the constructed model. Consequently, validation and changes are continuously made to the model throughout the modelling process.

The complexity, data availability and size of the model will, therefore, determine the amount of effort required to calibrate the system dynamics model (R. Walker and Wakeland, 2011). A clear strategy is required for calibrating the system model parameters, which forms part of the verification and validation process. The process of testing uncertainties through parameter calibration and sensitivity analysis, is addressed in §5.8.4 and §5.8.5, however the model's boundary adequacy test forms part of the policy implementation test.

Boundary Adequacy Test

The model boundary adequacy test aims to ensure that the sub-models and structures are sufficient for the purpose of the model. It is found that the model boundary and inclusions align with the 2018 Urban Water System Structure for the City of Cape Town, including additional retention and reuse parameters such as rainwater and stormwater harvesting, potable wastewater reuse and greywater reuse. The inclusion of alternative water sources in the urban water cycle, allow for the evaluation of potential conservation and demand management policies and strategies in the City of Cape Town.

The geographical boundary, time period and the refined model purpose, as discussed in Chapter 4.1.2, narrows the model audience and boundary. Subsequently, the constructed model should serve to represent a holistic urban water system, capable of providing decision support for evaluating policy interventions to reduce water scarcity in the City of Cape Town. The model adheres to the set requirements, evaluating policy alternatives over the period 2001 to 2040, aimed at utilising retained and recycled water streams as potential water sources to alleviate water shortages in the urban City.

In addition, the model allows for the investigation into the system's response to changes in available water resources, including the adjustment of water restrictions and allocation, as water supply (dam levels) increase or decrease. Therefore, the constructed model is found to be adequate and includes all relevant parameters for policy evaluation within the scope of the research study.

5.8.4 Model Calibration

Model calibration is in essence the process of drawing plausible parameter values from available data (Oliva, 2003). This process is especially useful in times when there are no parameter data available or data is not very well estimated. Calibration aims to find reasonable parameter values that match historical data, ensuring accurate representation of the system model structure. This step is necessary before model implementation can be conducted for policy evaluation, to assure the suitability and accuracy of the replicated model.

Once the units are checked and verified for assurance of a single standard to reduce confusion, the sensitivity testing becomes especially useful to validate smaller sections of the model for expected performance and parameter values (R. Walker and Wakeland, 2011). Comparison graphs provide the visual representation of model and parameter behaviour for comparison, model performance and revealing model behaviour, such as oscillation in the system (R. Walker and Wakeland, 2011).

In addition, the calibration phase requires reasonable modelling assumption to be made, however these assumptions must be supported, as oversimplification will yield the model ineffective and inadequate. The effect of these input assumptions on model output, made to represent uncertain input information which could not be collected, are tested and analysed using a sensitivity analysis (Hekimoglu and Barlas, 2010).

The period 2001 to 2017 was used to calibrate the model, whilst the period 2018 to 2040 was used to predict the system behaviour through model simulation. Population growth rates are calibrated for approximating *Urban Population*, which is a key parameter for estimating the total domestic water demand.

Domestic consumption is based on the total population residing within the City of Cape Town. The Western Cape Water Supply System provides water resources to the urban City, allocating 64% of the total water supply to the City, of which 70% is consumed by the residing population. Table 5.20 provides the modelled quantities and actual calibration data from census and annual reports.

Table 5.20: City of Cape Town Population Validation

Year	**Population**	**Growth Rate**	**Modelled**	**Error**
2001	2892243	2.6%	2892243	0%
2011	3740026	2.3%	3744980	0.1%
2012	3848500	2.3%	3832050	0.4%
2013	3889237	2.3%	3921140	0.8%
2014	3882662	0.742%	3983150	2%
2016	3972237	0.742%	4042680	0.9%
2017	4014765	0.742%	4072790	1.4%
2040	4634202	0.742%	4794780	3.4
Total Error				1.3%

Furthermore, the change in urbanisation and society, has impacted the average household size. Thus, the model incorporates the changing averages over the simulation period. The simulated values are compared to statistical data for validation of model accuracy, which is found to be set at an average of 1.8% error as summarised in Table 5.21.

Table 5.21: City of Cape Town Household Statistics

Year	Households	Modelled	Error
2001	759485	741600	2.4%
2011	1068572	1069990	0.1%
2012	1106000	1118850	1.2%
2013	1150662	1170490	1.7%
2014	1189507	1216230	2.2%
2015	1230810	1254000	1.7%
2016	1272160	1268090	0.3%
2017	1289703	1282200	0.6%
2040	1700000	1598260	6%
Total Error			1.8%

Domestic water consumption is influenced by the water restrictions and the adherence to water conservation measures. Although, the parameter *Consumption Efficiency* serves to adjusts the consumption behaviour of domestic users, the *Total Domestic Demand* indicates sharp oscillating peaks. This does not necessarily represent the real-world response to water usage. Using a calibration parameter, *Calibrate Domestic Use*, the high water usage during low water restrictions (level 3 or lower) is dampened. Figure 5.19 shows the water restriction levels for the *Calibrate Domestic Use* parameter simulated for fractions 1, 0.8 and 0.5.

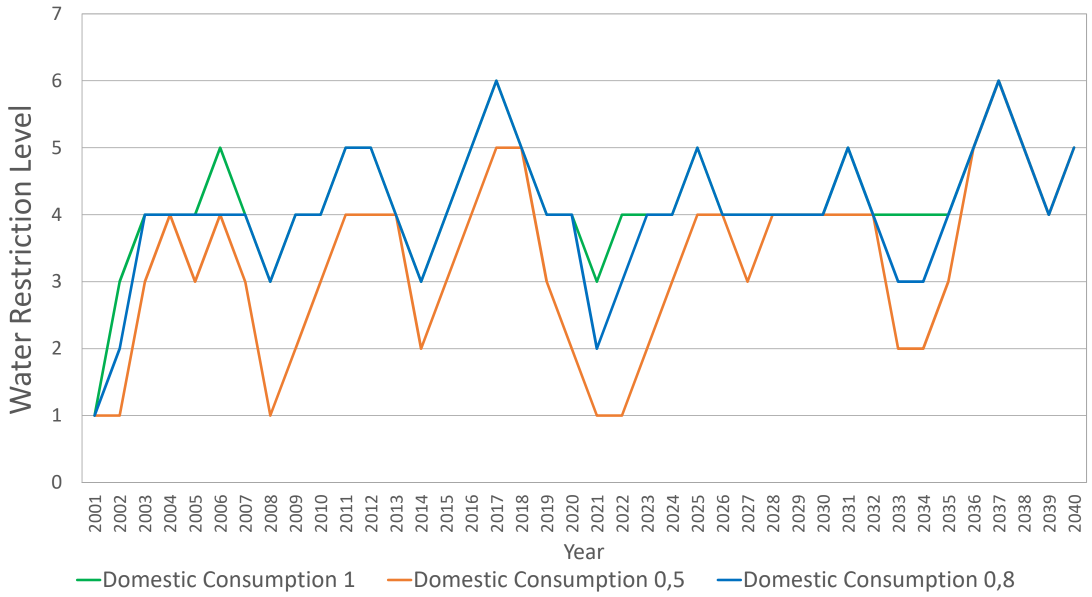


Figure 5.19: Calibration: Water Restrictions influenced by *Calibrate Domestic Use*

Using water consumption data from the 2019 Cape Town Water Strategy Report, the *Total Municipal Demand* simulated is compared with actual water treated by the City of Cape Town. The influence of *Calibrate Domestic Use* is included in the simulation. The results in Figure 5.20 indicate a delta in actual water treated by the CoCT compared to the simulated municipal water demand. The difference is attributed to the lack of responsive conservation measures, with water restriction implemented for the first time in 2001, only followed by constrained allocation in 2017. Actual water losses are also not included in the simulated *Total Municipal Demand*. Subsequently, the simulation results assume strict adherence to water restrictions, similar to the actual real-world response to constrained water allocations in 2018.

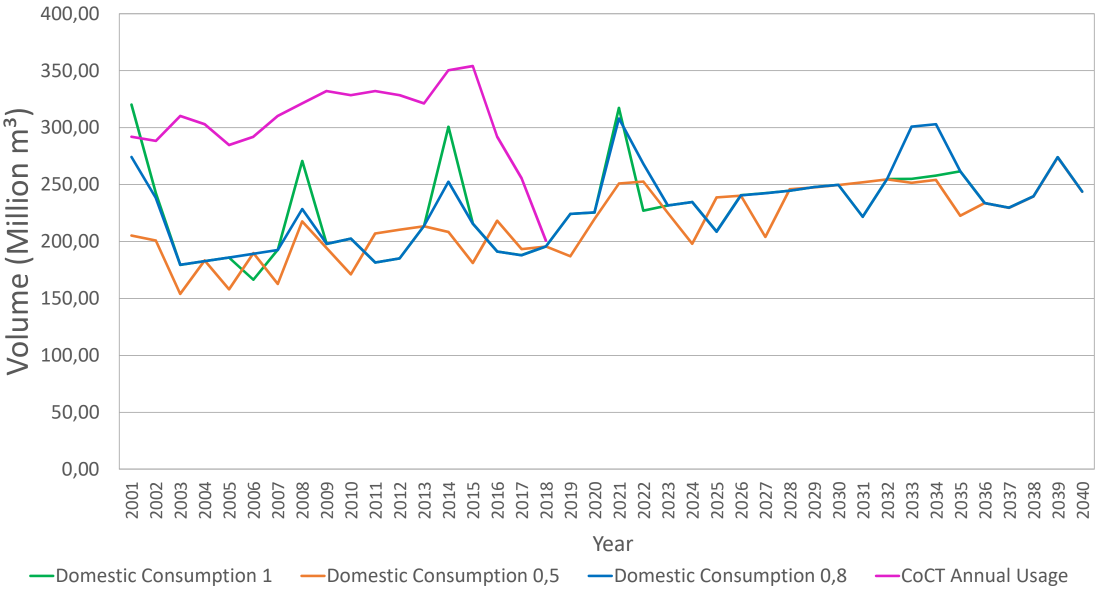


Figure 5.20: Calibration: Municipal Demand influenced by *Calibrate Domestic Use*

The real-world behaves in an oscillating manner, however, the response is not as profound as the simulated results. The *Calibrate Domestic Use* parameter, set at 0.8, is found to represents the real-world behaviour the best, allowing for water consumption to rise and fall as dam levels change.

Unknowns or uncertainties in model parameter values, including rates of change, are calibrated to better represent the real-world behaviour of the urban water system. Further adjustments to uncertain parameters are made during the scenario development phase in Chapter 7.3.

5.8.5 Sensitivity Analysis

Sensitivity analysis relates to the mathematical model's output uncertainty, in relation to the various sources of inputs (Choi and Jang, 2017). Varying the values and rates of selected variables is an approach used to test the sensitivity of the model to variable changes. The VENSIM® PLE modelling software allows for a sensitivity analysis of the model by tracking variable changes in selected ranges and comparing the behaviour and results of these data sets on sensitivity graphs. The sensitivity analysis plays an important role in addressing the uncertainty in system dynamics parameters to ensure the reliability of obtained simulation results (Hekimoglu and Barlas, 2010).

Pattern sensitivity is one procedure used to explore the effect of parameter uncertainty on the system behaviour patters, using a regression analysis approach for the sensitivity analysis (Hekimoglu and Barlas, 2010). However, the built-in sensitivity analysis tool is only available for Vensim® PLE Plus or more advanced packets, thus Synthesim can be used to run the simulations for the constructed system dynamics models.

Maani and Cavana (2007) summarised the process for conducting a sensitivity analysis into four simple steps. The first step requires the modeller to identify the parameters most likely to affect model behaviour, as well as the parameter based on uncertain and imprecise data. The second step aims to change the values of the selected parameters, in incremental percentages, for simulation runs that will allow for the third step. The third step identifies parameters that, during incremental changes, cause significant affects in model behaviour. The final step looks at analysing the behavioural changes against existing information and logic to determine the justification of simulated behaviour changes (Maani and Cavana, 2007). Ultimately the sensitivity analysis provides the modeller with key parameters, where a small change tends towards considerable changes in system behaviour. These parameters can either be classified as external, internal influencers or a combination of both (Maani and Cavana, 2007).

It should be noted that external and internal variables must be defined to determine the extent of control, as the external variables cannot be changed or controlled by management. Exogenous variables include precipitation, consumption patterns and catchment areas, which influence the behaviour of the total urban water system.

For demand management activities, the implementation of water restrictions are central to the adjustment of consumption behaviour in the City of Cape Town. Restrictions are imposed in relevance to the availability of water resources, specifically the WCWSS dam levels. Subsequently, the dam level (percentage of capacity) serves as the changing factor or trigger for restriction implementation. The model approximates the specified dam level activating the restriction level, as set out in the *Restriction Level* parameter equation in Appendix B.8

To test the impact and the model sensitivity, the dam level trigger for restriction implementation is lowered by 5% and increased by 5% from the initial run for comparison and evaluation.

However, to test the sensitivity of this approximation, several scenarios are simulated in VENSIM® to determine the impact on water consumption and availability in the City of Cape Town. For the initial activating trigger approximation and variants, the model reflects the behaviour as per Figure 5.21, Figure 5.22, Figure 5.23 and Figure 5.24.

Figure 5.21: Sensitivity Analysis: Comparison of Restriction - Dam Level

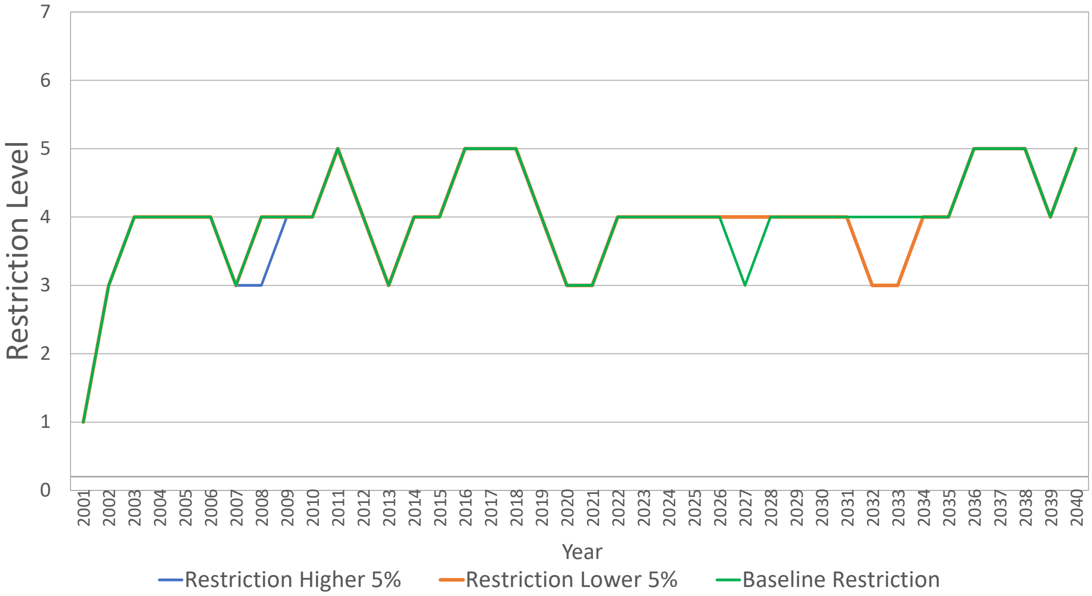


Figure 5.22: Sensitivity Analysis: Comparison of Restriction - Restriction Level

The variance in restriction levels indicate a change in response and not to the level of implemented restriction. Furthermore, the dam levels and subsequently the raw water volume increased or declined with changes in causation parameters. Thus, the water restriction level, based on the dam level, will delay or hasten the response to water shortages.

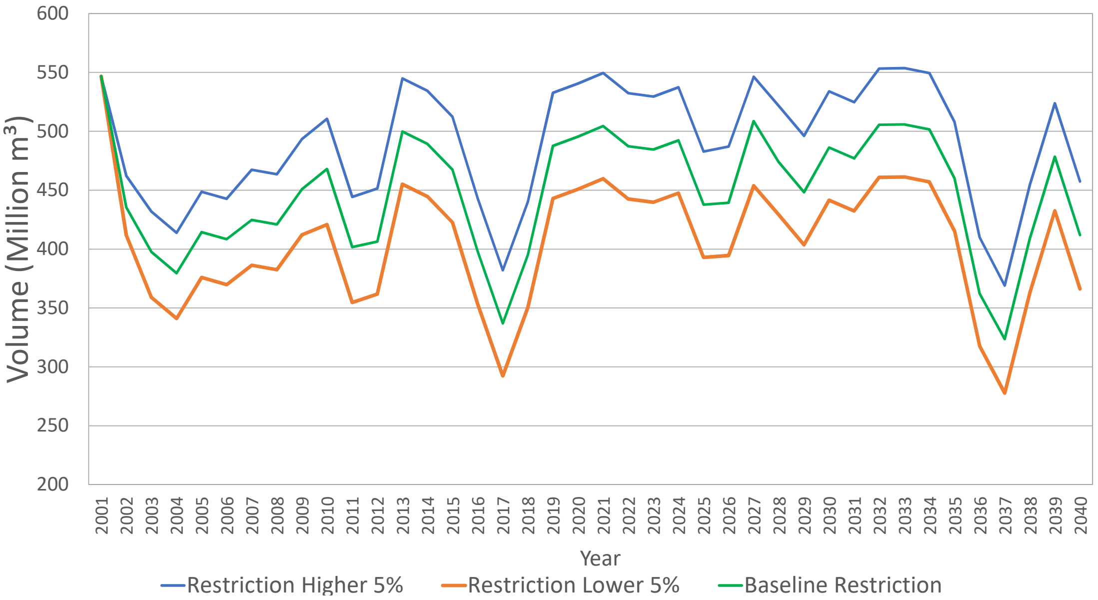


Figure 5.23: Sensitivity Analysis: Comparison of Restriction - Raw Water Volume

Figure 5.24: Sensitivity Analysis: Comparison of Restriction - Demand vs Yield

The model's sensitivity to different population and industrial growth rates on the total water demand and various parameter settings are tested and investigated in the scenario development process in Chapter 7.3. Therefore, the refinement and analysis of identified input variables, with imprecise data, are continuously evaluated and tested to determine the influence on system behaviour.

5.8.6 Primary Feedback Loops

The dynamic model is limited by a more linear representation of system interaction in comparison to the conceptual causal loop diagrams in Chapter 4. The most influential feedback loops affecting model behaviour are to be identified to note during policy development. The impact of both primary and secondary feedback loops within the complex urban water system need to be considered to ensure policy effectiveness.

The availability of fresh water resources is the pivotal point within the urban water system, from which conservation and demand management measures are determined. Using the causal tree for the *WCWSS Raw Water* in Figure 5.25, endogenous variables are circled. These parameters are internal to the system and can be influenced through policy implementation. Subsequently, the causal feedback for the dynamic model is presented in Figure 5.26 which indicate the direction of influence among system parameters.

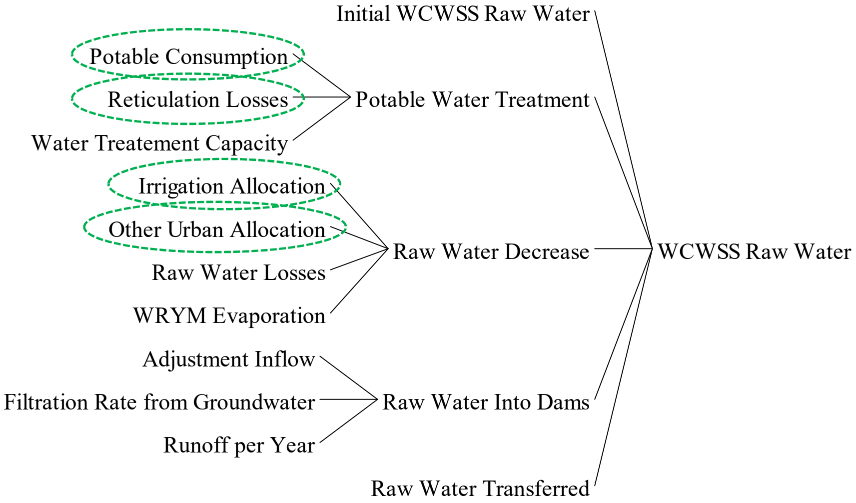


Figure 5.25: Causal Tree for WCWSS Raw Water

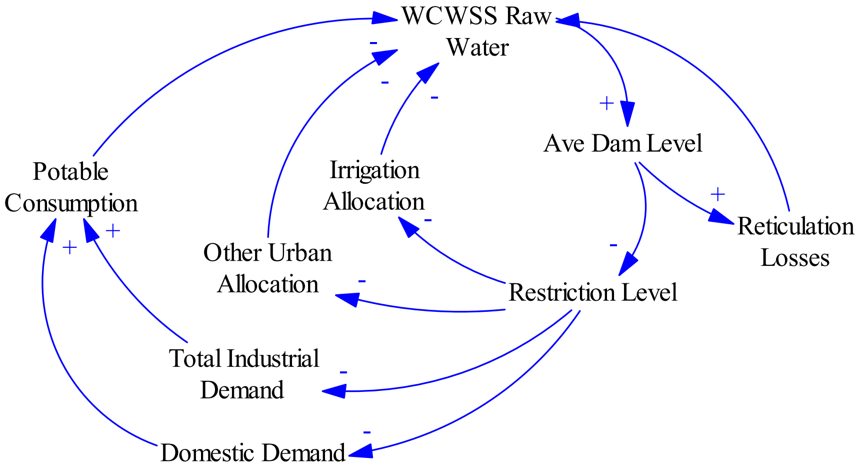


Figure 5.26: Primary Feedback for WCWSS Raw Water based on Causal Tree

Adjustments made to potable consumption and irrigation and urban allocation is primarily influenced by the implementation of water restriction. These restrictions respond in severity to the average level of water in the WCWSS dams. Whereas, reticulation losses increase with a rise in consumption, however conservation initiatives driven by policies in response to the decrease in available water resources, aim to minimise losses within the system.

5.8.7 Model Shortcomings

Although the model serves its purpose of providing the user with insight into the behaviour and response of variable changes to assist with policy evaluation, shortcomings are identified. These shortcomings are not necessarily inherent in the model, but originate from data inconsistencies or unavailable measurements. The model's success is dependent on the quality and accuracy of input data and although extensive effort into cleaning and collaborating several data sources have been done, the shortfall still exists.

These shortcomings include the difficulty in modelling runoff into the major WCWSS dams. Rainfall over the catchment area is based on approximated and predicted precipitation patterns, which serve as runoff into the surface supply dams. In addition, the causal relationship between the *Restriction Level* and *Avg Dam Level* is based on the assumptions that changes are implemented only once a year, which result in further model uncertainties. However, the sensitivity analysis serve to investigate the impact of changes in causal relationships and parameter values on the behaviour of the urban water system.

The majority of information and data is derived from the national and regional regulatory and supporting documents listed in Chapter 4.1.1. However, data does not necessarily coincide with each other, due to changes in data capturing procedures, authors and processes. Subsequently, data from StatsSA took preference based on its role in the national GWM&E policy evaluation system.

The calibration process allows for the refinement of variable data in accordance with available statistics and data to improved the representation of the real-world system. However, uncertainties still exist. Therefore, assumptions and estimations are used to depict various model variables, although the model allows users to change fractions and values as new data emerges or situations change.

Little information and data is available to support the modelling of decentralised wastewater treatment facilities in urban settings. Therefore, case study research is necessary to investigate the structure, challenges and behavioural links within a real-world application. The in-depth investigation allows for the extraction of supporting data and behavioural insights for the development of a dynamic system model representing real-world decentralised wastewater treatment plants.

Finally, although the conceptual models constructed in Chapter 4 are found to represent reality using causal feedback loops, the dynamic stock-and-flow diagrams constructed in Chapter 5 are limited to a more linear representation of the real-world, due to limitations of feasible information and data for feedback loops.

5.9 Conclusion

The dynamic modelling of the City of Cape Town urban water system allows for the in-depth investigation into the non-linear behaviour of the complex water system over time. Using the conceptual model structures and information extracted from public data sources and literature, the system dynamics model is constructed. Stocks, flows, connecting variables and feedback loops provide the structural parameters for model development.

The stock-and-flow diagrams in the dynamic model requires detailed investigation into the behaviour, relationship and value of system parameters. Subsequently becoming more time consuming to construct and validate than the qualitative models' causal loop diagrams on which they are built. Thus, model equations and quantitative data are extracted and formulated in the dynamic modelling phase. This process is iterative in nature with the validation of the model structure and behaviour bringing to light shortcomings and inaccuracies throughout the process. These are continuously addressed and changed to improve the representation of the real-world urban water system.

The research model differentiates between the quality of water sources and consumption patterns to identify potential retention and reusable water streams in the urban water system, which may be used to supplement water requirements. Potable and non-potable consumption habits for both domestic and industry users in the City of Cape Town are used as the basis on which the model aims to provide behavioural insight and investigate alternative water resources, to ultimately reduce the total demand for municipal water. Several decentralised sources of water, for example household greywater systems and the associate variables, are included in the model to provide decision-makers with the ability to investigate the impact of several scenario alternatives.

Consequently, the urban water system model strives to identify water streams in the urban water system for the purpose of retaining or reusing these sources as alternatives to the constrained Western Cape Water Supply System resources. The model is simulated and validated to ensure the accurate representation of the real-world system through a series of diagrams and equations that visually represent the dynamic relationship among these system parameters. The purpose of the system dynamics model is not to provide accurate prediction of model outcomes, but to offer insight and understanding to decision-makers in the urban water management sector. These insights should serve to identify alternative water sources from within the urban water system to supplement the demand for constrained resources.

Chapter 6

Modelling a Decentralised Water Filtration Plant

> *"Water is the foundation of life. And still today, all around the world, far too many people spend their entire day searching for it."* – The Water Project Inc.

The aim of this chapter is to drive the advancement of understanding the urban water system and the expansion of the knowledge field. The specific focus is on how the decentralised treatment of wastewater in industry can impact water stress in urban regions, such as the City of Cape Town (CoCT). Case study research is a valuable strategy for investigating and analysing specific data sets and information for the progression and enhancement of existing knowledge.

6.1 Introduction

To alleviate water supply stress experienced in the City of Cape Town, several alternative sources of water have been identified to serve as a resource in the urban water system. However, the problem is that the legislation and governance directing the extraction and utilisation of these potential sources of water, derived from waste streams and alternative sources within the urban water system, need to be evaluated and tested to ensure social, economic and environmental sustainability.

An in-depth understanding of the causal relationships and behavioural links among the complex system parameters is required to address the research problem. Subsequently, Chapter 4 applied the system dynamics methodology to develop a conceptual model, which serves as the basis for the dynamic decision support model in Chapter 5. The investigation found treated effluent, produced by decentralised wastewater treatment plants in industry, to be a potential source of potable water for urban consumption. However, there is little data and information available to the public regarding the impact, challenges, application and operations of decentralised wastewater treatment facilities operated by industry in the City of Cape Town, as well as within South Africa. Therefore, the constructed model for the decentralised wastewater treatment sub-model is limited to extrapolated assumptions, with little data and information to validate the constructed model.

For the decentralised wastewater treatement sub-model to be refined, an exploratory case study into the first corporate blackwater filtration plant at Old Mutual's Mutualpark in

Pinelands, Cape Town is conducted. This investigation provides input and real-life details to the pilot study, where large industries in urban areas aim to become self-reliant by establishing "off-the-water-grid" capabilities. Furthermore, case study research is advantageous to the development and refinement of the urban water system model for the City of Cape Town, as it allows for research to be conducted within the context of its application (Zaidah, 2007).

Therefore, the roadmap for the case study approach is illustrated in Figure 6.1, which serves to provide the structure and scope of this case study chapter. To identify and select the appropriate case study, literature research is conducted to identify relevant cases within the context of water reuse in urban settings, aimed at addressing water shortages.

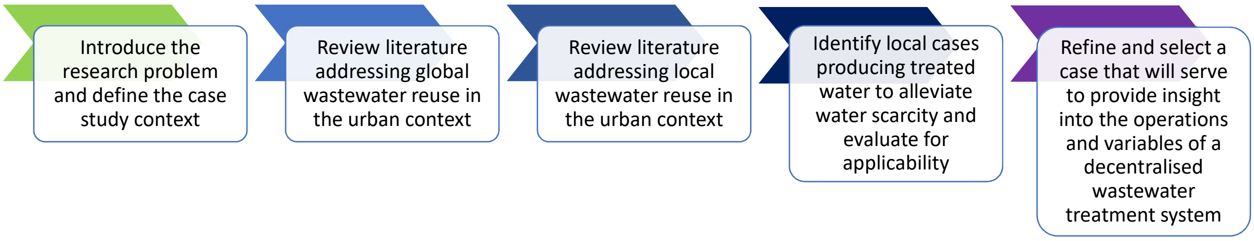


Figure 6.1: Initial Case Study Design

The case should address the operations and implementation of decentralised wastewater treatment facilities that produce potable quality water to on-site industry users in an urban settings. These cases should preferably be in the City of Cape Town, where the reuse of water should serve to alleviate water shortages experienced in the urban area by treating effluent produced on-site. Ultimately, the exploration of the appropriate case study should bring to light insights and key parameters for the refinement of the *water as a waste stream* subsystem.

6.2 Field of Knowledge

Traditionally, the reuse of wastewater primarily served to address water demand for agricultural purposes, however with the continual decline in water resources, water quality degradation and growing demand, the application for treated effluent has expanded to include additional applications, such as a source for industrial activities (Aoki et al., n.d.). Furthermore, treated wastewater as a source of irrigation is commonly used in Asia, Africa and Australia. Although, the water quality, treatment process and cost may vary, the recycled water ultimately aims to restrict the disposal of effluent and to provide an alternative source of water in water scarce regions (Mekala et al., 2008).

As the application for treated wastewater increase, the importance of holistic water resource management and appropriate policy frameworks are emphasised (Aoki et al., n.d.). Wastewater reuse requires proper attention to environmental protection, public health and sanitation services, with policies enforcing strict standards for reuse. In addition, external organisations, such as the World Health Organisation (WHO), aim to provide further guidelines for the reuse of wastewater (Aoki et al., n.d.).

The research design aims to address the research problem within the defined context. Therefore, the literature review for the case study research investigates the application, processes and insights derived from both internationally and locally applied research investigating the reuse of treated effluent in urban regions, specifically from decentralised wastewater treatment facilities. The literature review also provides the researcher with the opportunity to identify gaps in the knowledge field.

The research approach is sequential in nature, using the Stellenbosch University library's electronic data base and Google Scholar as the primary search engines for identifying case studies investigating the reuse of treated effluent in urban regions. The search is initiated as a global search, using key phrases such as *urban water scarcity, treated wastewater* and *water reuse* with results catalogued in Appendix A, Table A.6. To localise findings, additional key phrases were included in the search. Table A.7 lists the relevant studies addressing the reuse of treated effluent in South Africa and neighbouring countries. However, the literature search found no explicit reference or study relating to the application of decentralised industrial wastewater treatment facilities aimed at providing water for reuse in local urban regions. With even less reference to applications within the City of Cape Town.

Thereafter, additional internet searches were used to identify local projects and initiatives utilising decentralised wastewater treatment plants to generate water for industrial consumption. The internet search found that GreenCape conducted several case studies evaluating water resilient businesses in the Western Cape. It was found that Old Mutual, PPC Cement and Bayside Mall are acting to reduce water consumption and initiate the reuse of water in response to water shortages in the City of Cape Town. Furthermore, from the initial literature search several applications of wastewater treatment for reuse were identified within the local setting. The aquifer recharge in Atlantis, the wastewater treatment plant in Windhoek, Namibia, the direct wastewater reclamation system in Beaufort West, the wastewater treatment plant in Durban and the Mutualpark Water filtration plant as well as Karl Bremer Hospital's green administration building in Cape Town are evaluated to establish whether key results and parameters extrapolated from the potential case studies will serve to support the refinement and validation of the urban water system model.

<u>Windhoek: Direct Potable Reuse</u>

According to de Beer and Ilemobade (2016) and Z. Chen et al. (2013) there are four categories of uses for treated effluent, direct potable reuse (DPR), non-potable reuse (NPR), indirect potable reuse (IPR) and groundwater recharge. Furthermore, discharging treated wastewater into the natural water sources can benefit the ecosystem by improving stream-flow and prevent salt-water intrusion. The majority of wastewater reuse address non-potable water requirements such as irrigation, industrial application and ecological requirements to alleviate water scarcity, although Windhoek in Namibia is one exception (Owen, 2016).

Windhoek houses the worlds first direct reclamation system, the Georeangab Water Reclamation Plant, providing drinking water to consumers (Ivarsson and Olander, 2011). Namibia mitigates the extreme shortage of water by deriving a quarter of its water used from treated effluent, not just for industrial use but also as a source of drinking water

(Heymans, 2018). Windhoek has gone beyond providing treated wastewater for urban consumption, diverting reclaimed water to create wetlands and to maintain recreational areas (Heymans, 2018). Furthermore, the acceptance of direct potable reuse in Windhoek is due to effective campaigns educating the public, the system reliability and extensive positive media coverage (Z. Chen et al., 2013). Although Windhoek is a world leader in the reuse of water within the urban setting, the case does not fit the context of decentralised wastewater treatment facilities.

Atlantis Aquifer: Indirect Potable Use

Water stored in surface dams are subjected to high evaporation rates, whereas underground water storage negates the loss of water through evaporation. Subsequently, the Department of Water Affairs and Forestry (DWAF) developed the national artificial recharge strategy which serve to promote the use of sub-surface water storage. Managed aquifer recharge (MAR) has proven to be an effective conservation measure using indirect water recycling, transferring and storing surface water underground (Bugan, Jovanovic, Israel, et al., 2016). This is done using injection boreholes or infiltrating water from dams, basins or ponds to store in aquifers during periods of supply surplus, which can be extracted later during dry periods. Benefits extend further than water supply assurance, addressing the recovery of groundwater levels, improved quality of groundwater, prevention of seawater intrusion and ecological protection.

The Atlantis Water Supply Scheme (AWSS) serves to augment the municipal water supply to the urban town Atlantis, situated along the west coast of SA, approximately 50km north of Cape Town. Domestic wastewater is recycled to Green Drop status and used to artificially recharge the aquifer. Both recycled water and collected urban stormwater is stored as groundwater, to be extracted and reused in Atlantis, supplementing the groundwater yield (Bugan, Jovanovic, Israel, et al., 2016). Although the water system reuses treated effluent, albeit indirectly, the application of the case study is not suitable to refine the decentralised wastewater treatment for industry reuse.

Beaufort West: Direct Potable Reuse

Critical water shortages in Beaufort West, South Africa, has led to the construction of the first South African direct wastewater reclamation plant in 2010 (Bronkhorst, Millson, et al., 2016; Ivarsson and Olander, 2011). The plant is set to produce drinking water from treated effluent to supplement the existing water sources in the region. Although, the operation of the direct potable reuse plant enables Beaufort West to be better prepared for future drought events, the case does not allow for the refinement of the decentralised wastewater treatment sub-model.

Durban: Wastewater Treatment Plant

Durban, South Africa, houses several large water intensive industries demanding large quantities of water from the municipal supply. However, the growing shortage of water supply and infrastructure limitations have led to innovative collaboration between eThekwini Water Services (EWS) and the French based private company Veolia (Heymans, 2018). Veolia commissioned and supplied the wastewater treatment project, recycling domestic and industrial effluent to near potable standard water, to be used by large water intensive companies such as Mondi Paper and Sapref Refinery in Durban. The R74 million capital investment plant was commissioned in May 2001 as a Public Private Partnership (PPP) initiative to address water scarcity in the region (Engineering News, 2005; eThekwini Municipality, n.d.). Secondary benefits include the reduced wastewater discharge into marine outfalls, decreased water demand that makes potable drinking water available to urban consumers and lower tariffs per cubic meter of industrial graded water (Engineering News, 2005). Furthermore, the 20-year contract with Veolia (previously known as Vivendi Water) is responsible for the construction, ownership, operation and transfer of 10% of Durban's wastewater, at a reclamation rate of 47.5 million litres per day (eThekwini Municipality, n.d.).

This innovative approach to harness potential from a wide range of stakeholders towards optimising water management processes has proven to be beneficial on a socio-economic and environmental level. What is more, in recent news the eThekwini municipality together with Murray & Robers and Organica Water, is responsible for the first Resource Recovery Demonstration Facility in South Africa. The Durban wastewater treatment plant is located in a botanical garden that serves to eliminate unpleasant odours, reduce energy consumption and produce less sludge than traditional reclamation plants (Averda, 2018). This innovative approach combines engineering, architecture and wastewater treatment technology to provide a cost effective and more ecologically friendly alternative.

Although facets of the study is relevant to the research problem, the collaborative wastewater treatment project does not prove to be an "off-the-water-grid" concept, as it utilises municipal domestic and industrial wastewater to produce recycled water for resale to industries.

Karl Bremer Administration Building

The administration office for the Karl Bremer Hospital is a government-owned building designed and constructed to achieve a 5-star Green Star SA rating for sustainability. Amongst other design features, the 6615 m^2 building recycles and reuses both stormwater and wastewater on-site (Africanism, 2017). The Green Building Council South Africa (GBCSA) developed a set of green building rating tools, which are not enforced by legislation, but rather provide a common measurement and innovation recognition for the development and construction of green buildings. There are several categories, of which water is one, with allocated credits that score the incorporated environmental initiatives in the building design and construction (Building and Decor, 2017).

Although the building is connected to the municipal sewer system, all wastewater generated on-site is discharged into the blackwater treatment plant which treats the wastewater for reuse as water supply to the building's cooling towers (Malan, 2017). It is estimated that more than 76% of the cooling tower's water demand can be met with the reclaimed water from the on-site treatment plant, saving approximately 1.1 million litres of water per year (Malan, 2017). Furthermore, plans to supplement non-potable water demand for toilet flushing and urinals include harvested rainwater and the reuse of bleed-off water from the cooling towers, which is usually discharged. The infrastructure for stormwater drainage is designed to retain urban runoff on-site, preventing stormwater from entering the municipal stormwater systems. Natural landscaping incorporate bioretention swales, which are vegetated landscapes with sloped sides designed to collect, treat (filter) and infiltrate stormwater into the ground (Malan, 2017).

However, water treated at the Karl Bremer administration building is not suitable for potable reuse. Therefore, the Karl Bremer case cannot be used as a suitable case study for refining the decentralised wastewater treatment plant sub-model.

Mutualpark's Water Filtration Plant

In response to the ongoing drought in Cape Town, Old Mutual launched the first large blackwater filtration plant in 2018 at their Mutualpark office in Pinelands, Cape Town. The large corporate office space house roughly 9000 employees and contractors, consuming approximately 450 000 litres of water per day (Fredericks, 2018a). What is more, Mutualpark strives to become completely independent from municipal water resources, aiming to go "off-the-water-grid", zeroing the demand for municipal water (Borman, 2018).

Initial initiatives towards water efficiency were introduced in 2016, which resulted in a 30% reduction in water consumption at Mutualpark (Cassim, 2018). These interventions included the use of municipal treated effluent, pressure management, educational communication and reducing water-use activities. Air conditioning, landscaping and people were identified as the major water consumers at Mutualpark (Fredericks, 2018a). In additional to water-saving initiatives to reduce water demand, Mutualpark strives to obtain a Net Zero Water certificate, which is awarded to highly water efficient buildings, where the amount of water produced equals the amount of water consumed (Borman, 2018). Subsequently, Old Mutual investigated several alternative sources of water to address the potable water required per day. In response, the blackwater filtration plant was installed at Mutualpark with a production capacity between 650 000 and 800 000 litres a day (Borman, 2018).

The system utilises internally generated wastewater to produce water for direct potable reuse, serving as a decentralised water system to the industry. Furthermore, Old Mutual is responsible for the installation, operation and maintenance of the system at Mutualpark, with outputs from the filtration plant benefiting Mutualpark directly. This particular case proves to be an unique example of a decentralised wastewater treatment facility capable of producing potable quality water for reuse within the industry. Subsequently, reducing the dependency of the industry on municipal water sources.

Investigation into the operation and utilisation of the unique system should reveal new understanding and key parameters to address the research problem. Therefore, the case is relevant to the development of decision support models aimed at alleviating water scarcity through the reuse of waste streams in the urban water system. Insights into the operation, challenges and variables associated with the water filtration plant will serve to refine and validate the constructed model for decentralised wastewater treatment plants.

6.3 Case Study Design

To ensure that the case study is repeatable, a case study design is defined to provide justification and structure to the research study. The initial design in Figure 6.1 illustrates the process of identifying an appropriate case from literature, capable of addressing the research problem. Thereafter, selection criteria is derived from the *who*, *what*, *where*, *how* and *why* questions, with criteria and case study suitability listed in Table 6.1 for transparency and structure.

Table 6.1: Case Study Criteria

Criteria	**Description**	**Mutualpark DPR**
Who should the study address?	Decentralised Wastewater Systems	On-site blackwater filtration system
What am I studying?	The reuse of wastewater in industry to address water scarcity	Reduce municipal water requirements and treat wastewater for reuse
Where is the study necessary?	City of Cape Town	Pinelands, Cape Town
How will the study expand knowledge?	Provide key parameters, processes and insights to refine and expand the urban water system model	Pilot study and application, reducing municipal water requirements
Why is the topic important?	Provide understanding and insight for decision making to alleviate water stress in urban regions through the reuse of water waste streams	Water conservation management and technology for wastewater reuse

The particular study is selected as an appropriate case for addressing uncertainties in the urban water system model for the City of Cape Town. In addition to refining the *water as a waste stream* sub-model, the case research serves to address a gap in literature. Little information or exploration has been done in the knowledge field with regards to the application of decentralised wastewater treatment facilities supplying direct potable water in industry. The case study research allows for the investigation into system operation, utilisation and challenges identified during the pilot study, with additional evaluation into required policy and regulatory actions influencing the operations and effectiveness of the decentralised water reuse system.

Insights brought forward from the single-case study aim to expand the body of knowledge, while in-depth analysis proves to provide new ways of understanding the research problem. Furthermore, the Old Mutual's blackwater filtration plant falls within the context and boundary of the research study. The plant, established in 2018, is located in the City of Cape Town in response to severe water shortages experienced in the urban city. Subsequently, once the case study is selected, the data collection and case study exploration process follows.

An internet search found several electronic news articles presenting information and background on the industry based water filtration plant in South Africa. Information presented in these articles are derived from interviews conducted with the technical manager of the project and Old Mutual's Chief Operating Officer of the time. Supporting studies investigating the water saving initiatives conducted at Mutualpark campus were done by

GreenCape, highlighting actions taken by Old Mutual to address water shortages in Cape Town prior to implementing the blackwater filtration plant. Furthermore, technical presentations for the African-Utility Week 2018 serve as additional technical information (Fredericks, 2018a; Fredericks, 2018b). Informal discussions with the technical manager, Mr. K. Fredericks, focused the investigation and brought to light issues and opportunities associated with the operations, management and utilisation of the decentralised water filtration system. Several sources of information serves to triangulate the findings and focused investigations as depicted in Figure 6.2.

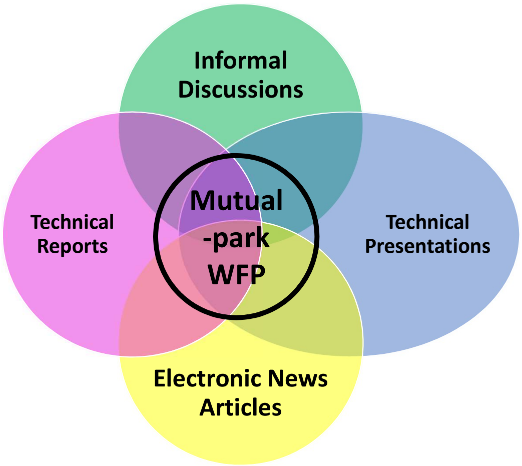


Figure 6.2: Data Triangulation for Case Study Research

6.4 Case Study

Although Old Mutual proved to successfully reduce water consumption by more than 30% (from 15 000 kl to 10 000 kl per month), through water saving interventions initiated in 2016, further actions were taken to minimise Mutualpark's dependency on municipal potable sources (Cassim, 2018). A water filtration plant was installed in 2018 to treat on-site blackwater to potable standard.

A collection sump was installed, that allowed for the collection of the wastewater (blackwater) from the office and campus buildings. For health precautions, the sump allows for excess blackwater to be directed into the municipal sewage system, if required. Thereafter, blackwater is processed to greywater (non-potable) and sent to the filtration phase of the plant. This process is strictly controlled to ensure high quality potable water as an end-product, adhering to the South African National Standard (SANS) 241, which stipulates the quality requirements and limits for acceptable and safe potable (drinking) water (*SANS 241: Drinking Water* 2015). The Mutualpark filtration plant and treatment process undergoes rigorous testing and process monitoring to obtain compliance to national standards and regulatory requirements (Borman, 2018). Samples are taken at each stage of the process on a daily basis to ensure that the produced water is of the highest quality.

In addition to the water filtration plant, Old Mutual has access to two boreholes and municipal treated effluent. Borehole water is abstracted and treated at the borehole treatment plant, which can produce up to 250 m^3 of potable quality water per day. This system functions as a backup source to reduce dependency on municipal water. Municipal treated effluent from Athlone's wastewater treatment plant serves as an additional source to supplement the blackwater entering the wastewater treatment plant at Mutualpark. Wastewater produced on campus is significantly less than water consumed, with the shortfall attributed to irrigation, evaporation (air conditioners) and potential leaks or consumption losses (Fredericks, 2018a).

High quality potable treated water from the groundwater treatment plant and the blackwater filtration plant is stored in two large storage tanks with a capacity of 460 kilolitres, from where potable water is distributed throughout the campus water ring (Fredericks, 2018a). The alternative water input in Figure 6.3 illustrates the input of treated effluent from the CoCT and Mutualpark blackwater to the water filtration plant. The groundwater abstracted from the two on-site boreholes are transferred to the groundwater treatment plant, dedicated to producing potable quality water from groundwater.

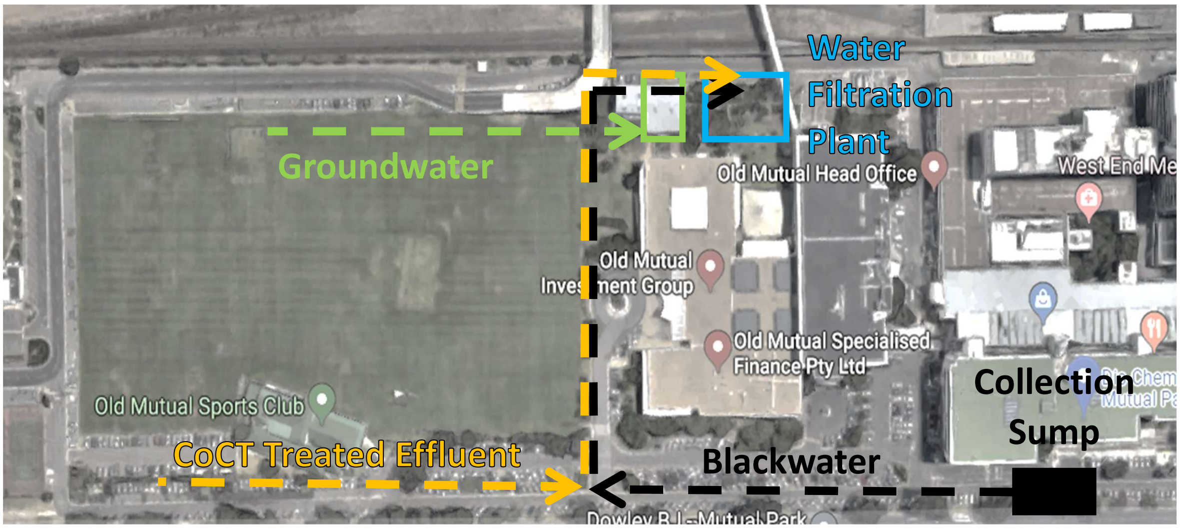


Figure 6.3: Mutualpark Alternative Water Sources Input (Adapted from Fredericks, 2018a)

The process flow is illustrated in Figure 6.4, which serves as the basis on which the casual loop diagrams and stock-and-flow diagrams are built. The (blue) internal loop represents the potable water system, that provide water for consumption to the campus. Potable water from the City of Cape Town can be directly inserted into the delivery system if the on-site filtered water becomes insufficient. During the treatment and filtration process, brine and waste is generated. The waste component is diluted with groundwater and/or treated effluent until the concentration is suitable for return to the municipal wastewater system. Blackwater from the city sewage system cannot enter the sump, however wastewater produced on-site can be directed into the municipal wastewater system.

Ultimately, Old Mutual strives to establish Mutualpark as a Net Zero Water institution, however losses exist within the system, which result in a requirement for addition water input from the City of Cape Town.

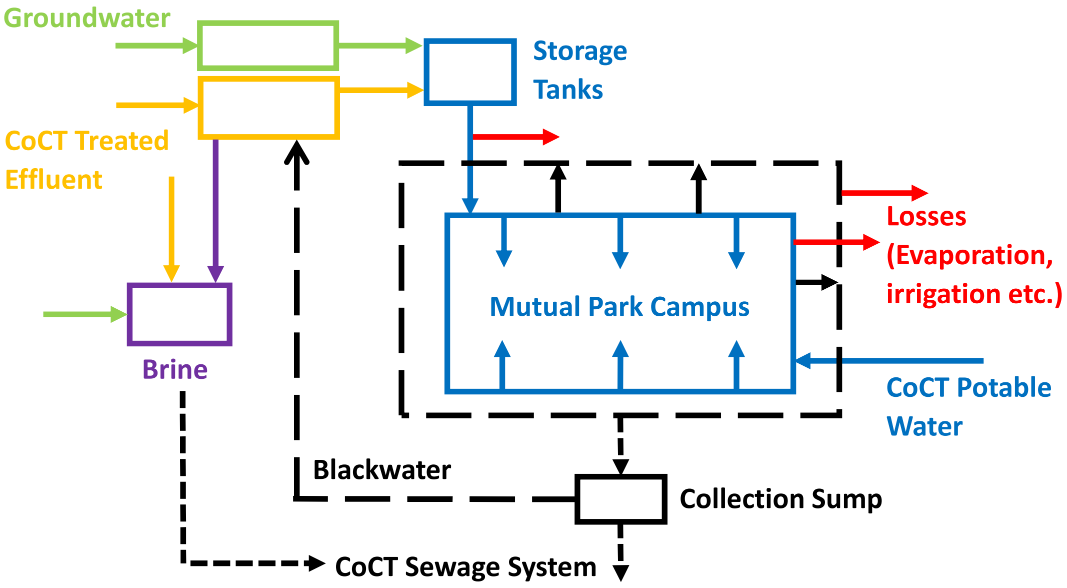


Figure 6.4: Mutualpark Water Process Flow Layout

The study aims to determine the dependency of Mutualpark on treated effluent and potable water from the municipality, while developing models to allow for the evaluation of various scenarios in water consumption and supply to assist decision making, risk mitigation and planning.

6.4.1 Data Analysis

Several parameters and corresponding units and values were derived and triangulated from available technical reports, presentations and electronic news articles (Borman, 2018; Cassim, 2018; Fredericks, 2018a; Fredericks, 2018b). These Mutualpark system variables and associated limits and capacities are captured in Table 6.2.

Table 6.2: Mutualpark: Baseline Parameter Values

Parameters	**Value**	**Unit**	**Value** (m^3/Year)
Average Mutualpark Employees	9000	People	
Potable Storage Tank Capacity	460	m^3	
Air Conditioning Evaporation	35	m^3/day	12 775
Borehole Abstraction Limit	250	m^3/day	91 250
Water Filtration Plant Capacity (Normal)	650	m^3/day	237 250
Water Filtration Plant Capacity (Stressed)	800	m^3/day	292 000
Mutualpark Water Average Requirement	450	m^3/day	164 250
CoCT Potable Water Average Requirement	180 000	m^3/Year	120 000

Yearly consumption is estimated based on the requirement of 15 000 *kl* per month before applied water saving initiatives. In addition to initial water saving actions and the implementation of the blackwater filtration plant, Old Mutual is investigating the potential for groundwater recharge, using rainwater harvesting and permeable paving (Cassim, 2018).

Water flow within the decentralised water system as illustrated in Figure 6.5 that shows several sources of water supply enter Mutualpark. Consumption leads to wastewater produced, serving as an input source to the water filtration plant, along with treated effluent from the City of Cape Town. Furthermore, groundwater abstracted from on-site boreholes are treated and used as potable water in addition to filtered water. However, due to losses within the system, potable water from the municipality is added to supplement system water demand. Therefore, system is not purely driven by decentralised wastewater treatment activities.

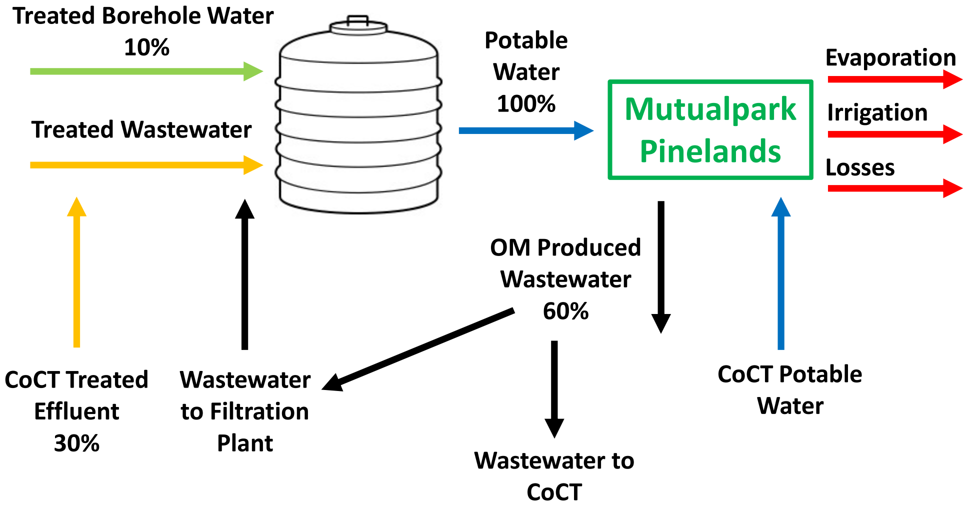


Figure 6.5: An Example of Mutualpark Water Flow

Water received by Mutualpark consist of several sources, both internal and external supplies, as depicted by Equation 6.4.1. Subsequently, the impact and dependency on these sources are to be evaluated to provide insight and understanding into the behaviour and likely response of the system.

$$\begin{aligned}\text{Total Water Received} &= \text{Municipal Potable} + \text{Borehole Water} \\ &\quad + \text{CoCT Treated Effluent} + \text{OM Wastewater Treated}\end{aligned} \tag{6.4.1}$$

The model in Figure 6.6 shows the water filtration plant consisting of eleven processing phases as per the design installed by PCM Consulting at Mutualpark (Fredericks, 2018b).

Utilising data extracted from a range of available sources to triangulate the single-case, the qualitative representation of the system structure can be represented with a causal loop diagram, visually indicating the relational links among system parameters.

6.4.2 Mutualpark Causal Loop Diagram

The study of an actual real-world application is used to gain an in-depth understanding of the operation and structure of a decentralised wastewater treatment system within the urban setting. By utilising the derived parameters and structures, a causal loop diagram of a decentralised wastewater system can be constructed, as seen in Figure 6.7.

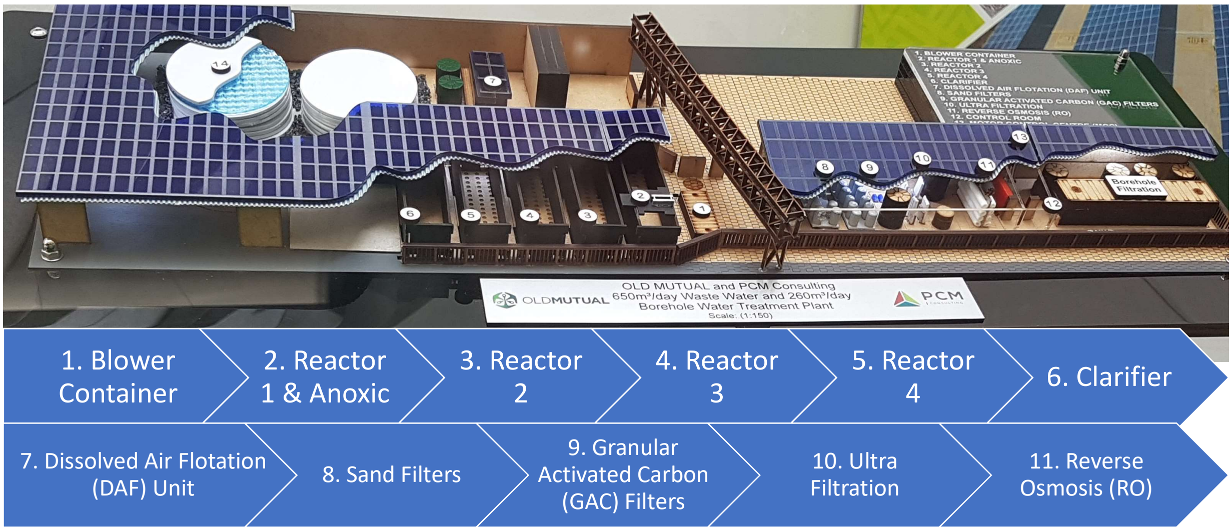


Figure 6.6: PCM Consulting Water Filtration Plant Process Phases

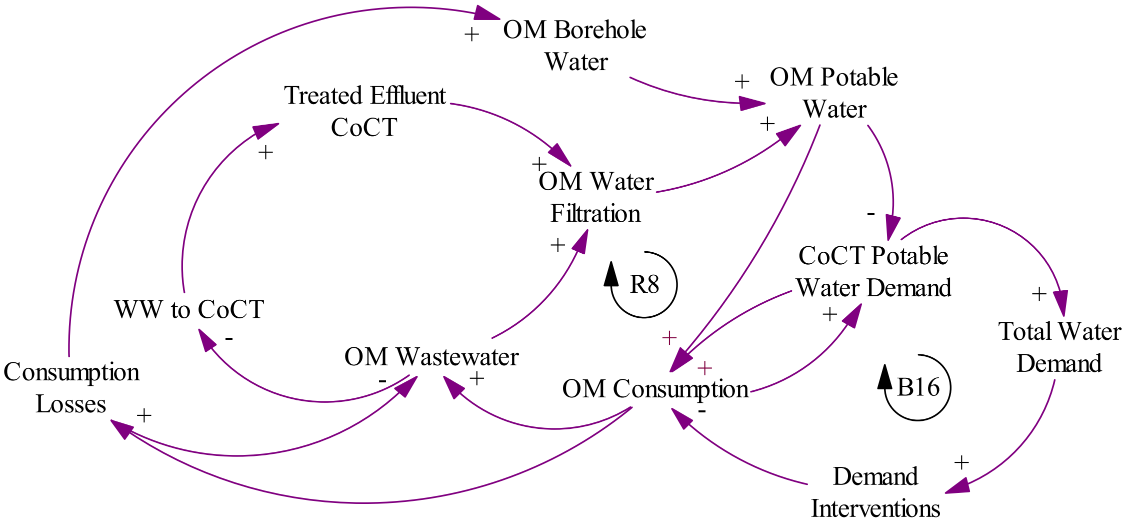


Figure 6.7: Mutualpark Causal Loop Diagram

The purpose of this case study research is to provide a realistic representation of value extracted from on-site wastewater sources and how the use of decentralised wastewater treatment facilities affect the water supply stress experienced in the City of Cape Town. Therefore, the reduction in demand from municipal potable sources serve as the primary results to be evaluated. Secondary streams of water sources such as groundwater abstraction and the use of municipal treated effluent to supplement on-site wastewater are unexpected elements that must be brought into the holistic urban water system. Feedback loop R8 represents the reinforcing behaviour among the consumption of potable water and the wastewater generations that serve as an input to the water filtration plant that produce potable water for consumption.

Subsequently, the causal loop diagram for Mutualpark incorporates the input from both *Treated Effluent CoCT* and *OM Borehole Water*. An internal Old Mutual investigation track and monitor water flows. These actions aim to identify losses for mitigation response.

Identified outflows are potentially due to evaporation, irrigation and consumption losses or leaks. Downtime or shortage of municipal treated effluent can therefore, inhibit the production of potable quality water at Mutualpark.

6.4.3 Mutualpark Dynamic Model

The dynamic model for the Mutualpark's water system is constructed using stock-and-flow diagrams that dynamically link model parameters using mathematical equations to represent the total system behaviour. The model parameters in Table 6.3 captures the stocks, flows and auxiliary variable for the Old Mutual decentralised wastewater treatment plant, which is categorised as part of the *water as a waste stream* sub-model, depicted in Chapter 5.6.2.

Table 6.3: Stock, Flows and Auxiliary Variables for Old Mutual's Blackwater Filtration Plant

Stock	Flow	Auxiliary Variables
OM Treatment Plant Capacity	Increase OM WWTW Capacity	OM WWTW Capacity Added
OM Storage Tank	Borehole Water Entering	OM Borehole Water Capacity
	Treated WW Entering	OM Wastewater Produced
	OM Potable Water Consumed	OM Water Requirement

The constructed stock-and-flow diagram in Figure 6.8 is derived from the conceptual model in Figure 6.7 and data extracted from technical reports and electronic articles. The model allows for the adjustment of fractions and input values to investigate the impact of introducing supplementary sources, behavioural changes and losses into the system. Subsequently, the system's response provides decision-makers with the ability to adjust parameters, determine stock buffers and allocate costs for intervention actions.

Simulating various scenarios provide decision-makers with a tool to evaluate likely system behaviour and gather insight to establish response plans and mitigation actions. However, the accurate observation and representation of the real-world system by the research case study should be establish through a process of validation before further investigation and scenario evaluation can be conducted.

6.5 Case Study Validation

To establish that the investigation accurately observed the real-world operation and structure of the Mutualpark water system, construct validation is applied. During the data collection phase, triangulation is used to look at the system from different perspectives, which require several data sources and data collection strategies. For this case study, data was obtained from Mutualpark's technical presentations, electronic articles reporting on the project and informal discussions with the technical manager of the blackwater filtration project.

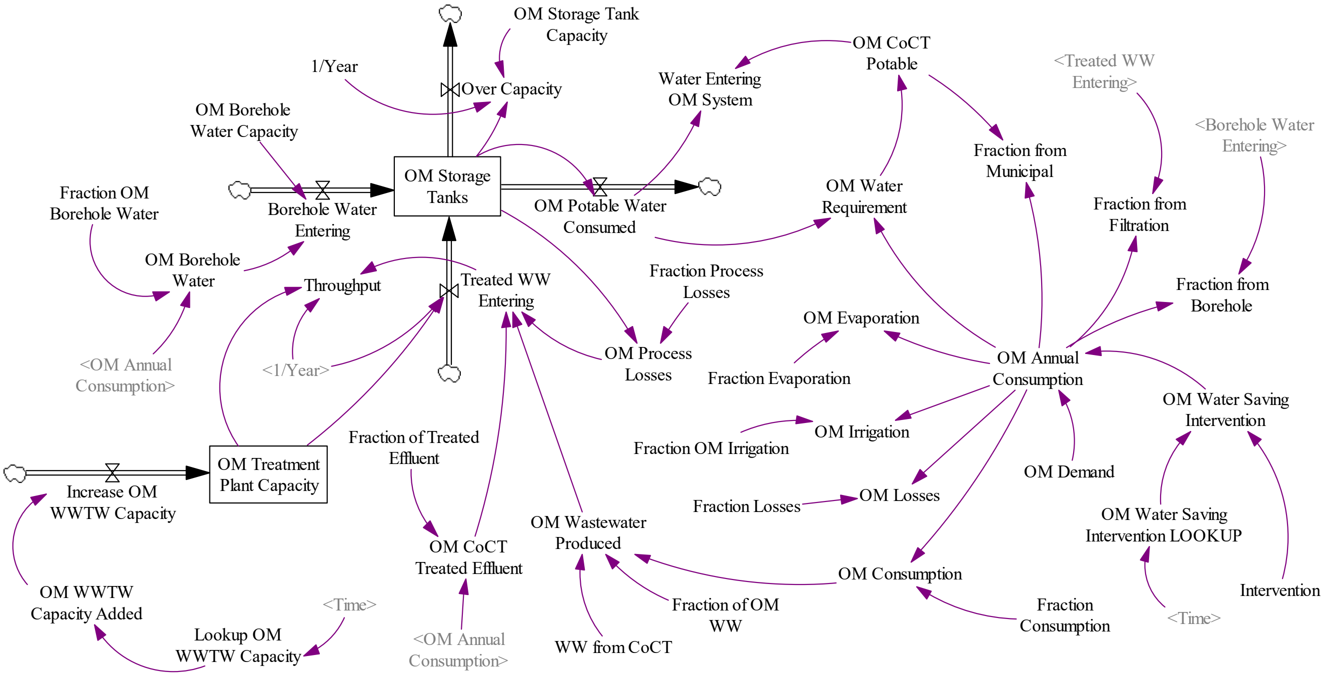


Figure 6.8: Mutualpark Stock-and-Flow Diagram

Planned data collection is compared with actual data extraction in Table 6.4. The sequential observation process aims at identifying and utilising data from a case study that addresses water shortages in the urban City of Cape Town through the utilisation of a decentralised wastewater treatment plant to ultimately reduce municipal water demand.

Table 6.4: Case Study Construct Validation

Planned Data Phase	**Actual Data Phase**
Review literature addressing global wastewater reuse in an urban context.	Wastewater reuse is popular in Asia, Africa and Australia, predominantly as a source of irrigation.
Review literature addressing local wastewater reuse in an urban context.	Wastewater reuse is utilised as a source of DPR and IPR in several towns.
Identify and refine local cases applying decentralised wastewater treatment systems to reduce municipal water use.	Old Mutual's blackwater filtration plant in Pinelands is identified as one of the first industry based decentralised wastewater system (DPR) in SA.
Internet search for technical and operational information on industrial based decentralised wastewater treatment plant.	Mutualpark's black water filtration plant technical presentations and available data and information is used to formulate system structure and triangulate data.
Verify process structures derived from literature and electronic search and investigation.	Technical data from literature serve to validate the model structure and variables for the Old Mutual's blackwater filtration plant CLD and stock-and-flow diagram.

In addition, a site visit at the Mutualpark campus provided the researcher with the opportunity to inspect the scale model in Figure 6.6 of the water treatment plant and gather additional information regarding the treatment processes and secondary systems. Subsequently, providing direct observation as another source of data and information to support the triangulation of the case study research.

To validate the data analysis phase of the case study, internal and external validation of the case study research is conducted. Internal validity aims to prove that the findings derived from the research study is based on the critical assessment of all available information and data. The process reports on the methods and perspectives used to extract, analyse and interpret data. Furthermore, the research should clearly define the relationship between case study variables and outcomes. Whereas, external validation aims to show that the analysis theory can be generalised to be applied within other settings in addition to the identified setting.

To ensure that data is not systematically falsified, the relational links between data and findings within the framework must be established with no unknown causal parameters. The critical investigation and analysis of available data sources and information allowed for the construction of a representative causal loop diagram that aims to illustrate the behavioural links among system variables. The case study design structure guides the data collection and analysis, subsequently assuring the internal validity of the research process. To address the external validation of the case study, the rational for case study selection should be clear with indication that the selected theory or analytic process should prove to be suitable for application in different settings and therefore, generalisable. The case study selection process in Table 6.1 provides clear guidance and criteria to be met for the selection of a suitable case study for addressing the research problem.

To refine the *water as a waste stream* sub-model, a real-world decentralised wastewater treatment facility in an urban setting was required to provide understanding and insight into the relational links among key parameters and how the system interacts holistically with the urban water system. The blackwater filtration plant at Mutualpark in Pinelands met the selection criteria and is therefore, selected as the preferred case study for investigation.

Finally, system reliability is assured to future researchers by providing well documented case study design and data analysis processes in addition to careful archiving and referencing of data sources and information. This provides consistency to address the underlying assumptions that threaten the future replication of the study. Articles and technical reports extracted for investigation during the critical literature review conducted in §6.2 is documented in Appendix A.3.

Annual consumption at the Mutualpark campus is distributed among several uses. Subsequently, the model simulates each user type as a fraction of the total annual consumption. The model can be altered to allocated fixed quantities of use for each user group, however fractions can also be calibrated to represent real-world consumer behaviour. Furthermore, water saving interventions reduced the overall annual consumptions. Intervention actions impact several facets, including the reduction in actual water consumption, more efficient irrigation and landscaping, the utilisation of water efficient air conditioning with reduced evaporation and the attention to leak detection and water losses within the system.

Calibration

To establish the usefulness of the constructed model, a comparison of model results and actual real world measurements and observations are made. Selected parameters are fixed to calibrate unknown variables to minimise comparison errors. Therefore, annual consumption is based on the 15 000 kL water demand per month, with a 30% decrease in consumption as a result of water saving initiatives implemented at Old Mutual in Pinelands (Cassim, 2018; Fredericks, 2018a). As the consumption losses account for water lost to the system for reuse, the totality of *consumed* water is set to be available as wastewater for treatment. Furthermore, the input to the water filtration plant is supplemented by municipal treated effluent, to produce adequate quantities of potable water for reuse.

Several observations have been made during the pilot study (Fredericks, 2018a). These parameters are fixed for observation A and observation B. While, the calibration of input variables and fraction of losses serve to limit the error between the real-world system response and the modelled system as shown in Figure 6.5 (Fredericks, 2018a).

Table 6.5: Mutualpark Decentralised Blackwater Filtration Plant Calibration

Model Parameter	**Obs: A**	**Sim: A**	**Error A**	**Obs: B**	**Sim: B**	**Error B**
Borehole Water	40%	40%	-	14%	14%	-
Filtered Water	52%	51.8%	0.4%	84%	84.01%	0.01%
Municipal Water	8%	8.2%	2.5%	2%	1.99%	0.5%
Fraction Treated Effluent	0.05	0.05	n/a	0.375	0.375	n/a
Fraction of OM WW	0.97	0.97	n/a	0.97	0.97	n/a
Consumption Losses	0.47	0.47	n/a	0.47	0.47	n/a

The calibration results found that the model's performance against the real-world system is sufficient for the model purpose. However, the production of treated wastewater for direct potable reuse is directly influenced by the quantity of wastewater input to the decentralised wastewater treatement plant. The system is designed to operate at 75% of operation capacity, utilising 25% municipal treated effluent as an input source (Fredericks, 2018a). To better understand the operating behaviour, the filtration plant throughput is evaluated against the fraction of treated effluent used in Table 6.6.

Table 6.6: Mutualpark Decentralised Throughput Design Calibration

Fraction Treated Effluent	**0%**	**5%**	**15%**	**25%**	**35%**	**45%**
Borehole Water	0%	0%	0%	**0%**	0%	0%
Municipal Water	51%	46.3%	36.8%	**27.2%**	17.7%	8.2%
Filtered Water	49%	53.7%	63.2%	**72.8%**	82.3%	91.8%
Throughput	26%	28.5%	33.6%	**38.6%**	43.7%	48.8%

The simulation results found that there is a 27.2% water supply deficit when 25% municipal treated effluent is used to supplement wastewater input into the blackwater filtration plant. However, groundwater treated on-site may serve to meet the water supply deficit.

Using borehole water in combination with treated municipal effluent and on-site wastewater, the requirement for municipal potable quality water can be minimised at 14% borehole water inflow (as per Observation B). However, for independence from of the City of Cape Town potable water, the borehole contribution needs to be 40% (as per Observation A). Figure 6.9 illustrates the comparison of total Mutualpark campus consumption and the output of potable water produced on-site as groundwater input changes. Model parameters for the simulation run investigating the influence of on-site groundwater use is expanded on in Appendix C.6.

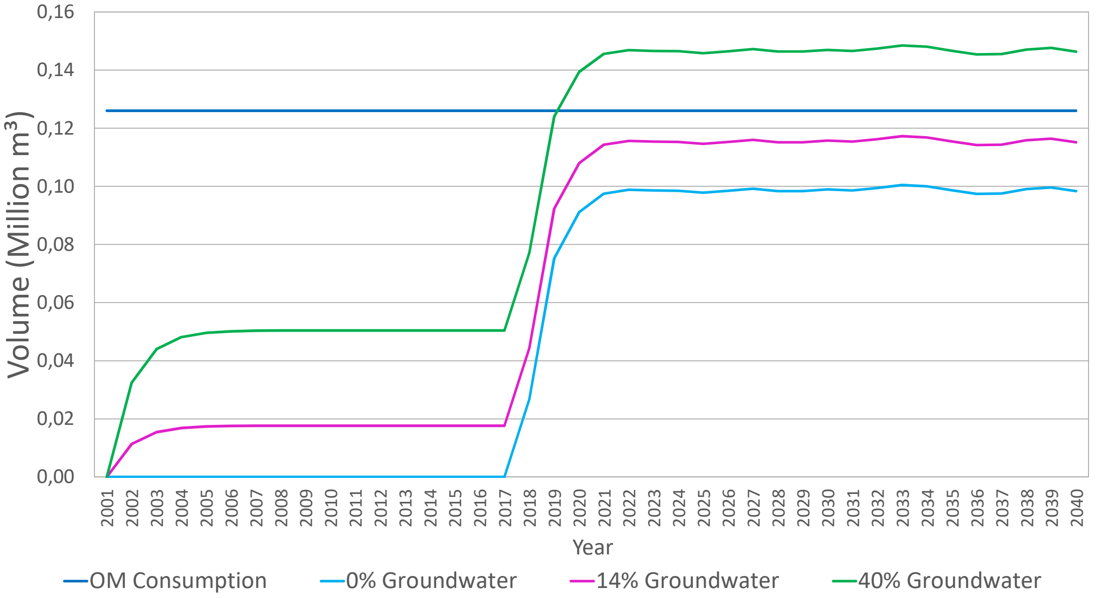


Figure 6.9: Using Mutualpark Groundwater to Increase Potable Water Production on Campus

Parameter Evaluation

High municipal water cost, environmental responsibility and the assurance of available water resources are motivating factors for establishing decentralised wastewater treatment facilities on-site for industry use. The model serves to provide decision-makers with a practical tool to investigate the influence and behavioural response that parameters adjustments have on the internal water system, with specific reference to the requirement of external water sources.

Several parameters influence the final municipal potable water requirement to meet the water demand for Old Mutual Pinelands. An analysis of various scenarios are conducted to identify the primary influencers and behaviour of the system in response to parameter changes. Table 6.7 captures parameter changes and the impact on municipal demand for potable water.

Table 6.7: Parameter Evaluation for Mutualpark Decentralised Blackwater Filtration Plant

	Evaluations				
Model Parameter	**A**	**B**	**C**	**D**	**E**
Decentralised Wastewater Plant					
Fraction of OM Borehole Water	0	0	0.15	0.15	0.15
Fraction Process Losses	0	0	0.05	0.05	0.05
OM CoCT Treated Effluent (m^3/annum)	0	0	0	0	13 356
Wastewater from CoCT (m^3/annum)	0	0	0	0	0
Fraction of OM WW	0	0	0	0.7	0.7
Fraction of Treated Effluent	0	0	0	0	0.2
Old Mutual Consumption					
OM Demand (m^3/annum)	180 000	180 000	180 000	180 000	180 000
OM Water Saving Intervention	0	0.3	0.3	0.3	0.3
Fraction Evaporation	0.1	0.1	0.1	0.1	0.1
Fraction Irrigation	0.3	0.3	0.3	0.3	0.3
Fraction Losses	0.07	0.07	0.07	0.07	0.7
Fraction Consumption	0.53	0.53	0.53	0.53	0.53
Municipal Potable Demand (m^3/annum)	180 000	126 000	107 100	88 520	85 230

Evaluation A serves as the baseline to establish the total municipal demand without any water saving initiatives or alternative water sources supplementing water demand. Evaluation B incorporates the affect of water saving initiatives, reducing demand by 30%. Evaluation C, D and E introduces alternative inputs, firstly borehole water is introduced into the system, then internally generated wastewater is treated for reuse and finally municipal treated effluent is added to supplement wastewater for treatment to reduce potable water demanded from the City. Water saving initiatives proved to have a significant impact on water consumption with the reuse of wastewater and treated groundwater reducing municipal water consumption further.

During the analysis of the case study, Old Mutual were putting sensors and measurements in place to identify sources of water loss, during both production and consumption, which will allow for more accurate population of parameter values. Furthermore, the parameter evaluation found that the model responds as expected to replicate real-world behaviour, reducing the demand per month from 15 000 *kl* to 10 000 *kl* with the initial water saving intervention (Cassim, 2018).

At present, Old Mutual does not incorporate stormwater harvesting as an alternative supplementing source of water for reuse at Mutualpark. Therefore, the model does not include the reuse of harvested stormwater, although adjustments can be made to the dynamic model to integrate the utilisation of an additional input variable. The rooftop area of the Mutualpark office building is approximated at 166 000 m^2. If a runoff coefficient of 0.9 and an average rainfall per annum of 450 mm is used, rooftop runoff alone can produce 67 230 m^3 per year.

$$\text{Runoff} \;=\; 0.9 \;\cdot\; 166\,000\; m^2 \;\cdot\; 450\; mm \;\cdot\; 0.001 \;=\; 67\,230\; m^3 \tag{6.5.1}$$

Additional on-site urban runoff can potentially serve as a source to infiltrate groundwater as artificial recharge or to be used as an input into the blackwater filtration plant to account for the delta in wastewater input. Further parameter evaluation in Appendix C.6 investigated the impact of utilising urban runoff.

6.6 Conclusions

The assurance of quality water is essential to the economic well-being of commercial and industrial entities within the urban City of Cape Town. However, water shortage threatens the availability of sufficient water supply at cost-effective prices. Conservation initiatives aim to reduce consumption of scarce water resources by investing in water saving devices, demand management and diversification of water supply to include reusable and retained water sources. Although, a significant fraction of water demand can be supplemented by non-potable quality water, such as greywater for toilet flushing and irrigation, the substitution of potable quality water requires water treatment processes and facilities capable of producing high quality potable water for reuse.

To refine the constructed *water as a waste stream* sub-model, a real-world case study was identified to provide insight and understanding into the structure, advantages and challenges associated with operating and utilising decentralised wastewater treatment plants to address urban water shortages. In response to the 2017 drought in the City of Cape Town, Old Mutual invested in a blackwater filtration plant located on-site at the Pinelands Mutualpark campus. The plant treats campus wastewater to potable quality water for reuse as part of Old Mutual's aim to become Net Zero Water certified.

The investigation found that losses occur within the on-site industrial water cycle. Subsequently, the decentralised system utilises inputs from both groundwater resources and municipal treated effluent to produce sufficient potable quality water for reuse on campus. Losses are attributed to evaporation, irrigation and consumption and production losses. The wastewater generated on-campus is not sufficient input to the blackwater filtration plant to meet the water demand. As operations become more efficient and alternative water supply from municipal effluent becomes more assured, less potable quality municipal water will be required to supplement water produced by the decentralised blackwater filtration plant.

The case study research allowed for the exploration of the decentralised system, exposing the operations, challenges and likely impact of utilising a decentralised wastewater treatment plant to substitute or supplement municipal water resources. Ultimately, findings and insights from the case study are used to refine the *water as a waste stream* sub-model to better represent the real-world urban water system.

Chapter 7

Testing Policy Scenarios

> *"It is not the most intellectual of the species that survives; it is not the strongest that survives; but the species that survives is the one that is able best to adapt and adjust to the changing environment in which it finds itself..."* – Leon C. Megginson on Charles Darwin's Origin of Species (1964)

The aim of this chapter is to develop and test several scenarios for alternative water futures to provide system insight and understanding to decision-makers. This is achieved through the evaluation of various water policy structures aimed at ensuring sufficient and sustainable water supply to the urban City of Cape Town (CoCT). Scenario planning involve the development of future stories in such a way as to encourage broad consideration of decision points, patterns, behaviours and issues associated with potential future scenarios (Forrester, 1998).

These scenario futures may differ significantly as a result of key differences in drivers, based on different structures in the system dynamics model. Hence, this process is not merely the exploration of models through the sensitivity analysis of model parameters, but the evaluation of model structures for alternative futures.

7.1 Scenario Development and Simulation

Before scenarios for simulation runs can be developed a list of previously proposed interventions and strategies aimed at addressing similar socio-economic problems, such as water scarcity in urban cities and in the Western Cape, should be compiled. The exploration of policy interventions, applied or attempted in the field of study, is required to effectively develop intervention scenarios that attempt to capture a wide range of potential future possibilities (Maani and Cavana, 2007). For the research study, these policy interventions include attempts to reduce water stress by addressing aspects in the three water roles. These water roles require an integrated water management approach to address water scarcity in a sustainable manner.

Literature is a valuable source for identifying suitable future intervention possibilities and should be chosen based on effectiveness and suitability of interventions in similar regions and situations. Additionally, the likelihood of future implementation improves the relevance for intervention selection and execution. Scenario planning is a valuable tool for providing a common background for estimating which policy or intervention alternatives are likely to assist or prevent potential scenarios from realising (Maani and Cavana, 2007).

The cost and risk associated with each intervention should be considered and ranked, using similar reference units to facilitate an equal measurement structure (Maani and Cavana, 2007). The value associated with benefits gained, such as water saved and the cost of projects should be of a comparative nature. Unfortunately, the unavailability of project specific details restrict the effectiveness of intervention comparison for both cost and benefit results (Simonovic and Rajasekaram, 2004). Furthermore, indicative costing and income may lead to a generalisation of possible solution overview. Therefore, a scenario grid for testing and a summary of model scenarios with input parameters, should be constructed for ease of use and transparency.

Scenario development allows the decision-maker to understand the potential future behaviour and uncertainties of the system by identifying drivers of change, system structure and causal links. The purpose of the model should clarify what matters in the constructed model, thus providing guidance to which scenarios should be developed for testing (Choi and Jang, 2017). For example, Choi and Jang (2017) found the local economic growth to be the sector that matters in the specific model. Thus, the percentage of growth in the Gross Regional Domestic Product (GRDP) was selected as policy scenarios.

Finally, the simulation model should serve as the test for accuracy and plausibility of assumptions, model consistency and the future impacts of the simulated scenarios (Maani and Cavana, 2007). This requires the scenario design to include a basic scenario on which comparative evaluation of impact and affect can be measured. Subsequently, providing information and support for decision making and policy development.

Future augmentation programmes for the City of Cape Town stipulated in the 2018 GreenCape Market Intelligence Report, the 2018 Water Outlook Report and the 2019 Cape Town Water Strategy Report are used as a source for validation and scenario planning. These current documents serve to provide a basis for investigating the impact and effectiveness of various planned and suggested alternatives. These alternatives ultimately aim to alleviate the water supply stress experienced in the City of Cape Town.

7.1.1 Urban City Demand Management

The Western Cape Water Supply System (WCWSS) is the source of 98% of the City of Cape Town's fresh water supply. Exogenous variables, for example precipitation or rainfall runoff, influence the volume of water in the dams, groundwater recharge and irrigation demand. Subsequently, climate change impacts the rate and quantity of precipitation in the region, whereas urban activities affect and promote climate change. It is therefore, evident that various system factors or parameters impact and link among each other. The behaviours or trends of these parameters are represented as mathematical equations and causal links for modelling purposes.

However, it is not the objective of the research study to investigate the system's behaviour and response to climate change and urban development. Hence, several variables fall outside the model boundary. The 2019 Cape Town Water Strategy Report, the 2018 Water Outlook Report and the 2018 and 2017 GreenCape Market Intelligence Reports on Water in the Western Cape provide current planned projects and augmentation schemes aimed at addressing the growing concern related to water scarcity in the region.

Although the model aims to identify and evaluate potential sources of water generated from waste streams and retained water within the urban water system, the connecting parameters and sources are inherent to the constructed model. These exogenous parameters are added for completeness and to allow for response evaluation. The poor rainfall in the Western Cape, specifically in the catchment area of the six major WCWSS dams, has resulted in additional intervention actions being implemented and the fast-tracking of augmentation projects. Furthermore, several demand and conservation interventions are also increased to address water losses and consumption patterns in the city.

Constrained Water Allocation

The 2018 total yield of the WCWSS is approximately 570 million m^3 under unconstrained conditions, of which 64% is allocated to the City of Cape Town. The remainder is set at fixed allocations to other urban areas and irrigation supply. With the decline in available surface water, as a result of continuing drought in the region, the Department of Water and Sanitation (DWS) has supported the capped allocation of irrigation supply to avoid running out of water, reserved for basic human needs.

The water allocation targets in Table 7.1, for constrained and unconstrained conditions are set out by the DWS. This table is an adaptation of the WCWSS Yield and allocation table in the 2018 Water Outlook Report.

Table 7.1: WCWSS Yield Allocations under Constrained and Unconstrained Conditions

System Consumers	City of Cape Town	Irrigation	Other Urban	Total Yield
Constrained (Mm^3)	178	58	13	248
Unconstrained (Mm^3)	324	144	23	570

Restriction levels trigger the initiation of constrained and unconstrained water allocation from the WCWSS. However, restricting the allocation of irrigation supply will not ensure water supply alone. The domestic and industry demand in the City of Cape Town are the major consumers of water sources, thus restriction levels are implemented in accordance with available water stock in the WCWSS dams (CoCT, 2019a).

Water Restrictions

The regulation of average daily consumer consumption in the City of Cape Town is conducted in steps, or more relevant *Restriction Levels*. These restrictions are introduced to manage the demand for both domestic and industry users in the urban city. The domestic usage amounts to 70% of the total water demand in the City, with the remaining 30% consumed by industry. Where industry is the term used to describe the collection of commercial, municipal, industrial and other economic drivers in the city.

The demand management implemented by the DWS and the City of Cape Town aim to ensure dam levels remain above 15%, as water becomes difficult to extract below this level. Domestic restrictions range from encouraged savings (Level 1) to basic collection of 25 litres per capita from central distribution points (Level 7). Savings in the industry and agricultural sectors are also mandatory, however consumption reductions are based on percentage savings, for example level 6B requires industry to reduce consumption by 45% from unconstrained demands.

For this model, the unconstrained conditions are categorised up until level 3 water restriction, as no fixed consumption limit is set prior to level 4 water restriction. Thereafter, constrained conditions apply for the consumption of water for level 4 and higher. The dam level is the determining factor for the implementation of water restrictions. Subsequently, these restrictions are evaluated at the end of each hydrological year to assess the assured availability of water supplies for the following year, under reasonable assumptions for water demand and water inflow into dams.

According to the 2018 Water Outlook Report, the 2018 consumption restriction set at 450 million litres a day (MLD) for the City of Cape Town is distributed in a certain manner. Firstly, the 50 l/day allowance per capita, equates to 200 MLD for a population of 4 million. Secondly, industry consumes an estimated 150 MLD, leaving 100 MLD for the inability to adhere to demand management or water losses within the system (CoCT, 2018a).

Management of Non-Revenue Water

To curb losses in the reticulation system, several efforts have been made by the City of Cape Town to reduce water lost through burst pipes, leaks and faulty metering. These losses are categorised as non-revenue water, representing potential municipal revenue loss, which include apparent and real losses. Real losses is approximately 9% of the total system input, which have been reduced with extensive efforts in pressure management, leak detection systems, monitoring and repair work as well as improving metering and billing systems in the urban reticulation system.

According to the 2017 GreenCape Market Intelligence Report, opportunities to reduce non-revenue water losses in the system, lies in the private sector. These activities form part of the Water Conservation and Water Demand Management (WCWDM) plans that are driven by the National Development Plan, which require a reduction of 15% in demand from the 2012 baseline values. Nonetheless, several augmentation projects are scheduled to increase the annual yield to address the supply side of the water system.

7.1.2 Future Augmentation Projects

Although surface water augmentation projects are relatively inexpensive in comparison to non-surface water schemes, the available feasible surface water areas in the region, serving the City of Cape Town, has been developed to near capacity. The urban city is predominantly dependent on surface water supplies, however to increase the reliability of this supply source, which depend on annual rainfall, additional non-surface water schemes should be added (CoCT, 2019a). These augmentation schemes include groundwater, reuse of wastewater and seawater desalination additions. The cost associated with these diverse water sources may prove to be substantially higher than prevailing water cost. Therefore, the costs and benefits of these projects are to be compared to the current surface water cost of R5.20 per m^3 (CoCT, 2018a).

The water augmentation programme has changed and evolved since the initial proposed plans in the 2007 Western Cape Water Supply System Reconciliation Strategy. Furthermore, drought resilience is essential to the sustainable development and well-being of the urban City. Several programmes have been fast-tracked to ensure water supply to the City of Cape Town. However, the cost of additional yield is much higher than programmes and efforts towards demand savings.

Surface water augmentation planned for 2021 aims to add 23 million m^3 to the total WCWSS yield, which is a slightly higher estimation than the surface water augmentation yield of 15 million m^3 for 2022 committed in the 2019 Cape Town Water Strategy. Furthermore, the increase in groundwater abstraction is the second water resilience priority, as the operating and capital costs are significantly lower than the other yield sources, costing between R6 - R9 per m^3.

Groundwater Augmentation

The projected yield increase from City of Cape Town groundwater sources include incremental increases in abstraction from Cape Flats aquifers, refurbished Atlantis aquifer and the planned future incremental abstraction from the Table Mountain Group (TMG) aquifers. The total potential sustainable yield over the planned augmentation period amounts to approximately 150 MLD, divided among the sandy aquifers (75 MLD) with recharge requirements and the TMG aquifers (75 MLD) without recharge requirements (CoCT, 2018c).

Groundwater augmentation plans vary and are adjusted with new findings and results from feasibility studies, however the estimated total yield falls within the abstraction range, 100 - 150 MLD. However, these abstraction levels may differ with drought years, to supplement strained surface water resources.

Reuse Wastewater Augmentation

Several future projects for water reuse treatment works are identified to produce water for use in industry, irrigation, as recharge and as direct or indirect potable water supply to the City of Cape Town. The planned increase in yield from 2023 is predominantly attributed to one large reclamation plant for indirect potable reuse of 70 MLD. Current projects include the temporary 10 MLD Zandfliet production of reusable water by June 2019 (CoCT, 2018d).

Other project alternatives being investigated include water recycling for aquifer recharge in Atlantis, Athlone, Zandvliet, Macassar and the Cape Flats.

Desalinated Seawater Augmentation

Desalination of seawater, although an expensive water alternative, is the only water source that assures supply. Thus, the alternative is part of the current augmentation programmes for the City of Cape Town. Temporary desalination plants are planned for Strandfontein, Monwabisi and the V&A Waterfront, to add a combined 16 MLD from May 2018. Larger permanent desalination plants are planned to add between 120-150 MLD, however suitable sites are being investigated and feasibility studies are being conducted.

A pilot plant is planned at Koeberg, to add 20 MLD, which will serve as the baseline and design information for future plants on-site. Furthermore, the cost per m^3 can run up to R25, with long lead times for completion of additional yield projects. While the energy costs (3.5-4 kWh) are approximately double in comparison to the reuse of treated effluent (2 kWh) per m^3 of produced water. Although the cost of operating and implementing desalination plants are high, the advantage lie in the assurance of water supply.

Stormwater Harvesting Augmentation

Stormwater from urban runoff in the City of Cape Town is predominantly discharged into the ocean, which could have been reused as a source of water for urban use or aquifer recharge. Australia has taken a more sustainable approach to reusing stormwater, utilising the Sustainable Drainage System (SuSD) which imitates nature (Nicolson, 2017). Furthermore, the United States Environmental Protection Agency (EPA) provides a Storm Water Management Model (SWMM) that predicts the quality and quantity of water runoff in urban regions. Model applications include the mapping of flood plains, designing and sizing drainage and storage systems and impact evaluation of flow into the sewage system. The application software is open source with further information available online at *https://www.epa.gov/water-research/storm-water-management-model-swmm*.

In South Africa, the University of Cape Town has done several studies relating to the reuse and impact of retaining and using stormwater as an alternative source of water. Research units such as the Urban Water Management and the Future Water institutes are actively developing the knowledge field surrounding the capturing, storage, treatment and reuse of stormwater. At present the Atlantis aquifer is recharged through stormwater infiltration captured in large ponds. However, it is estimated that the potable water requirements in the City of Cape Town can be relieved with the reuse of stormwater by 33 million m^3 per year (Nicolson, 2017).

Subsequently, several policies and legislation govern the management of water resources and services, guiding the implementation of conservation and augmentation projects to align with national and provincial objectives. In Appendix A.2, Table A.5 summarises the applicable resources addressed in both national and regional policies in South Africa.

7.1.3 Water Related Legislation

The National Water Act of 1998 regulates and protects water resources, stipulating eleven *uses* of water, which include storing, abstracting and discharging of water resources. These uses require a licence unless it is for non-commercial use, within reasonable domestic use, roof-top rainwater harvesting, or within lawful use (Reddick and Fundikwa, 2018). Subsequently, groundwater can be used domestically without a licence, however licensing is required for industrial or commercial use. Furthermore, all alternative water resource infrastructure and discharge processes have to comply with relevant regulations and acts, such as the Environmental Affairs' brine discharge permit and National Building Regulations.

The Water Service Act aims to promote the effective management and conservation of water resources, through the assurance of efficient, affordable and sustainable water services. These services include the provision of quality water that meet the South African National Standards for Drinking Water (SANS 241:2015). The water quality is monitored by sampling and incentive based programmes such as the Blue Drop Programme.

Furthermore, municipal by-laws empower the relevant municipalities to enact laws with respect to water and sanitation services. These by-laws serve to reduce waste, manage demand, impose water restriction, carry out water audits and specify the standards for relevant water and sanitation fittings. Subsequently, water tariffs increase with the implementation of restrictions to curb demand and to adjust revenue income as a result of reduced water consumption (Reddick and Fundikwa, 2018).

There is an absence of regulations and national standards for installations of alternative water sources such as greywater, rainwater and groundwater systems. However, the City of Cape Town has provided an outline of installation guidelines for domestic and commercial properties (CoCT, 2019b). These include the requirements for municipal approval of groundwater drilling and plumbing installations. Moreover, new developments are required to install alternative water systems to address non-potable purposes, such as irrigation, laundry and toilet flushing.

The effectiveness and costs associated with water related strategies and policies are evaluated on the basis of achieving objectives, however the process of thorough policy evaluation and testing is time consuming and expensive. For this reason, simple alternative methods or models for providing broad understanding and insight into the behaviour of the urban water system in relation to policy actions are required.

The complexities of policy development and implementation in social systems make it difficult to demonstrate and observe the impacts of policy actions. Hence, decision support tools serve to assist the evaluation and decision making process for policy alternatives.

7.2 Water Scarcity Measurements

The development of water scarcity indices have led to the refinement of basic human water requirements, concluding that the minimum requirement, as per basic human needs, totals to 50 *litres/day per capita* distributed according to Table 7.2 (Brown and Matlock, 2011).

Table 7.2: Basic Human Water Requirements

Requirement	**Per Capita Usage**
Minimum Sanitation Water	20 litres/day
Minimum Bathing Water	15 litres/day
Minimum Drinking Water	5 litres/day
Minimum Food Preparation Water	10 litres/day

This threshold of meeting basic human needs is an alternative measurement of water stress levels, such as Falkenmark's benchmark indicator for water stress, where a yield of 1000 m^3 or less per capita per year, serves as an indicator of water scarcity in the region

(Brown and Matlock, 2011).

Furthermore, the WCWSS Reconciliation Strategy provided criteria for screening and comparing intervention alternatives (Van der Berg et al., 2007). These included:

1. Intervention Yield
2. Total and Per unit costs (Unit Reference Values)
3. Impacts (Positive and Negative)

The Unit Reference Values (URV) present the cost of intervention divided by the added yield or water saving associated with the cost. Hence, a fixed baseline or present value is important for comparative analysis. Water supply stress as a measurement index, introduced in Chapter 5.7.1, is measured based on the difference in available water yield and demand shown in Equation 7.2.1.

$$\text{Water Supply Stress} = \frac{\text{Municipal Demand}}{\text{Available Yield}} \tag{7.2.1}$$

Table 7.3 provides an example of presenting the summarised results for scenario yield, water stress and cost of the tested scenario.

Table 7.3: Scenarios: Comparative Cost and Benefit

Scenario	**Yield (m^3)**	**Cost (Rand)**	**URV (R/m^3)**	**Stress Index**
Scenario 1	xx	xx	xx	xx

The evaluation and testing of various scenarios and alternative parameter settings, allow for the exploration of the urban water system behaviour. This process allows for the investigation into the system's response to policy actions, aimed at providing insight and understanding to the decision making process.

7.3 Scenario Development and Testing

Several scenarios are evaluated using system dynamics models to provide insight into the behaviour of the urban water system and to identify the best approach for sustainably reducing water stress experienced in the City of Cape Town. Traditional augmentation projects are available in public documentation and literature. These projects are aimed at increasing the total urban water system yield, as per planned reconciliation strategies and future augmentation schemes. The project alternatives serve as the baseline for reducing water scarcity in the City, with associated cost of additional yield used as a performance measurement factor.

Although the baseline scenario incorporates several augmentation alternatives, the combination of these projects aim to address the supply deficit of approximately 350 million litres per day for the City of Cape Town in the next 25 years. However, smaller increments of augmentation projects are distributed over the time period.

7.3.1 Scenario 1: Business as Usual

The business as usual scenario serves as the baseline against which several intervention scenarios are tested. For this scenario it is assumed that no changes are made to the consumption patterns over the simulation period, other than demand management restrictions and constrained water allocation. However, the baseline model investigates the behaviour of the urban water system without demand management interventions and wastewater reuse or groundwater supplementing raw water supply.

Model Baseline

The model set-up for the baseline run does not incorporate the affects of demand restrictions on the consumption of industry and domestic users. Normally, the level of restriction implemented will be based on the combined water level of the major WCWSS dams. However, the baseline serve to establish the impact of unconstrained demand and zero supplementation of raw water sources on the total municipal demand and available yield over the simulation period. Table 7.4 provide the parameter settings and values for the first scenario, assuming the daily per capita consumption per person is 242 litres per day, while usage in the industry, agricultural and groundwater abstraction remains unconstrained. Fractions are assigned a dimensionless (Dmnl) unit for simulation purposes.

Table 7.4: Scenarios 1: Baseline Parameter Values

Parameters	**Value**	**Unit**
Consumption Efficiency	1	Dmnl
Industrial Demand Reduction	0	Dmnl
Fraction of Potable Industrial Demand	0.3	Dmnl
Fraction of Treated Effluent to Industry	0.1	Dmnl
UGEP Baseline	406	Million m^3/Year
CoCT Allocation	324	Million m^3/Year
Baseline Per Capita Consumption	88.33	m^3/(Year*People)

The model structure and adjustments are summarised in Appendix C.1.1 for transparency and completeness in the scenario development phase. The WCWSS yield model is based on the planned augmentation schemes, including seawater desalination, centralised potable reuse schemes, surface water diversion and groundwater abstraction.

The City of Cape Town receives an allocation of 64% of the total system water yield, which proves to be insufficient without restriction and alternative water source supplementation. The total demand growth in Figure 7.1 indicates the change in total municipal demand for several economic growth patterns. For this model the industrial demand growth is equated to potential growth in Gross Domestic Product (GDP).

The demand continues to grow with the rise in population and economic growth, as per the baseline scenarios for GDP growths over the range 1.5%, 2.7% and 3.9% from 2017.

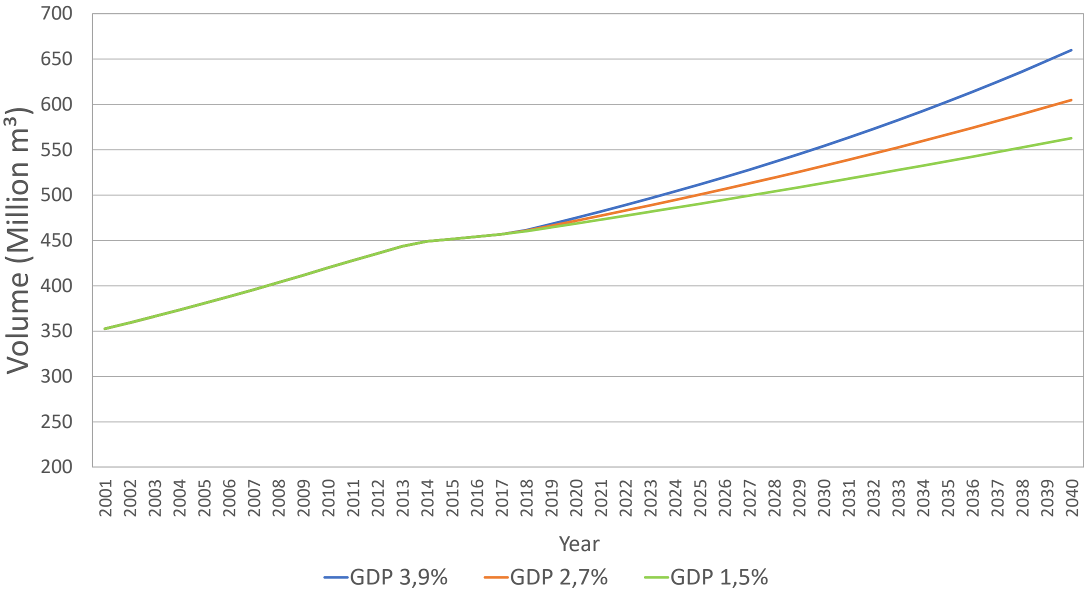


Figure 7.1: Scenario 1: CoCT Baseline Demand with Industrial Growth

Wastewater Reuse

The reuse of treated effluent for industrial and irrigation purposes serve as a supplementing source of non-potable water to the industry demand, thus reducing the overall consumption of municipal potable water. However, as water consumption declines, the wastewater received reduces. Consequently, the capacity of wastewater production for reuse is measured against the total wastewater received at the Wastewater Treatment Works.

The allocation of water resources by the WCWSS remains unconstrained, yet the non-potable demand for industrial consumers are supplemented by treated effluent. Figure 7.2 displays the total CoCT demand, supplemented by treated effluent, for the three economic growth patterns, indicating a reduction in total municipal water demand.

The supplemented non-potable water is taken as a fraction of the *Wastewater Input to WWTW*, limited by the *Municipal Effluent Capacity*. Furthermore, the *Fraction of CoCT Treated Effluent for reuse* is set at 0.05, to represent the 5% water treated for reuse under unconstrained conditions. However, the drive from the national Water Conservation and Water Demand Management (WCWDM), result in a rise in reuse of treated effluent. Figure 7.3 shows the change in volume of treated effluent available for supplementing industrial water demand from 5% to 10%.

Furthermore, water conservation and demand management relies heavily on the implementation of usage restrictions for successful reduction in water consumption.

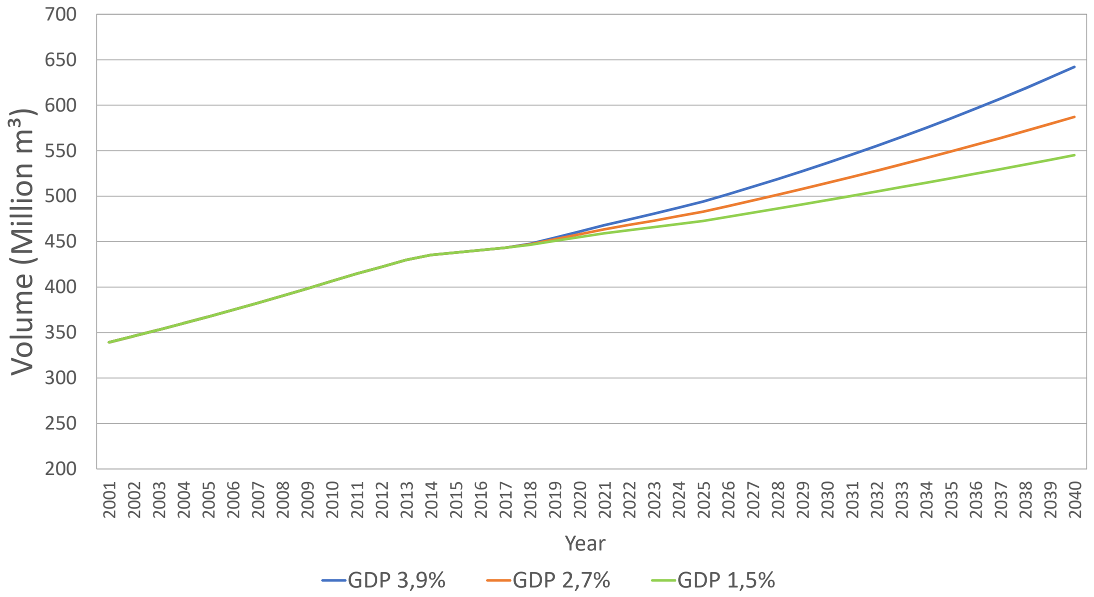


Figure 7.2: Scenario 1: Unconstrained Municipal Demand with Supplemented Water from the WWTW

Figure 7.3: Scenario 1: Treated Effluent based on a 5% and 10% Reuse Rate

Demand Restrictions

The restriction of both domestic and industrial consumption limits are important policy driven actions aimed at addressing the majority users of restricted WCWSS water resources. The system water allocations are categorised as either constrained or unconstrained, based on the level of water restriction implemented at the period of evaluation.

The restriction levels are set in accordance with WCWSS dam levels, evaluated at the end of the hydrological cycle for the assurance of critical water supply. For this model, rainfall runoff serve as the raw water inflow into dams, which can be derived from precipitation and dam catchment area data, or historical annual inflow of runoff. The model can be constructed to investigate both alternatives, however precipitation values provide a better depiction of real-world behaviour.

Subsequently, the water level of the dam is the fraction of *WCWSS Raw Water* in the dam system over the *WCWSS Dam Capacity.* The trigger fraction can be adjusted by the decision-makers to provide insight into the behaviour of the system in relation to changes in restriction patterns. Figure 7.4 shows the causal behaviour among *Avg Dam Level* and *Restriction Level* for the model in relation to precipitation input.

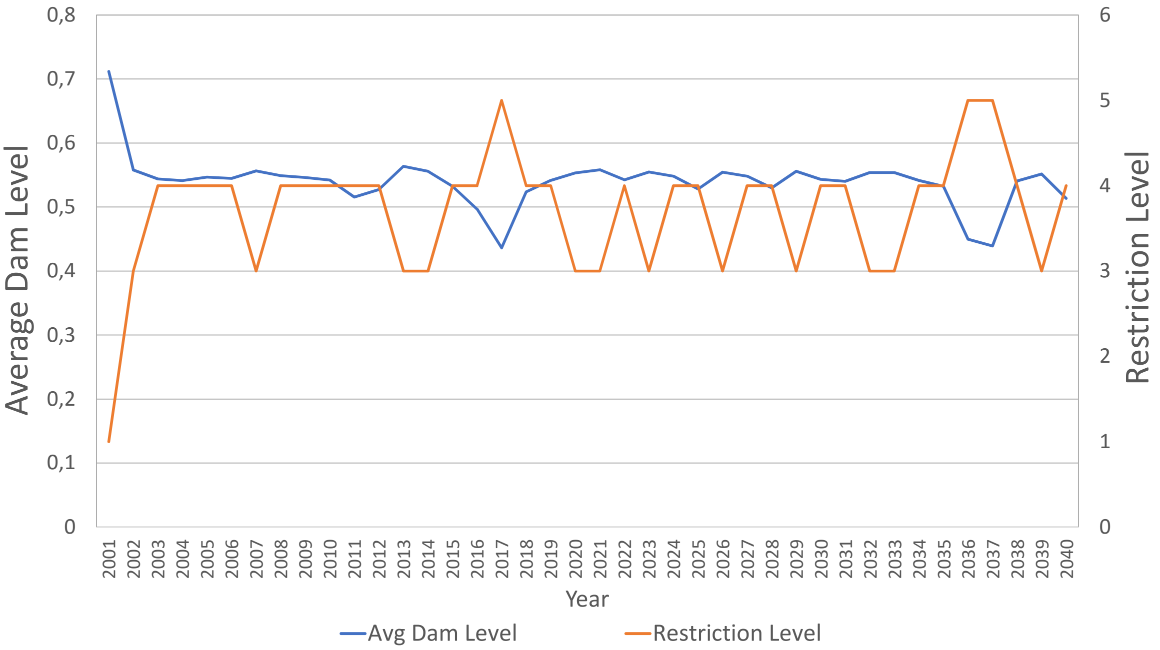


Figure 7.4: Scenario 1: Dam Level Triggers for Restriction Levels

In addition, the restriction levels result in changed per capita and industrial demands, which ultimately impact the outflow of raw water and therefore the dam levels. Consequently, the expected oscillation in water restriction, shown in Figure 7.4 is to be expected.

The strict adherence to restrictions is not realistic. However, Figure 7.5 shows the total City of Cape Town water demand in comparison to planned total allocated WCWSS yield capacity with implemented restriction policy. The WCWSS yield capacity does not reflect the total available water supply over time, as the supply is dependent on annual precipitation and consumption. This behaviour represents the real-world potential deficit as a result of growth in demand and constrained water sources.

The yield capacity remains the same for the three GDP growth scenarios. Figure 7.5 depicts both the yield capacity with planned augmentation projects and the yield fixed at 2018 capacity. The results show that without additional supply sources, demand will far exceed available yield. The parameters for Scenario 1, listed in Table 7.5, adhere to the strict implementation of consumption restrictions and the allocation of water resources as per demand management interventions.

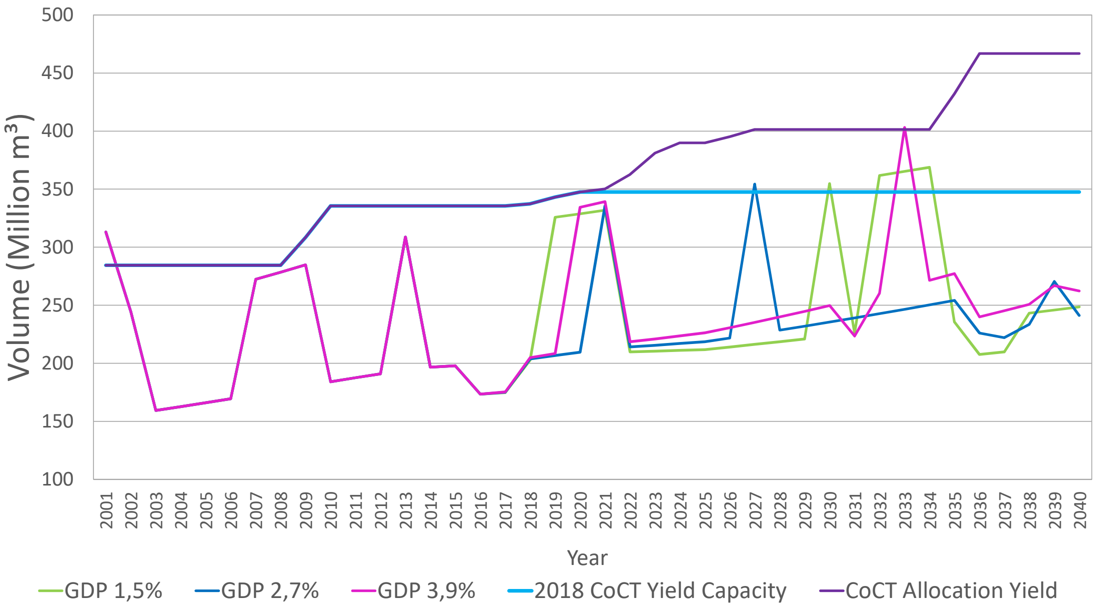


Figure 7.5: Scenario 1: Total Demand with Restrictions and CoCT Yield

Table 7.5: Scenarios 1: Demand Management Parameter Values

Parameters	Value	Unit
Initial WCWSS Raw Water	546,7	Million m^3
Initial Catchment Area	713,5	Million km^2
Select Economic Growth Rate	1.5%	1/Year
Lookup CoCT Allocation	Constrained: 178	Million m^3/Year
	Unconstrained: 324	Million m^3/Year
Lookup Urban Allocation	Constrained: 11.3	Million m^3/Year
	Unconstrained: 23	Million m^3/Year
Lookup Irrigation Allocation	Constrained: 58	Million m^3/Year
	Unconstrained: 144	Million m^3/Year
Lookup Groundwater UGEP	Constrained: 256	Million m^3/Year
	Unconstrained: 406	Million m^3/Year

Water restriction are found to be a crucial water conservation and supply assurance approach. However, curbing water demand is not sufficient to ensure available and affordable water resources to the City of Cape Town. Thus, alternative water sources are added to increase the system yield. Furthermore, several water streams in the urban water system hold the potential for alleviating water pressure on fresh water resources, through the reuse, retention and reduction of water resources within the urban system.

To address the shortfall evident from Scenario 1, various scenarios for alternative generation and retention of water sources are investigated in Chapter 5, using the system dynamics modelling to assist decision-makers with policy evaluation in the urban City. Identified water streams include the retention of rainwater runoff, the reuse of greywater and the decentralised treatment of effluent for reuse.

As research surrounding the reuse of harvested stormwater develops further, the model can be expanded and adjusted to include stormwater harvesting as a primary source in the evaluation. Harvested stormwater is, therefore, only included in the model as a source for aquifer recharge and as a potential supplementary source of input for decentralised wastewater treatment plants. The model allows decision-makers the opportunity to explore the impact of hypothetical scenarios of stormwater capture, storage and reuse.

7.3.2 Scenario 2: Rainwater Harvesting

Advantages of rainwater collection is not limited to the reduction in potable water demand, but also the added benefit of reducing urban surface run-off during high levels of precipitation, reducing the risk of damage due to flooding.

Government incentive schemes such as the United Kingdom Enhanced Capital Allowance (ECA) scheme, allows the cost of water saving technology to be written off from taxes, which drives the user acceptance and application of these investments. Figure 7.6 is an example of reconfigured rainwater harvesting system by Kingspan Water for urban usage (Pickworth, 2014). However, the system still allows for laundry and toilet water requirements to be supplemented by potable or alternative water supplies.

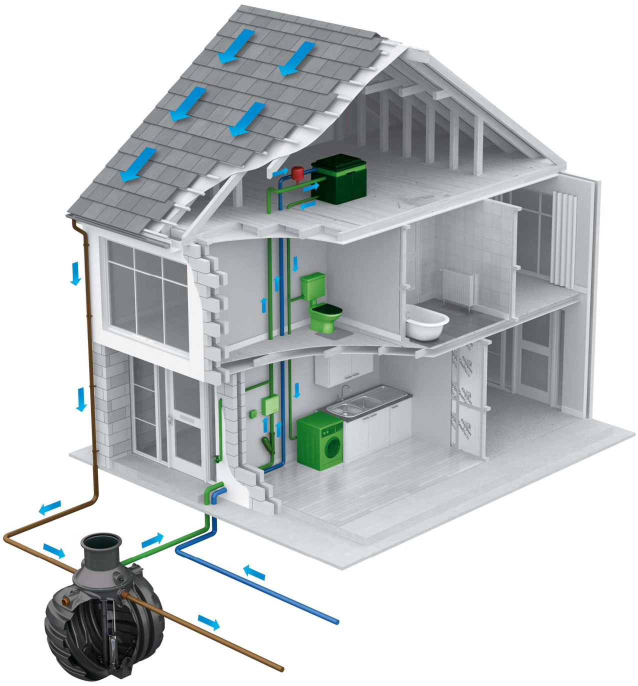


Figure 7.6: Kingspan Rainwater Harvesting System: Domestic Use (Source: Pickworth, 2014)

In more rural parts, rainwater harvesting serves as a source of upliftment, allowing for a close to home water source for domestic and garden usage, thus improving health and the standard of living. Moreover, reduced rainwater runoff in urban areas, as a result of rainwater and stormwater harvesting, has ecological and environmental benefits resulting in a reduction in flooding risks and damages. Furthermore, the retention of runoff reduce the pollution entering the urban water system and prevents sewage overflow into wetlands.

For evaluation purposes, the financial viability of decentralised water harvesting systems should be tested. The cost and lifespan of rainwater system in comparison with potable water supply costs are used as evaluation measurements. The domestic demand saving per annum is compared to alternative augmentation schemes and centralised alternative water supply options. It is important to identify variables influencing the generation of alternative water sources. For rainwater harvesting, the amount of households, consumption patterns, population growth and tariff structures were found to influence the outcome of the scenario evaluation. These insights provide clarity and support to decision-makers for evaluation and development of policies for management of urban water systems.

Captured and stored rainwater serves as a supplementing non-potable water supply for households and industry. Hence, suitable sizes for storage tanks in relation to expected runoff during the dry and wet periods in the year, attribute to the availability assurance of alternative water resources for domestic and industry consumptions in the City of Cape Town.

Commercial businesses and municipal entities will also benefit from the installation of such decentralised systems, which provide assurance of water availability and cost savings. These alternative sources are dependent on rainfall. In the City of Cape Town, rainfall predominantly occurs in winter periods, when the demand is significantly lower than dry warm summer months with minimum precipitation. However, the limited capacity of collection tanks do not allow for maximum retention of runoff and can therefore, only substitute demand to a certain extent. Although water consumption patterns differ significantly between summer and winter periods during non-constrained years, the recent demand management efforts and water restrictions has limited outdoor water usage. Therefore, reducing the predominant factor causing the difference in consumption patterns.

Adequate capacity of catchment tanks should be estimated to ensure available water supply over dryer periods. According to the study conducted by Viljoen (2014), losses due to overflow, evaporation and absorption in the rainwater collection, reduce available rainwater harvested to between 70% and 80% of the rainfall volume as per precipitation and runoff surface area. Overflow from rainwater harvesting tanks can be collected in addition to surface runoff by stormwater harvesting channels and tanks or reservoirs. These alternative sources serve as offsets for non-potable water demand. Ultimately reducing the total demand and consumption of scarce water resources in the semi-arid regions, wherein the City of Cape Town lies.

Domestic Rainwater Harvesting

The retention of rainwater through the capture and storage of rooftop runoff transforms an urban water stream into a source of non-potable water, that serve to supplement the total demand for municipal water resources. The model investigates the extent of water savings that can be made through the installation of rainwater harvesting systems in the City's households. The model parameter values for Scenario 2, domestic household rainwater harvesting, is depicted in Table 7.6.

Table 7.6: Scenarios 2: Domestic Rainwater Harvesting Parameter Values

Parameters	Value	Unit
Avg Capacity of Rainwater Tank	10	m^3
Avg Size of HH Roof	50	m^2/Household
Total HH with Rainwater Tanks	Adjusted by Policy	Household
Fraction of FHH with Rainwater Tanks	0.5	Dmnl
Fraction of IFHH with Rainwater Tanks	0.01	Dmnl
Roof Runoff Coefficient	0.9	Dmnl

The inflow entering tanks are limited by the combined capacity of rainwater tanks, which in turn is limited by the number of households utilising rainwater harvesting systems. Subsequently, the potential policy intervention in relation to installation of rainwater harvesting systems and the total system capacity in the City of Cape Town is tested. The *Potential Rainwater Stock* generated by both average rainfall (490mm/annum) and 2018 Water Outlook precipitation values are compared with the combined capacity of rainwater systems in the City. Figure 7.7 indicates the missed opportunity in relation to the retention of potential water resources.

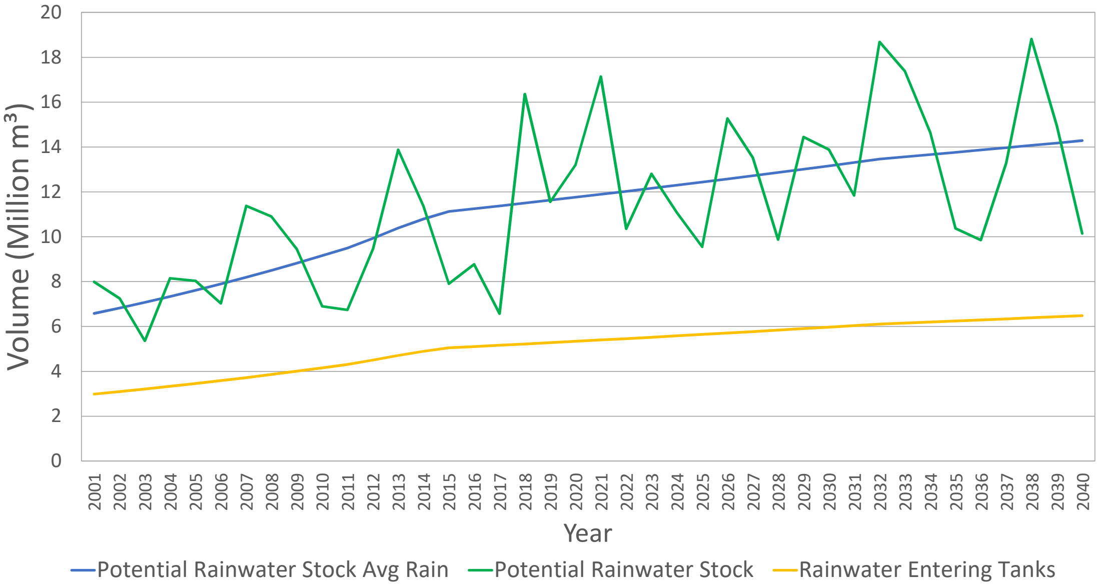


Figure 7.7: Scenario 2: Domestic Rainwater Harvesting - Potential Volume of Inflow

By changing the capacity of the rainwater harvesting systems in households, the system indicates the ability to increase non-potable yield for household usage. Model simulation results show the changes in combined storage capacity with adjustments made to *Avg Capacity of Rainwater Tank* from 10 m^3, 20 m^3 and 30 m^3. Consequently, the comparison is made in Figure 7.8, indicating the potential runoff inflow from precipitation on household rooftops and available storage capacity.

Rainwater harvesting is challenged by its dependence on precipitation, reducing the reliability of the alternative water system as a source of water supply during drought periods. However, the simulated results bring to light the potential retention gap in capturing rainwater runoff from residential rooftops. Subsequently, the yield can likely be doubled

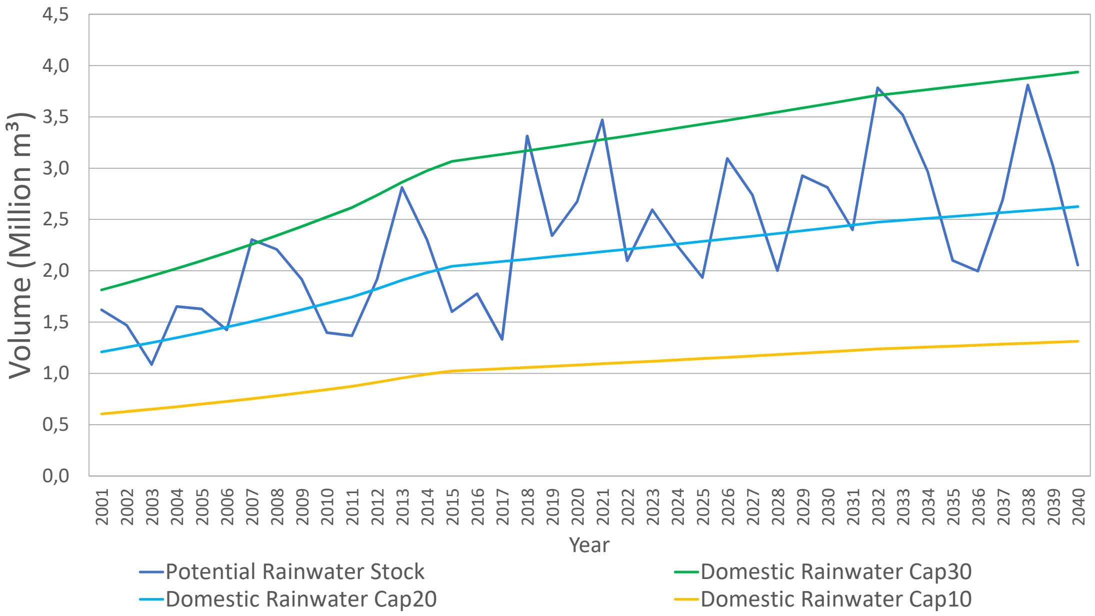


Figure 7.8: Scenario 2: Domestic Rainwater Harvesting - Tank Capacity Evaluation

from 5 m^3 to 10 m^3. The modelled results also show that extensive capacity of storage systems, do not necessarily result in additional yield.

Policy intervention for this future scenario aim to increase the fraction of households with rainwater harvesting systems as a means of retaining water within the urban water system, which ultimately reduce the total non-potable water requirement in households. For the investigation into the yield generation, the *Avg Capacity of Rainwater Tank* is equated to 10 m^3. Assigning different fractions, namely 0.1, 0.5 and 0.7 to the parameter *Fraction of FHH with Rainwater Tanks*, allow for the evaluation of potential volume harvested rainwater per level of intervention. The change in the fraction of formal household with 10 m^3 rainwater tanks are illustrated in Figure 7.9. The results indicate that the *Fraction of FHH with Rainwater Tanks* equated to 0.5 serves as a reasonable assumption.

Although the capacity of rainwater storage has the potential to be expanded, it is unlikely that city households will be able to accommodate larger structures. Therefore, the yield from harvested rainwater can be increased by financing, or enforcing the installation of the non-potable alternative supply systems through policy intervention.

Industrial Rainwater Harvesting

The process of investigating the use of rainwater harvesting systems for supplementing industrial non-potable demand is similar to the domestic rainwater harvesting approach. However, the scale and number of industries differ in the model. Table 7.7 provide the parameter values used to evaluate the response and behaviour of the industrial rainwater harvesting system (The National Academies of Sciences, 2016).

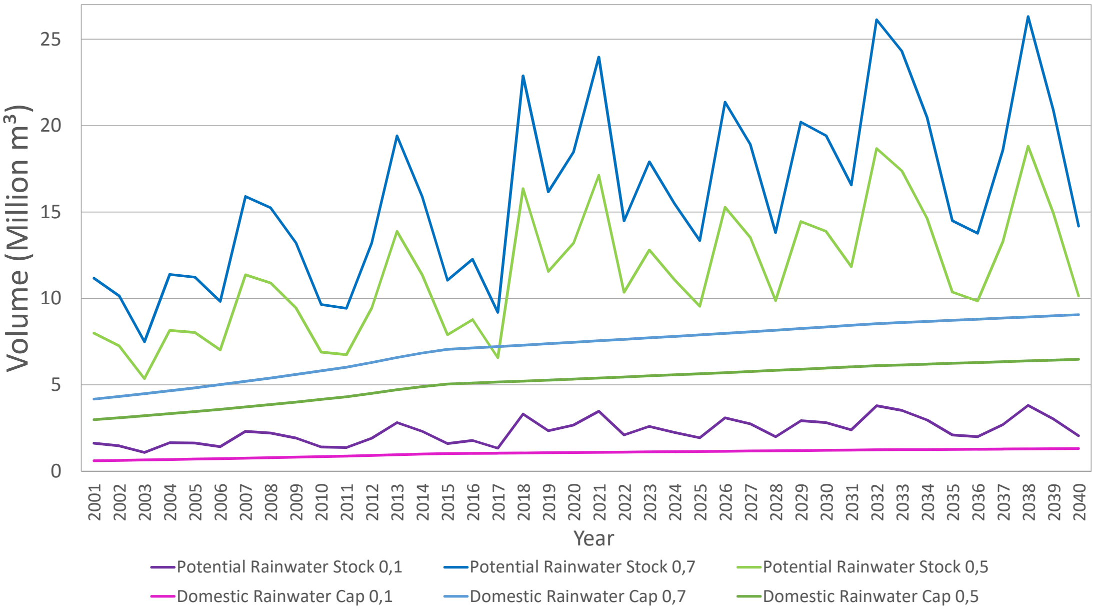


Figure 7.9: Scenario 2: Domestic Rainwater Harvesting - Fraction of Households with Rainwater Tanks

Table 7.7: Scenarios 2: Industrial Rainwater Harvesting Parameter Values

Parameters	**Value**	**Unit**
Avg Capacity of Industrial Rainwater Tank	100	m^3
Avg Size of Industry Roof	500	m^2/Industries
Total Industries with Rainwater Tanks	1000	Industries
Industry Roof Runoff Coefficient	0.9	Dmnl

For industry, the capacity of rainwater tanks can be significantly larger, with big rooftop areas that serve as the catchment area for rainfall. Limitations on storage tanks, such as underground tanks, must adhere to the 2010 City of Cape Town By-law requirements. This by-law requires that storage tanks should allow for the inspection, maintenance and cleaning of the structure, unless the tank is a concrete tank, constructed in accordance with building regulations.

The starting parameter values are changed to investigate the response of the system, including the capacity of rainwater storage tanks. Figure 7.10 shows the inflow of water into tanks, limited by the varying combined rainwater harvesting capacity for industry. The simulation is based on a total of 1000 industries with an average of 500 m^2 roof catchment area.

The yield from the captured rainwater in Figure 7.10 is significantly lower than the industrial requirement. However, this is based on the implementation of limited facilities and storage capacity. To test the system response to an increase in system implementation, the total industries using rainwater harvesting systems with a capacity of 100 m^3 each was increased in increments. Figure 7.11 illustrates the rise in yield with an increase in industrial rainwater harvesting systems.

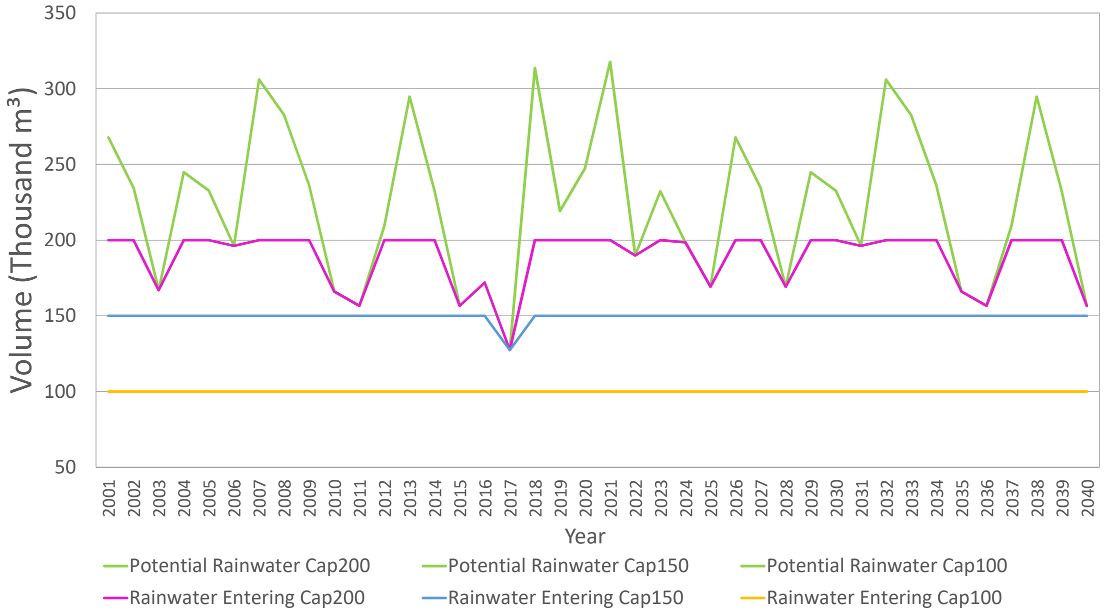


Figure 7.10: Scenario 2: Industrial Rainwater Harvesting - Inflow into Rainwater Tanks vs System Capacity

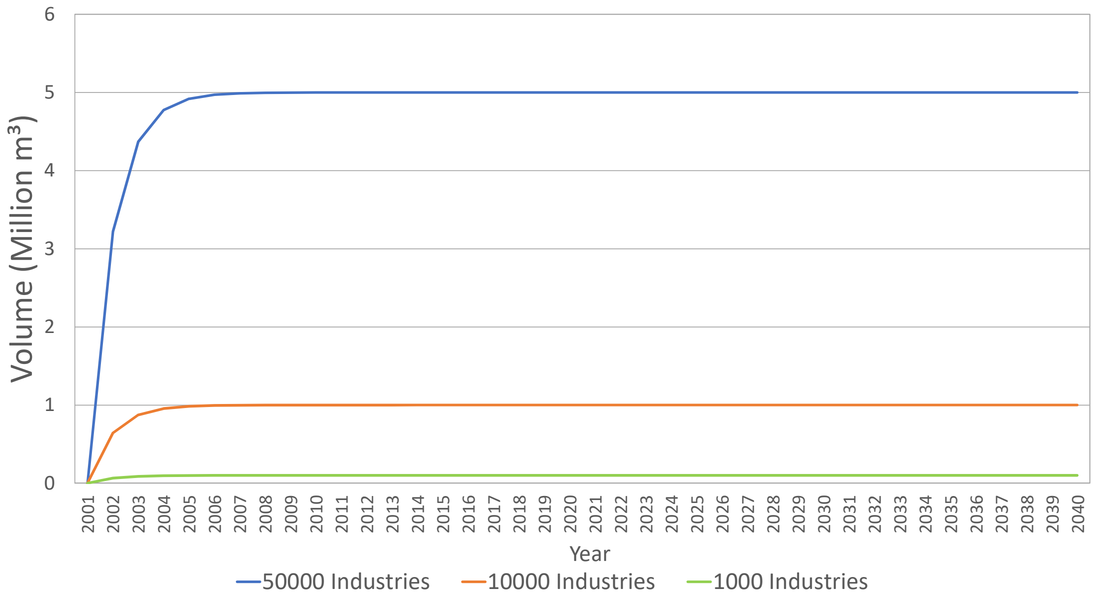


Figure 7.11: Scenario 2: Industrial Rainwater Harvesting - Yield Increase with Increased Industry Systems

Nonetheless, the industrial non-potable requirement can be supplemented to an extent by the harvesting of rainwater as seen in Figure 7.12. The industrial water storage system is compared at 100 m^3 per facility, ranging from 1 000, 10 000 and 50 000 facilities implementing these rainwater harvesting systems.

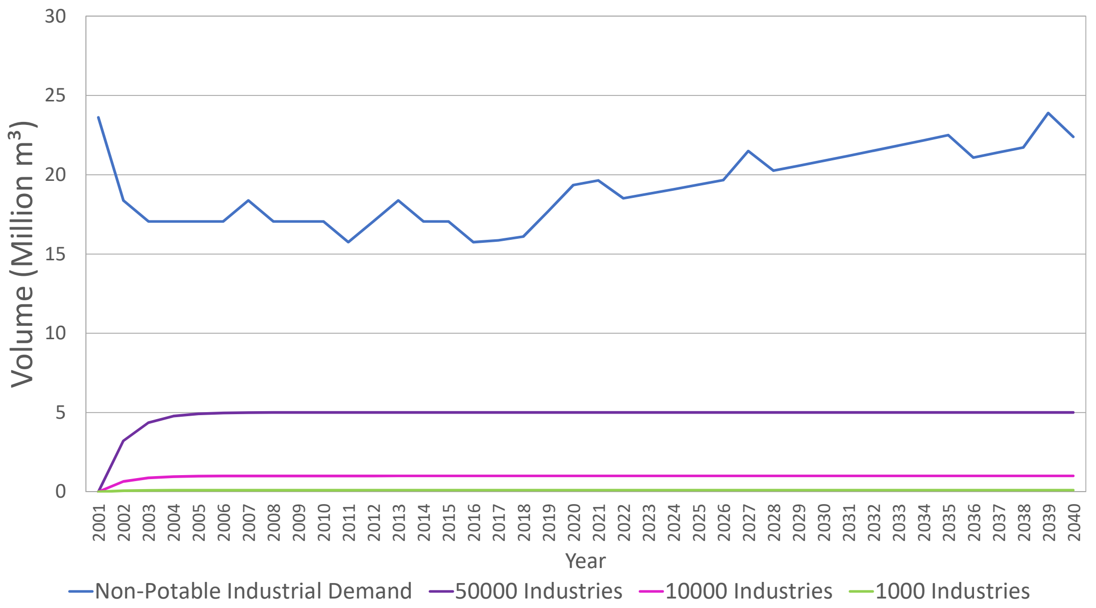


Figure 7.12: Scenario 2: Industrial Rainwater Harvesting - System Yield vs Non-Potable Requirements

Policy intervention can serve as the driver towards an increase in rainwater harvesting system uptake, with potential to increase facility storage capacity and catchment. Additional waste streams can add to the total supplementing resources, which include the reuse of stormwater and greywater for non-potable purposes, for both industry and domestic consumption.

Stormwater Harvesting

Chapter 5.6.2 investigates the retention and reuse of urban runoff in the City. With runoff in built-up areas amounting to 55% of precipitation as seen in Equation 7.3.1.

$$\begin{aligned}\text{Precipitation (Urban)} \;&= 0.3 \cdot \text{Evapotranspiration} + 0.55 \cdot \text{Runoff} + 0.1 \cdot \text{Shallow} \\ &\quad \text{Infiltration } + 0.05 \cdot \text{Deep Infiltration}\end{aligned} \tag{7.3.1}$$

In 2010, 30.1% of the City of Cape Town 2408 km^2 area comprised of urban built-up. Therefore, a significant volume of stormwater is generated with potential reuse value. Rainwater harvesting serves to dampen the runoff into stormwater channels, however simulation results in Figure 7.13 shows that the impact is not meaningful.

The model simulates the refill of rainwater tanks during peak flows to investigate the likely impact rainwater harvesting will have on total urban runoff. From Figure 7.13 it is evident that rainwater captured is limited by the available runoff generated by precipitation and rooftop area. The simulation results correlate with Fisher-Jeffes (2017)'s reported observation that found rainwater to be relatively ineffective in reducing urban stormwater runoff during peak flows. Further elaboration on equations and simulation results for urban runoff are presented in Appendix C.2.

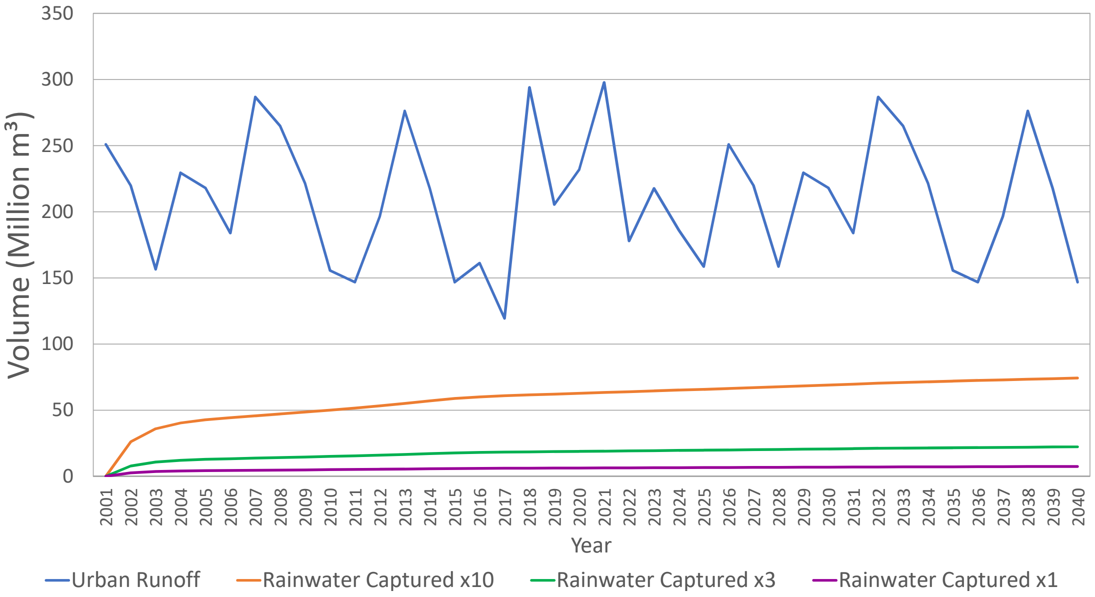


Figure 7.13: Scenario 2: Potential Stormwater Runoff and Rainwater Harvested

7.3.3 Scenario 3: Reuse of Greywater

The reuse of waste streams for sustainable water management is central to the circular economy approach for addressing water scarcity in urban areas (Dominguez et al., 2018). There are several alternative treatment processes for optimal and environmentally sustainable reuse of greywater. However, the model only investigate the potential alleviation of water stress in urban water systems through the use of greywater as a supplement to non-potable water requirement. Therefore, the study does not investigate or evaluate the variety of suitable technologies and treatment processes.

Greywater is generally defined as the wastewater from showers, baths and hand basins. Contrary to greywater, the wastewater from kitchen sinks and washing machines containing higher solid content and undesirable chemicals, which are detrimental to the environment, are defined as blackwater. Thus, the potential for reducing municipal water consumption lie in the reuse of greywater as a source of non-potable water.

However, greywater should not be stored without treatment, as pathogens are likely to grow, which pose a health risk and produce unpleasant odours. User behaviour is one facet that should be addressed through education campaigns and policy, to encourage the use of environmentally friendly detergents, soaps and other products to reduce the toxicity of generated greywater in domestic households.

For industry, greywater is generated through various processes, including rinsing and cleaning, in addition to employee usage. Thus, behavioural changes should include the emphasis on improvement and sustainability of water based industrial processes.

Although household greywater systems are generally used as a source for irrigation, the prevailing dry condition and constrained usage of municipal water has encouraged the usage of greywater for predominantly non-potable indoor purposes. These include laundry and toilet flushing, which benefit the downstream systems in the sanitation reticulation system, as water continues to flow through. Furthermore, Think Water booklets issued by the City of Cape Town aim to guide the safe reuse of greywater within households, reiterating the need to treat greywater stored for periods longer than 24 hours (CoCT, 2017c).

For the purpose of the model the generated greywater in domestic households and industry is estimated as a fraction of potable water consumption. Furthermore, the priority of reuse is set to address the water requirement for flushing toilets rather than for irrigation purposes.

Domestic Greywater Reuse

To evaluate the potential of the underused greywater resource in domestic households, the application and generation of greywater needs to be specified through investigation. The use of greywater is mainly limited to irrigation and toilet flushing, however sophisticated greywater systems produce treated water that can be used for other non-potable demands, such as laundry. However, the installation of greywater systems into direct plumbing must adhere to building regulations and relevant legislations

The diversion of a fraction of greywater to the sewage system is necessary to prevent blockages and ensure sewage flow to downstream systems and users, such as the wastewater treatment works. To ensure that water is not lost or removed from the system, greywater reuse should be limited to indoor non-potable usage to balance the need for sewage water, which serve as a potential potable and non-potable resource once treated.

The cost of a basic household greywater system can range from R12 000 to R20 000, with sophisticated conversions into plumbing systems ranging between R50 000 to R120 000 (Sekano, 2018). The storage capacity and period for greywater harvesting should be limited, with system tank capacity approximating 100 *l*, while the holding period before reuse is recommended to be less than 24 hours.

The system dynamics model allows for the behavioural evaluation of the domestic water use and greywater generation of the City of Cape Town urban water system. The limitations and non-potable requirements are incorporated into the evaluations of parameter changes, to provide a real-world representation of the system performance. Key parameters for the domestic greywater system model is captured in Table 7.8.

Table 7.8: Scenarios 3: Domestic Greywater Reuse Parameter Values

Parameters	**Value**	**Unit**
Fraction Greywater Captured	0.5	Dmnl
Fraction of Capita Using Greywater	1	Dmnl

The *Per Capita Non-Potable Demand* can be supplemented with the reuse of *Per Capita Greywater*. Therefore, the simulation runs compare the generated greywater based on parameter changes for the *Fraction Greywater Captured*. Figure 7.14 shows the comparison of required non-potable water per capita and the generated greywater per capita for changes in *Fraction Greywater Captured*: 0.3, 0.5 and 0.7.

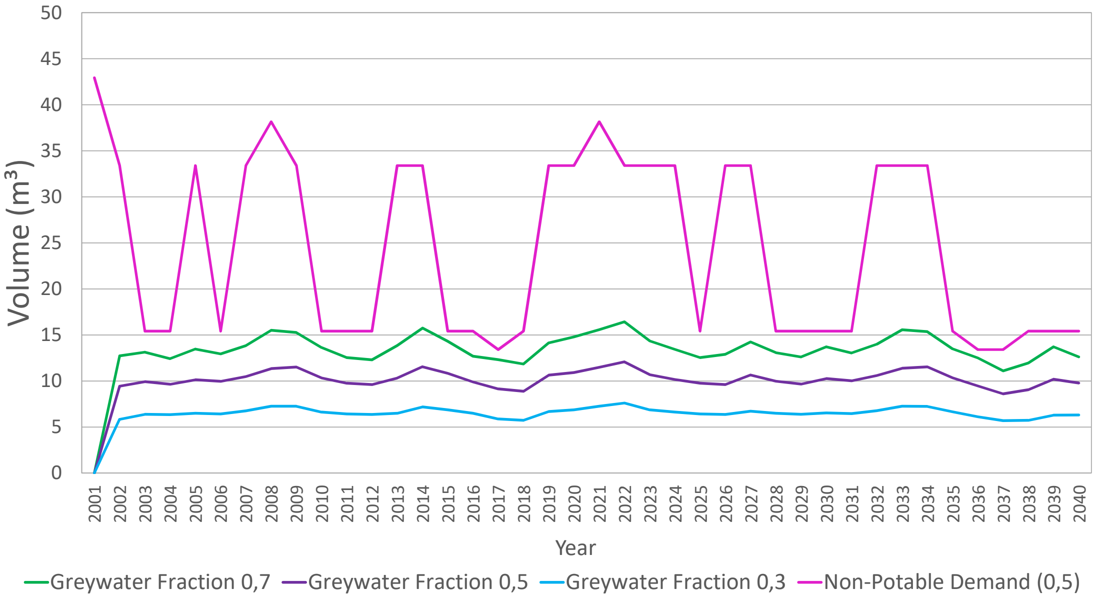


Figure 7.14: Scenario 3: Domestic Greywater - System Yield vs Non-Potable Requirements

The simulations brought to light that 50% reuse of potable water for non-potable purposes is adequate. The model assumes that the total quantity of greywater generated is reused as non-potable water. However, supplementing non-potable water, reduces the potable (municipal) water demanded per capita, which in turn, reduces the amount of greywater generated. The *Fraction of Capita Using Greywater* also significantly influence the amount of greywater available for reuse. The system dynamics model depicts the causal relationship, which allow decision-makers to investigate future scenarios, implementing greywater policies for addressing water shortages in urban areas.

The behaviour of greywater generation and reuse differ for industrial consumption, thus the system response to input variables are investigated for use in industry.

Industrial Greywater Reuse

The model simulation aims to provide insight into the behaviour and response of intervention initiatives on the urban water system. Several parameter fractions listed in Table 7.9 influence the generated quantity of reusable greywater for reducing municipal water demand.

Table 7.9: Scenarios 3: Industrial Greywater Reuse Parameter Values

Parameters	Value	Unit
Fraction of Industrial Greywater Generated	0.3	Dmnl
Fraction of Potable Industrial Demand	0.7	Dmnl
Fraction of Industry Utilising Greywater Systems	0.5	Dmnl

The change in the fraction of greywater reuse and the utilisation of greywater systems in industry influence the total greywater generated. Changing the *Fraction of Industrial Greywater Generated* shows that the total potential alternative non-potable water resource generated declines or increase in response. To test this, the *Fraction of Industry Utilising Greywater Systems* is set at 100%, while the *Fraction of Industrial Greywater Generated* is changed from 0.3, 0.5 and 0.7. However, non-potable water requirements can only be supplemented to the extent of the non-potable demand. Figure 7.15 shows that as the *Fraction of Industrial Greywater Generated* per industry is simulated higher than 0.5, the potential greywater yield supplements the total required amount of non-potable water required (orange line).

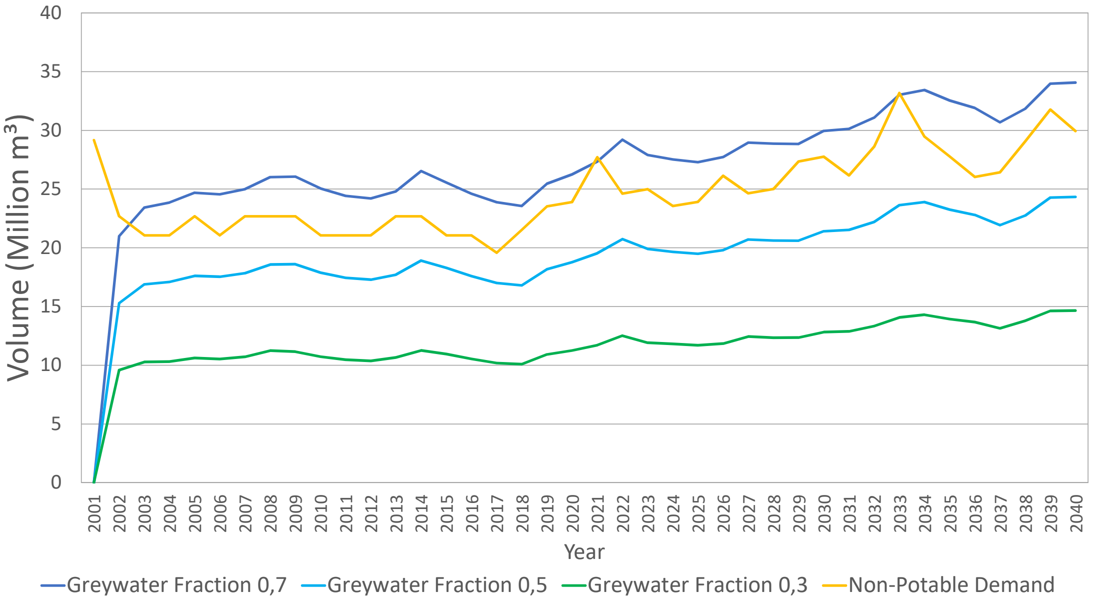


Figure 7.15: Scenario 3: Industrial Greywater - System Yield vs Non-Potable Requirements

Subsequently, the behavioural response of the system, to changes in the fraction of industries utilising greywater systems, is evaluated. The parameter for greywater generated is fixed at 0.3, while the *Fraction of Industry Utilising Greywater Systems* is varied between 1, 0.7, 0.5 and 0.3. The system response to the fraction of industries utilising greywater systems are captured in Figure 7.16.

Unfortunately, the total industrial, commercial and municipal facilities in the City of Cape Town is unknown in the research study. Thus, the fraction of facilities utilising greywater reuse as an alternative source is used to determine the potential yield for policy intervention. Traditionally, the generated wastewater is discharged to centralised wastewater treatment works in the City. However, on-site wastewater treatment facilities serve as an alternative future scenario aimed at producing potable quality water for private utilisation or sale.

7.3.4 Scenario 4: Decentralised Wastewater Treatment

Water scarcity and pollution threatens the well-being and growth of the economy. Consequently, the importance of water resource conservation and protection is inherently important to the industrial sector. The utilisation of greywater and harvested rainwater alleviates the demand for non-potable functions, however potable water requirements remain a large fraction of the total water demand.

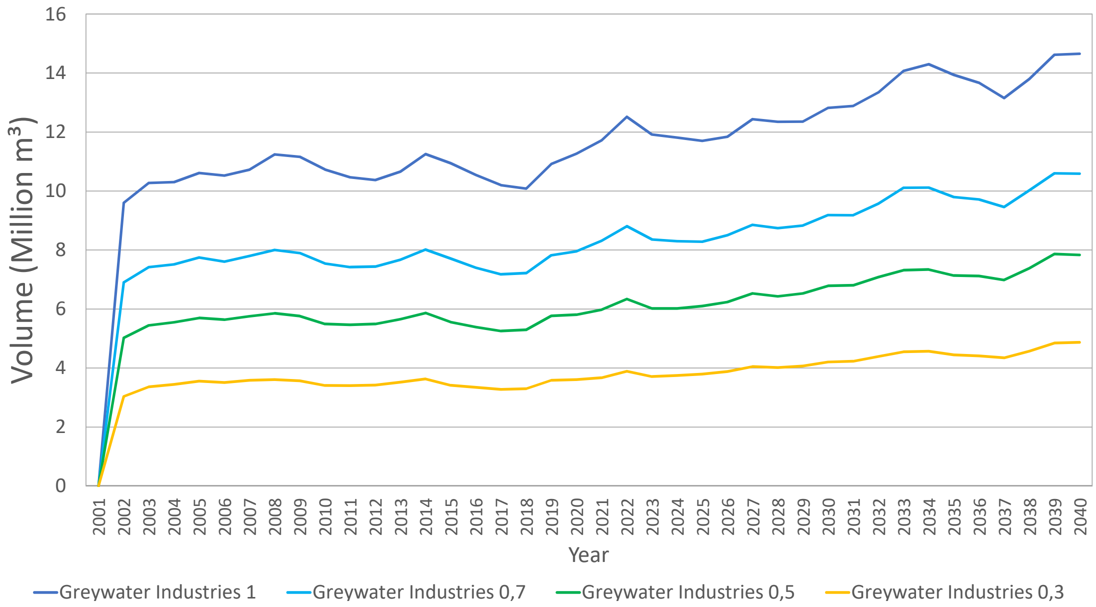


Figure 7.16: Scenario 3: Industrial Greywater - System Yield vs Industrial Greywater System Uptake

The assurance of water resources is another facet of importance to industry, as profit-driven operations depend on the availability of water. An alternative source of potable water can be generated through decentralised effluent plants. These plants may serve an individual industrial facility, or several. Large cities such as Beijing in China, have found that the popularity of decentralised reclamation systems has risen and become vital to sustainable water management (Libralato et al., 2011). Subsequently, the research study investigates the usefulness of these smaller industry based reclamation plants.

There are several wastewater recycling methods, technologies and applications. However, the model categorise the treated effluent as potable quality. The production of quality recycled wastewater reduce the reliance on municipal water resources and assures water supply for operation. Furthermore, the implementation may result in either an increase in total water usage, while remaining within the allocated municipal water constraints, or a reduction in total industrial water use. Unfortunately, the wastewater reclamation process is reliant on the volume input of wastewater. The model takes these restrictions and operational dependencies into account.

The case study conducted in Chapter 6 highlights several complexities that exist within a decentralised wastewater treatment facility. These complexities include the dependency on additional input sources such as groundwater and treated effluent from centralised sources to supplement wastewater produced on-site. Stormwater and rainwater runoff are also found to be likely sources of alternative input into the wastewater treatment facility. As losses occur within the decentralised system, municipal treated effluent is contributing towards the total inflow into the on-site system to supplement wastewater produced internally.

The case study utilises groundwater as an additional input into the potable water system. However, groundwater is treated to potable quality at a separate treatment unit which is directly connected to the decentralised reservoir. Other industries or commercial entities may differ, utilising groundwater as a direct input into the treatment plant without prior processing. Parameters are derived from case study findings and triangulated with reported information abstracted from regional documentation such as GreenCape reports.

During the initial model development, based on literature and technical reports, the model assumes that the output capacity of each decentralised wastewater treatment plant is based on 1000 m^3 per day process capacity. Thus, the system wastewater input needs to be slightly higher to compensate for the removal of solid waste and the internal water consumption of the system. The parameter *Fraction of Wastewater Transformed* is used as the compensating factor. However, the case study brought to light additional considerations. These include the consumption losses attributed to evaporation, irrigation and leaks within the system. As a result, wastewater produced on-site is significantly lower than initial operational output or actual consumption.

Using the fraction of actual consumption, based on simulation results and documented findings from the case study, the total volume of water eligible for wastewater generation is estimated. Subsequently, only a fraction (0.53) of total water demand is transformed into on-site wastewater for reuse, resulting in a shortfall in water production to meet internal water demand. As the decentralised wastewater treatment plant has the production capacity to meet the annual demand, additional inflows can serve to supplement the on-site generated wastewater. The additional inflows will allow for the production of additional recycled water. Alternatively, potable water from municipal sources will be required to meet the unmet demand. The key parameters for the decentralised wastewater treatment plant model is listed in Table 7.10. Both the original and adjusted models are generated to allow for comparison and further analysis.

Table 7.10: Scenarios 4: Industrial Decentralised Wastewater Treatment Parameters

Initial Model Parameters	**Value**	**Unit**
Fraction for Re-treatment	1	Dmnl
Fraction Supplemented	0.7	Dmnl
Initial Industrial Reuse Plant Capacity	0	m^3
Fraction of Wastewater Transformed	0.95	1/Year
Yearly Industrial Treatment per Facility	365 000	m^3/Year
Adjusted Model Parameters	**Value**	**Unit**
Fraction from Borehole	0.14	Dmnl
Fraction CoCT Treated Effluent	0.25	Dmnl
Fraction from Filtration	0.79	Dmnl
Fraction from Municipal (potable)	0.21	Dmnl

Municipal treated effluent is a popular alternative water source used to supplement wastewater inflow therefore, the system is reliant on the availability of treated effluent sources. Groundwater, stormwater and rainwater are other resources with the potential to supplement input into the wastewater treatment system. At present, for various health and economic reasons, the City does not allow for municipal wastewater from the main sewage system to be diverted into the decentralised system for treatment.

The financial implications are considered to evaluate the plausibility of such systems in the City of Cape Town's industrial sector. Larger companies, dependent on water resources for operation, find additional benefit in the assurance of supply and the reduced risk of operation loss. However, the spacial requirements limit the size of the effluent plants, thus several industry facilities may utilised a shared plant.

The economic growth results in an industrial production growth, which consequently generates additional wastewater. Furthermore, decentralised wastewater treatment plants require extensive capital investment and space to house the facility. The model investigates the production of treated effluent for reuse as a potable water source. Taking into account the cost and facility requirements, the model simulated the number of implemented facilities with a 1000 m^3 treatment capacity. Treatment plants were added in ten year periods from 2018, simulating 10, 20 and 30 plants as they accumulate over the time intervals in 2018, 2028 and 2038. The input requirements for generating potable water on-site is illustrated in Figure 7.17, using insights derived from case study findings and technical reports as stipulated in Table 7.10.

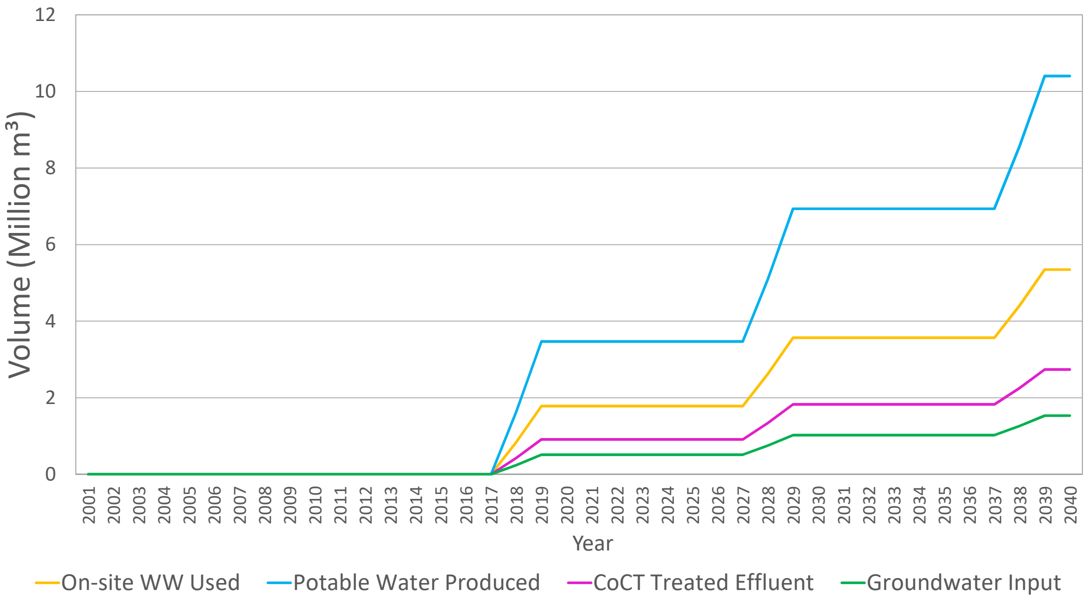


Figure 7.17: Scenario 4: Industrial Wastewater Generated with Input Requirements

However, the use of privatised treated effluent reduce the input into the municipal sewage system, resulting in less water waste reaching the centralised wastewater treatment plants in the City. The model accounts for this loss to the centralised system. Furthermore, there is additional benefit in utilising less municipal potable water. The high cost for both potable water and commercial sewage, which is calculated at up to 95% of the water consumption account, is significantly reduced.

Therefore, the cost and benefit of interventions for addressing water scarcity in the urban city is compared for evaluation. Subsequently, the results and insight provided by the model for the future scenario, ultimately serve as decision support for policy development and evaluation.

7.4 Cost and Benefit of Interventions

The financial benefit of implementing demand and conservation management interventions lie in ensuring sustainable water supply for economic and social growth, whilst creating employment opportunities. Furthermore, revenue water lost through leaks and system losses carry an economic value equivalent to associated water tariffs. The 2015 Water Demand Management and Strategy report provides insight into the economic benefit, in Rands, that can be achieved through water-loss reductions in the City of Cape Town (Flower et al., 2015). These costs are measured against the annual water savings (m^3) made by the associated intervention or mitigation activity. Therefore, it is important that the economic values should be standardised in Net Present Value (NPV) or a similar non-biased measuring method.

The consumption of municipal water by the domestic and industry sectors are compared for each iteration of intervention action. These actions include the reuse and retention of water streams in the urban city. Furthermore, the simulation baseline compares the implementation of water conservation and demand management activities. Thus, the cost and benefit of alternative sources introduced in the scenario discussion in §7.3 is measured against the constructed baseline. The baseline includes the utilisation of centralised treated effluent for industrial purposes, groundwater, water restrictions and fixed WCWSS water allocations.

7.4.1 Cost and Benefit: Domestic Users

Restricted water allocations regulate the consumption limit of domestic users based on the level of water in the major WCWSS dams. The model provides adjustment of *Consumption Efficiency* to better represent the real-world urban water system. Hence, several model parameters are fixed for evaluation purposes. These parameters and the associated values are captured in Table 7.11.

Table 7.11: Cost and Benefit: Domestic User Parameter Values

Parameters	**Value**	**Unit**
Consumption Efficiency	0.9	Dmnl
Fraction of Capita Using Greywater	0.5	Dmnl
Fraction of FHH with Rainwater Tanks	0.5	Dmnl
Calibrate Domestic Usage	0.8	Dmnl

Several waste streams have the potential to supplement non-potable water demand for domestic consumption, thus reducing the total municipal demand. During the simulation period, population in the City rise and as a result the total households too. Utilising 2018 as the reference point for investment cost, the cost and benefit is compared for supplementing domestic groundwater, harvested rainwater and generated greywater.

The model structure in Figure 7.18 use the parameter *Baseline ZERO supplement* and red arrows to remove or add intervention actions. These actions supplement the non-potable domestic demand, hence reducing the total demand on the municipal water system in the City of Cape Town.

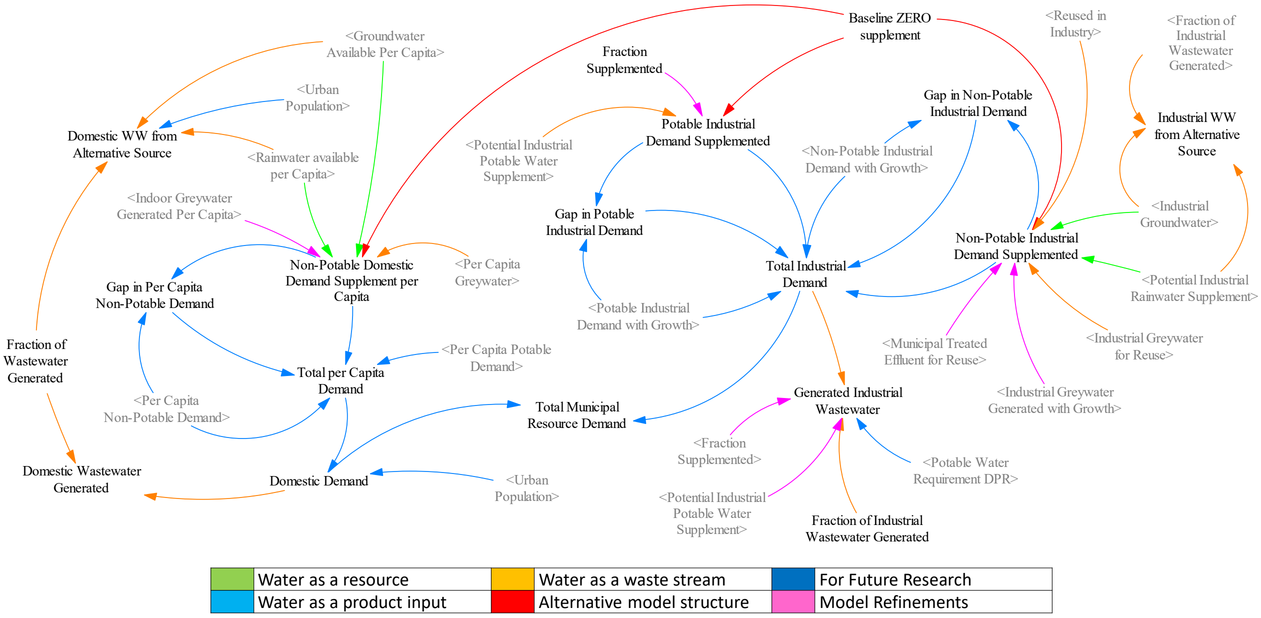


Figure 7.18: Model Structure for Municipal Demand

Furthermore, the potable demand for domestic use is solely supplied by municipal sources. Each supplementing source derived from urban water system waste streams are simulated and compared.

Domestic Rainwater Harvesting

Using the set parameters in Table 7.11, the *Fraction of FHH with Rainwater Tanks* are adjusted from 0.3, 0.5 and 0.7 for simulation. The total households are taken as the 2018 values to estimate the cost of generated annual non-potable water for indoor use. The results are summarised in Table 7.12 for review and evaluation. The unit cost per system is approximated at R25 000, estimating the price per m^3 at R250.

Table 7.12: Cost and Benefit: Domestic User Parameter Values

Fraction = 0.3	**Parameters**	**Value**	**Unit**
	Formal HH with Rainwater Tanks	311 914	Household
	Storage Capacity for Rainwater Harvesting	3 136 000	m^3/annum
	Cost of Domestic Rainwater	R 775	Million Rand/m^3
Fraction = 0.5	**Parameters**	**Value**	**Unit**
	Formal HH with Rainwater Tanks	519 857	Household
	Storage Capacity for Rainwater Harvesting	5 215 420	m^3/annum
	Cost of Domestic Rainwater	R 1 288	Million Rand/m^3
Fraction = 0.7	**Parameters**	**Value**	**Unit**
	Formal HH with Rainwater Tanks	727 800	Household
	Storage Capacity for Rainwater Harvesting	7 294 850	m^3/annum
	Cost of Domestic Rainwater	R 1 802	Million Rand/m^3

Popular water tank manufacturing companies, for example JoJo tanks, guarantee the water tank systems for eight years, however lifespans are known to exceed 20 years. For the model, it is conservatively assumed that the cost for the system, returns ten years of annually harvested rainwater. The cost per m^3 is found to be approximately R250. However, these systems have the potential to assure supply, harvest more than conservatively simulated, whilst operating for much longer. These factors will significantly reduce the per volume water cost.

What is more, the harvested rainwater serves to reduce the total demand for municipal water, thus resulting in a rise in water volume, which ultimately affects the level of water restriction implemented. This causal impact is described in Chapter 4.4.1 and Chapter 5.4.3. Subsequently, the simulation results provide comparative model response with changing domestic demand patterns as illustrated in Figure 7.19.

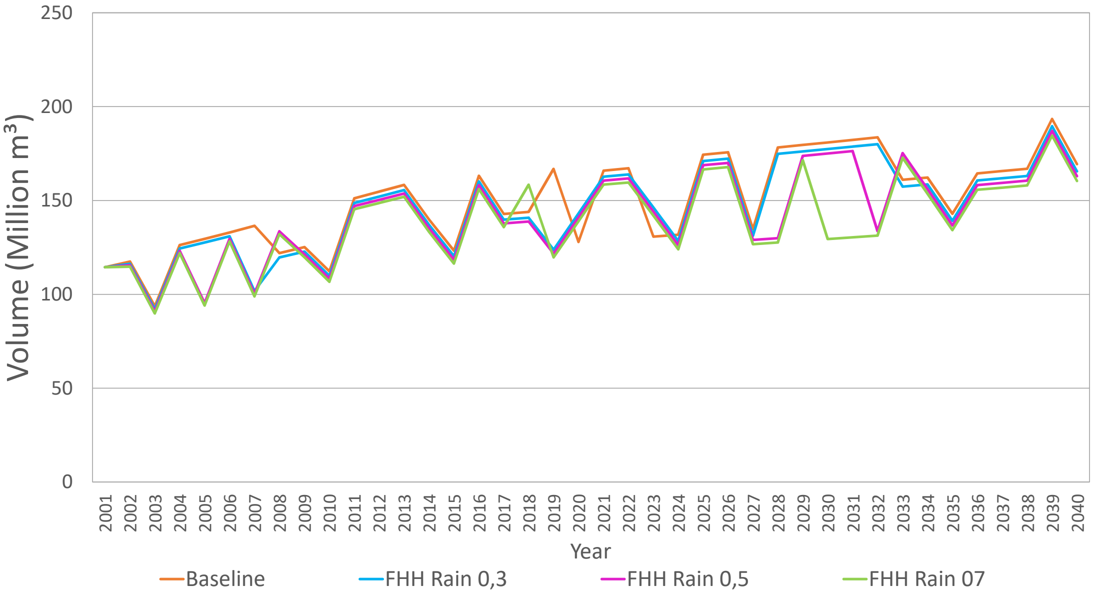


Figure 7.19: Domestic Demand for Municipal Water: Harvested Rainwater Supplement

The pattern indicates the change in implemented water restriction levels, which constrain and limit the domestic water consumption. The orange line represents the baseline, with no supplemented sources of water added to the system. Furthermore, the model indicates an overall reduction in water demand as a result of supplemented non-potable water demand from harvested rainwater.

The cost associated with implementing policy intervention actions relating to the installation of rainwater harvesting systems in the City of Cape Town is based on the total supplementing yield. Thus, total urban yield from rainwater retention depends on the total households implementing these systems. Other supplementary sources extracted from the urban water streams include the reuse of water within households.

Domestic Greywater Reuse

Domestic greywater is generated through the use and consumption of potable water supplies. Depending on the level of water restriction and allocation limits implemented at the present time, the fraction of potable water consumed varies. For the simulation, the *Fraction Greywater Captured* was established at 0.5 in §7.3.3. Furthermore, generated domestic greywater is reused for non-potable purposes, preferably indoor. Thus, reusing greywater for indoor functions ensures the continual flow of sewage to centralised wastewater treatment works.

Unfortunately, greywater cannot be stored without treatment, requiring sophisticated household greywater systems with water treatment processes, which are expensive to install. The average household size is becoming smaller, reducing the total household generated greywater. These systems can be shared among several households to divide costs and increase system input. The shared cost among households are based on R120 000 per greywater system installed for use among two to four households.

The high cost of system installation leads to the assumption that to improve the economic viability of the alternative resource approach, the system is shared among four households. The cost in 2018 is approximately R750 per m^3 if the life span of the system equalled one year. The life span of a sophisticated greywater system is 20 years. Using an conservative approach of a 10 year life span, the total water saved over the 10 year period is used to estimate the cost (Ilemobade et al., 2012). Subsequently, the cost per m^3 is taken over the combined water reuse production, which amounts to approximately R75 per m^3 using 2018 simulated values. The cost does not account for required maintenance on the domestic greywater treatment systems.

Nonetheless, a significant reduction in demand for municipal water resources are achieved through the process of greywater supplementation. Figure 7.20 shows the overall reduction in domestic municipal water demand. Although the usage patterns are out of phase with the baseline scenario, the oscillating behaviour of the system remains present.

Utilising both harvested rainwater and generated greywater as a source of non-potable water, the total domestic water demand prove to reduce considerably as illustrated in Figure 7.21.

However, it is unlikely that all households utilise greywater reuse systems. The simulation results in Figure 7.22 show the influence of changes in the *Fraction of Capita Using Greywater* systems have on the total municipal demand. A reasonable assumption estimates the *Fraction of Capita Using Greywater* to equate 0.5.

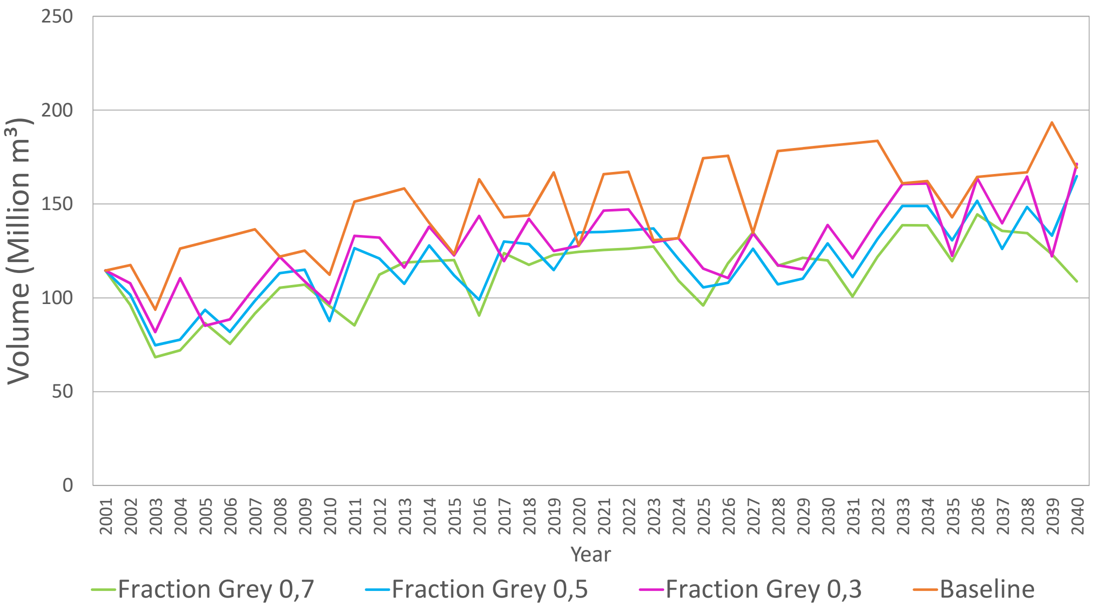


Figure 7.20: Domestic Water Demand with Domestic Greywater Supplement

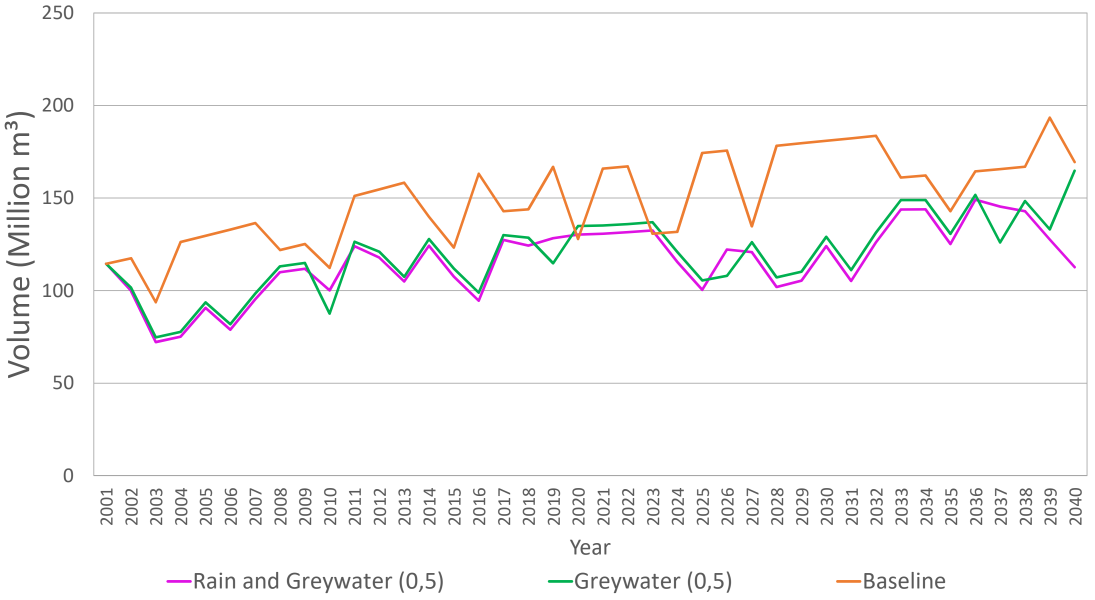


Figure 7.21: Domestic Water Demand with Domestic Greywater and Harvested Rainwater Supplement

The final supplementary source of non-potable water for domestic use is mostly utilised by higher income households. Groundwater is abstracted through boreholes sunk at residential homes used for non-commercial purposes to supplement non-potable water uses.

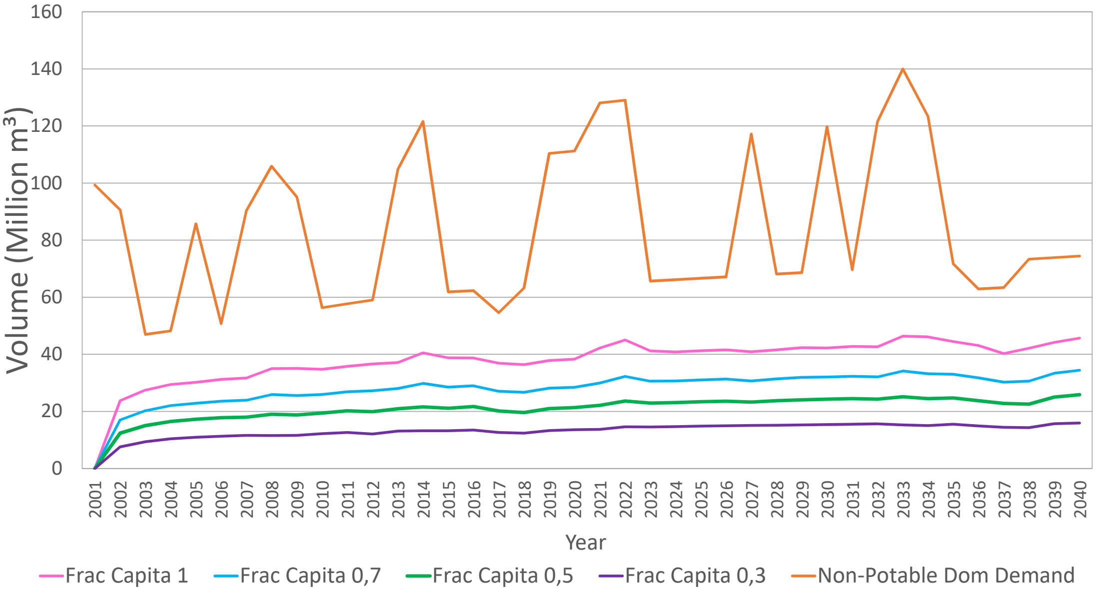


Figure 7.22: Domestic Water Demand with Domestic Greywater Supplemented by a Fraction of the Population

Domestic Groundwater Supply

Groundwater is traditionally used as a source of irrigation in domestic households. However, with the drive towards water conservation, regulations and restrictions are limiting the consumption and usage of groundwater resources in the City of Cape Town. Boreholes are expensive to install, costing up to R160 000 each. However, the abstraction of groundwater is limited to 40 m^3 per annum on a 1000 m^2 housing stand, which the City plans to measure and monitor in the near future.

Due to the cost of decentralised groundwater systems, approximately 2% of households in the City of Cape Town are utilising domestic groundwater to supplement non-potable water functions. With the constraints on irrigation application, the groundwater reservoirs require artificial recharge. City aquifers are generally recharged through artificial systems that utilise treated effluent and stormwater runoff to balance the groundwater resources.

Assuming that groundwater resources are not exploited beyond the regulated allowance, the portion of groundwater supplementing non-potable water use is relatively small. Figure 7.23 compares the *Total per Capita Demand* with different supplementing sources.

The baseline, orange line, is the demand supplemented only by domestic groundwater supply, whereas the light blue line indicate demand per capita without any alternative non-potable sources. The greywater reuse in green indicates the total demand when supplemented by greywater sources. Adding harvested rainwater sources to the greywater, the pink line shows the further reduction in demand with the combined supplementing sources of alternative water.

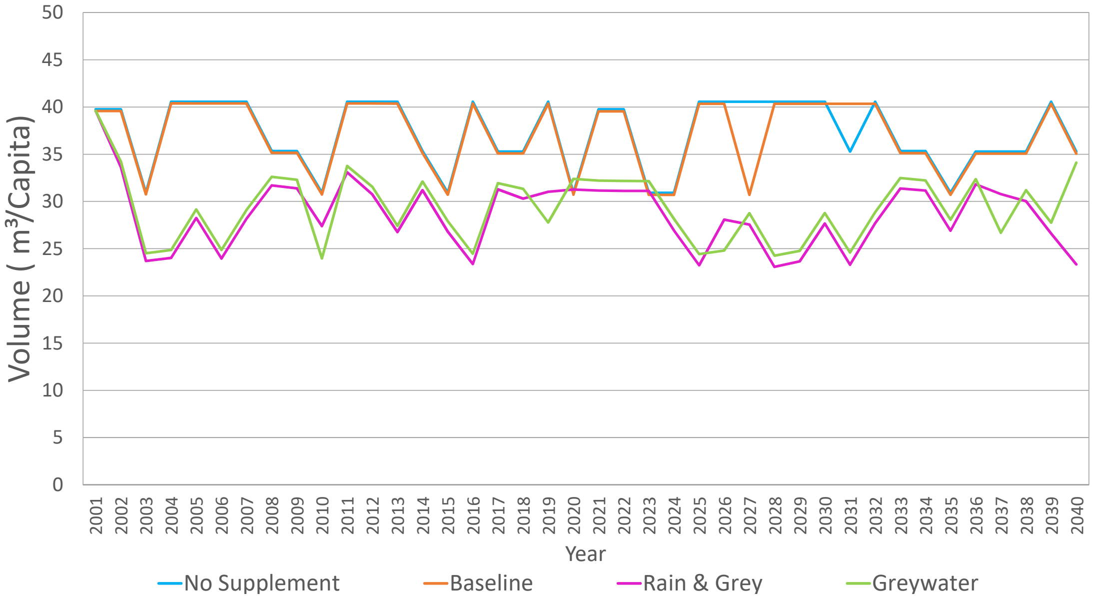


Figure 7.23: Municipal Water Demand with Domestic Groundwater Supplement

The cost consideration for groundwater consumption is not included in the policy evaluation testing. The research study aims to predominantly investigate the reuse and retention of alternative water streams in the urban city. Industry consumption can similarly be reduced through the utilisation of several alternative water sources.

7.4.2 Cost and Benefit: Industry Users

Industry users include municipal, commercial and manufacturing facilities, demanding 30% of the City of Cape Town's total water consumption. The economic dependency on water resources, emphasises the need for diversifying water sources and the conservation of available water resources. Restrictions on water consumption does not only affect residential entities, but the agricultural and industry sector too. The research study aims to evaluate several alternatives for supplementing and adding to the status quo consumption in the industry sector.

Industrial growth and implemented restrictions influence the demand pattern over the simulation period. Similarly to domestic consumption, the dam level triggers the implementation of several levels of water restriction. These restrictions impact the allocation of water resources. The model structure allows for the simulation of fixed allocations, 30% of constrained allocation (178 million m^3 per annum) at water restriction level 4 and higher or unconstrained (324 million m^3 per annum) City allocation at restriction level 3 and below. Alternatively, industrial consumption is based on the percentage saving required as per restriction level. This alternative provides a more realistic representation of consumption behaviour in the industry sector. Consequently, the industry water allocation and consumption is also constrained by water restrictions based on average dam levels in the WCWSS.

To meet the deficit between demand and allocated water, alternative sources of water are utilised. Rainwater can be harvested in larger volumes as a result of additional storage space and increased catchment areas (The National Academies of Sciences, 2016). Greywater reuse is another alternative waste stream capable of supplementing non-potable water requirements in the industrial sector. The economic reliance on water, requires an assurance of affordable water supply. Hence, the treatment of wastewater at decentralised locations for potable reuse is evaluated as an alternative source of water for industrial use.

To evaluate the model response to industries supplementing water sources, the *Baseline ZERO supplement* parameter in Figure 7.18 is used to zero the domestic and industrial supplementing sources. Individual sources of alternative water for use in the industry sector is investigated and simulated to provide insight into the behaviour of the system in-light of possible future scenarios.

Industrial Rainwater Harvesting

Harvested rainwater provides a relatively consistent quantity of non-potable water to industry, based on the storage capacity of the system and the annual rainfall. The parameters established in §7.3.2 set the capacity of industrial rainwater harvesting system at 100 m^3, with the total number of industries utilising the system ranging from 1000 to 50 000. Furthermore, the average rooftop catchment area is defined at 500 m^2 with a runoff coefficient set at 0.9.

The total cost for an industrial rainwater harvesting system is estimated at R250 000, based on the cost of a domestic system, times the increase in capacity of ten. The life span of the system is conservatively taken as 10 years, however these systems will ordinarily be functional over a longer period. The cost per m^3 is assumed conservatively at R250, taking the maximum yield as system capacity. In reality, these tanks can fill numerous times with adequate rainfall, mostly over wet winter months.

Generated rainwater yield supplement non-potable water demand, reducing the total demand for municipal sources. The *Total Industries with Rainwater Tanks* is simulated for 10 000, 30 000 and 50 000 facilities in the City of Cape Town utilising rainwater harvesting as a supplementary water source. The impact on *Total Industrial Demand* is shown in Figure 7.24.

Non-potable water demand accounts for 30% of industrial water allocation and can therefore, only be supplemented up to a point. The light blue line indicates the total industrial water demand when no alternative water sources serves to supplement total water demand. The baseline in dark blue indicates the pattern of demand for industrial water use with extensive municipal treated effluent and groundwater supplemented. Therefore, the baseline can provide sufficient non-potable water to industry when 30% of total industrial consumption can be met using non-potable water sources. However, the substitution of non-potable water to this extent only effect users with access to municipal sources of non-potable water. Therefore, it is important that decentralised alternatives be considered to assure water supply in the event that municipal water sources are not available.

The pink, orange and green line show the reduction in water demand, with the increase in industrial facilities utilising harvested rainwater as a supplementary source of non-potable water. To further reduce the municipal water demand and the dependency on groundwater and municipal treated effluent, additional supplementing water sources are exploited, which include the reuse of generated greywater.

Figure 7.24: Industrial Water Demand with Industrial Harvested Rainwater Supplement

Industrial Greywater Reuse

The reuse of generated greywater serves as an alternative source of non-potable water. Greywater is generated from industrial potable water functions such as rinsing, showers, hand-basin and similar water consumption activities. The *Fraction of Industrial Greywater Generated* is taken as 0.3 of the industrial potable water demand. Although, the consumption of municipal water is constrained by restrictions during periods of low water levels, the growth in demand is modelled to be in-line with economic growth of 1.5% per annum from 2017 (Adewumi et al., 2010).

The *Fraction of Industry Utilising Greywater Systems* are tested to evaluate the behaviour of the system. The simulation compares the *Total Industrial Demand* for fractions 0.3, 0.5 and 0.7. Subsequently, the comparison of water demand in Figure 7.25 shows that the utilisation of generated greywater in industry can significantly reduce the total municipal water demand by supplementing non-potable industrial water requirements.

However, the non-potable demand in industry for toilet flushing and cleaning is estimated at 30% of the total demand (Reddick and Fundikwa, 2018). Thus, supplementing sources may be in excess, which for the purpose of the model is assumed to be utilised for irrigation. Consequently, the lost fraction of water does not reach the centralised or decentralised wastewater treatment works.

The cost associated with the installation of a greywater system is taken as an equivalent to domestic reuse systems at R75 per m^3 in 2018. Therefore, the cost of the total water savings is based on the fraction of facilities in industry utilising greywater reuse systems to supplement their non-potable water demand. Alternatively, sophisticated decentralised wastewater treatment plants can be installed at larger industrial facilities to supplement potable water demand.

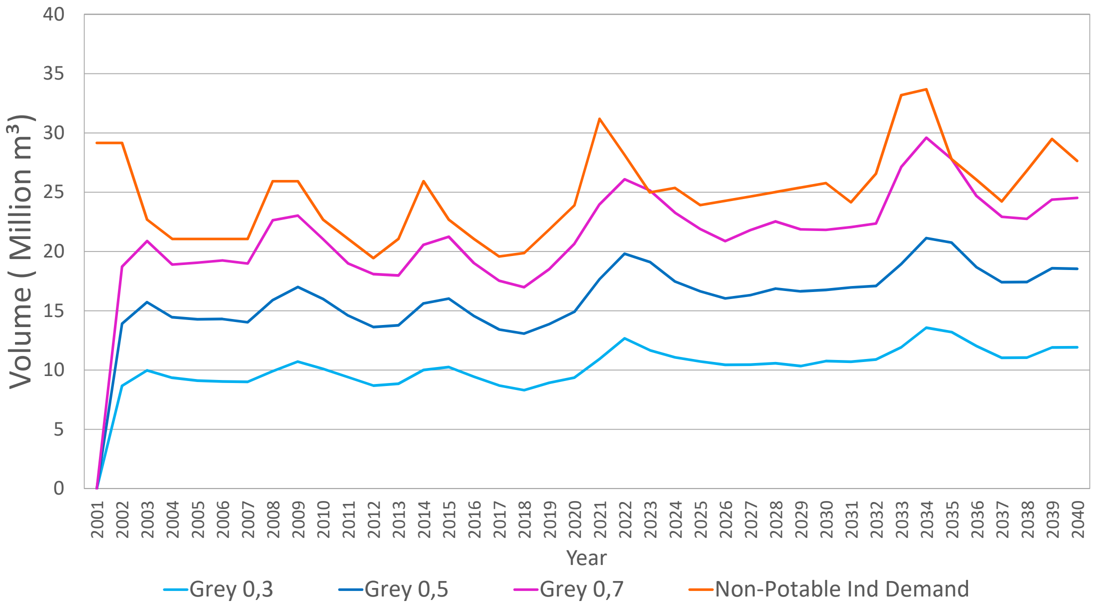


Figure 7.25: Industrial Non-Potable Water Demand with Industrial Greywater Supplement

Policy intervention for the utilisation of greywater systems require funding and incentives to realise potential yield and water savings from the implementation of decentralised greywater systems in industry. Pay-as-you-save initiatives by government entities are examples of encouraging waste stream utilisation for water conservation actions. This will provide alternative water options to new expensive water augmentation programmes, assuring the economic feasibility and availability of suitable water for economic investment in the City.

Industrial Decentralised Wastewater Treatment

The 2018 GreenCape Market Intelligence Report estimated the cost at R10-15 million per wastewater treatement facility with a production capacity of one million litres a day. Hence, the high cost and required facility area restrict the number of industrial users implementing such large and costly systems. However, the assurance of potable water for economic activities are essential and the reuse of potable quality treated effluent provides the benefit of added water supply.

The potable water demand in industry can be supplemented by the on-site generated treated effluent, reducing the demand on the municipal system. The generated wastewater is based on the sum of municipal and supplemented treated effluent water used, multiplied by the *Fraction of Industrial Wastewater Generated*. Furthermore, the *Generated Industrial Wastewater* is then treated on-site, with the excess discharged to centralised municipal wastewater treatment works. In most instances wastewater produced on-site is not sufficient for input into decentralised wastewater system to produce an adequate amount of usable potable quality water. Therefore, alternative inputs such as municipal treated effluent and groundwater sources are used to supplement input into the treatment plant. The required amount of municipal treated effluent is accounted for in the model, reducing the total volume of municipal treated effluent available to supplement industrial non-potable water requirements.

In §7.3.4, the total number of industry facilities with decentralised wastewater treatment plants were simulated and compared. The simulation found that 10 facilities per 10 year cycle, initiated in 2018, serve as sufficient representation of the addition water resources to the system.

Although the municipal demand is reduced through the supplementation of several alternative resources, the consumption and the associated waste generation in the model should account for the actual usage of total water resources. The supplemented potable water for industrial use varies with the *Fraction Supplemented*. In Figure 7.26, the quantity of water supplemented depends on the fraction of water used as an alternative source to municipal water. These reuse fractions were simulated for 0.3, 0.5, 0.7 and 1.

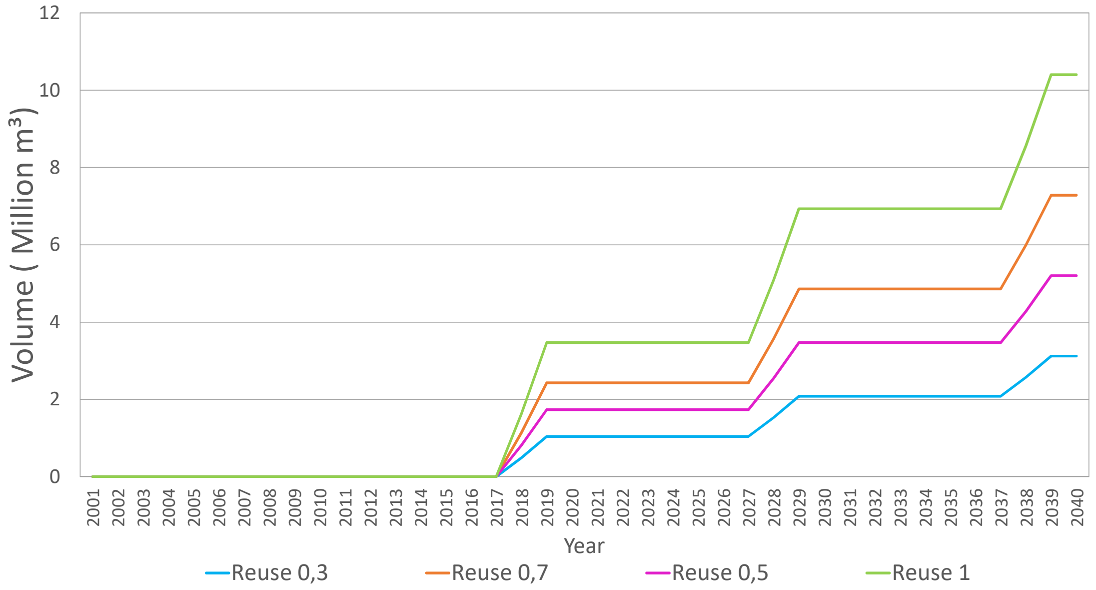


Figure 7.26: Industrial Water Demand Supplemented with change in Fraction Supplemented

The impact of several alternative water resources serving as supplementary supply to municipal water sources, influence the need for augmentation programmes. The annual yield for urban water usage is compared to the total urban water demand, with and without subsidiary sources. The cost of water waste stream alternatives and the benefit in terms of yield generation and sustainability of the urban city is evaluated for comparison to assist the decision making process.

7.4.3 Cost and Benefit: Total Urban Water System

A comparison of initiated policy actions in the City of Cape Town serves to establish the usefulness and feasibility of developed future scenario alternatives. To meet the objective of the research study, water streams in the urban water system are identified to evaluate the potential for value extraction. From these, the potential value is investigated, which aim to serve as alternative sources of water supply to ultimately reduce water supply stress experienced in the urban water system. The future scenarios are based on the utilisation of the identified water streams to address the water scarcity in the City of Cape Town.

Future augmentation plans include incremental implementation phases, of which the 2018/2019 planned projects are investigated to simplify cost evaluation and scenario comparison. The 2018 Water Outlook Report provide estimated capital expenditure budgets for several augmentation projects aimed at increasing water supply to the City of Cape Town. The additional 20 million m^3 yield planned over the 2018/2019 period for the city amounts to the cost as set out in Table 7.13 (CoCT, 2018a).

Table 7.13: New Water Augmentation Costs for 2018/2019

Water Source	Capital Budget	Operating Budget	Yield
Groundwater	R950 million	R163 million	10.55 million m^3
Water Re-Use	R560 million	R93 million	3.65 million m^3
Desalination	None	R415 million	5.8 million m^3
Total Cost	R 1 510 million	R 671 million	+ 20 million m^3

The additional 20 million m^3 added through the augmentation programme for 2018/2019, adds to the 178 million m^3 constrained allocation for the City of Cape Town (CoCT, 2018c). The new planned augmentation programme for implementation over the next ten years is set out in the 2019 Cape Town Water Strategy. The yield and cost distribution for the new water programme is allocated according to the augmentation phase, type and the year of planned implementation. Table 7.14 reflects on the initial (2020) augmentation portion of the new water programme as set out in the water strategy (CoCT, 2019a).

Table 7.14: New Water Programme Costs for 2020

Water Source	Capital Budget	Operating Budget	Yield
Cape Flats Aquifer P1	R610 million	R36.5 million	7.3 million m^3
Table Mountain Group P1	R375 million	R27.5 million	5.5 million m^3
Total Cost	R 985 million	R 64 million	+ 12.8 million m^3

For the model, the 2018/2019 values in Table 7.13 are used as reference for comparison with the costs of alternative water sources over the same time period for consistency. Further augmentation plans from 2018 to the end of 2026 aim to supply an effective yield of 154 million m^3, which include demand management interventions. With future augmentation plans forming part of the adaptable water programme to yield an additional 91 million m^3 by 2040 (CoCT, 2019a).

Contrary to water supply management, water demand management continues to reduce the dam draw-down. Demand management and conservation efforts and programmes have achieved 68% savings on water use from 2015, estimating the total usage reduction at 700 MLD. However, these water demand management interventions carry a cost. The 2019 Cape Town Water Strategy includes the water demand management effort for 2019 as part of the New Water Programme, estimating the capital cost at R410 million and an operating cost of R3 per m^3, effectively yielding 26 million m^3 per annum (CoCT, 2019a).

Additional costs are incurred with demand intervention activities through the decrease in water consumption, pressure management, addressing water losses and adding diverse water resource infrastructure. With the average budget on maintenance and upgrades approximating R1 billion per annum. The rise in costs and the reduction in revenue water consumption has led to higher water tariffs for the water users in the City.

The budget expenditure for the 2018 water demand management activities are estimated around R300 million. This budget excludes the asset replacement budget of R1 billion. Hence, the constructed system dynamics model aims to identify alternative water sources, to alleviate the water deficit in the City of Cape Town in an affordable manner, whilst utilising system waste streams and retaining water within the urban water system. This approach strives to ultimately improve the sustainability and well-being of the urban City of Cape Town.

The impact on municipal water demand is investigated through several simulation runs and future scenario developments.

Scenario 1: No Supplement and Baseline

The allocated water supply to the City of Cape Town with the planned water augmentation yield is used as the comparison for intervention policy actions. Water demand management and restrictions are still applied in accordance with water availability in the major WCWSS dams. Without supplementing sources of alternative water supply, or additional water allocation from the WCWSS, the municipal demand exceeds the available supply as seen in Figure 7.27.

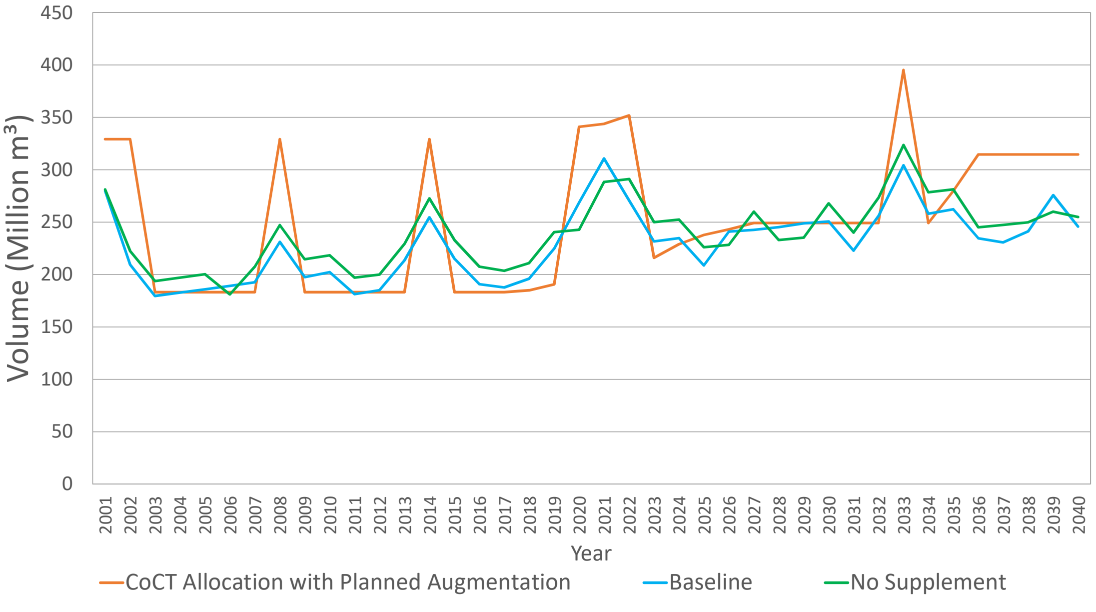


Figure 7.27: Scenario 1: City of Cape Town Water Allocation and Municipal Water Demand

Regardless of the additional yield added to the City of Cape Town allocation as a result of new water augmentation schemes, the water supply deficit continues to stress water allocation in the City. Even under strict demand management constraints with supplementing municipal demand, using groundwater and municipal treated effluent (Baseline), the allocated water yield to the City of Cape Town is exceeded. Subsequently, water stress continue to rise in the urban city.

Scenario 2: Rainwater Harvesting Supplement

Harvested rainwater from both industry and domestic entities results in a reduction in water stress, however the deficit is still pertinent as seen in Figure 7.28. The total volume of water supplemented per annum is restricted by the storage capacity of the rainwater harvesting systems.

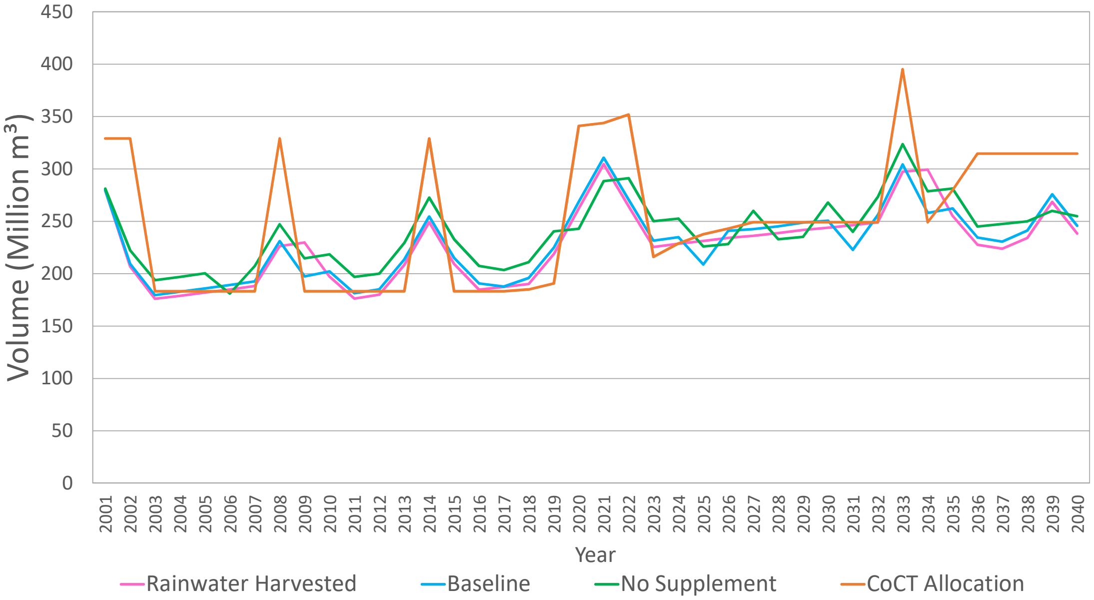


Figure 7.28: Scenario 2: The Impact of Rainwater Harvesting on the Municipal Water Demand

Table 7.15 summarise the total added yield per annum and associated cost of intervention, taking the number of industrial facilities utilising rainwater harvesting tanks at 10 000 and the fraction of formal households in the domestic sector at 0.5. With the resulting water supply stress value indicating that a shortfall in supply is still prevalent even with the supplemented harvested rainwater.

Table 7.15: Scenario 2: Comparative Cost and Benefit

Parameter	**Yield** (m^3)	**Cost** (Rand)	**URV** (R/m^3)	**Water Supply Stress**
Potential Industrial Rainwater Supplement	1 million m^3 per annum	R250 million	R250/m^3	1.1
Domestic Rainwater Harvested	5.15 million m^3 per annum	R1 288 million	R250/m^3	1.1

The rainwater harvesting system is based on conservative assumptions, of which the lifetime and water captured are underestimated. In reality, storage tanks can be filled numerous times. Thus, the cost per m^3 is halved when the assumption change that the rainwater harvested is doubled per annum.

Additionally, minimum maintenance and operational costs are associated with the collection of rainwater runoff for supplementing non-potable water function in both industry and households. Furthermore, the added benefit of reducing stormwater runoff, alleviates pressure on the sewage system, subsequently preventing damage and health risks. These additional benefits, along with water assurance, support the policy development relating to the implementation of rainwater systems in the City of Cape Town.

Water stress measured in 2018 is above one (1), indicating that the deficit still exists. Hence, additional water sources are required to meet the total municipal demand and reduce water supply stress in the City.

Scenario 3: Greywater Reuse Supplement

Greywater reuse allows for the reduction of total water demand from the municipal system relative to the utilisation of potable water consumption. The *Fraction Greywater Captured* for domestic reuse is established at 0.5, while the *Fraction of Industrial Greywater Generated* is fixed at 0.3. The utilisation of greywater systems is further influenced by the *Fraction of Capita Using Greywater* systems and the *Fraction of Industry Utilising Greywater Systems*, which are set at 0.5 and 0.7 respectively. The quantity of potable water consumption influence the generated greywater, subsequently affecting the total water demand and the WCWSS dam level.

The cost of installing greywater systems to a significant fraction of the 1.29 million households in the urban city is a costly initiative. However, several incentive schemes and funding options may alleviate the total municipal cost. The model estimate the cost per m^3 to be approximately R75 for domestic greywater systems. This cost is translated to industry based systems, as the yield calculation is based on the fraction of potable water consumed by industry and not per facility.

Domestic greywater systems is assumed to be shared among four households with an estimated cost of R120 000 per sophisticated greywater system, with a 10 year lifespan. The operating and maintenance costs are low in comparison to reticulation system upkeep, limiting the majority of cost to capital expenditure. Subsequently, the simulation results stipulate the potential yield supplemented by greywater reuse in the City of Cape Town in Table 7.16. Based on simulation results in Figure 7.29, the reduction in water supply stress indicates that the municipal demand can be sufficiently subsidised by greywater in 2018 for the City of Cape Town yield to meet the demand.

Table 7.16: Scenario 3: Comparative Cost and Benefit

Parameter	**Yield** (m^3)	**Cost** (Rand)	**URV** (R/m^3)	**Water Supply Stress**
Domestic Greywater Generated	20.9 million m^3 per annum	R1 570 million per annum	R75/m^3	0.7
Industrial Greywater for Reuse	7.7 million m^3 per annum	R580 million per annum	R75/m^3	0.7

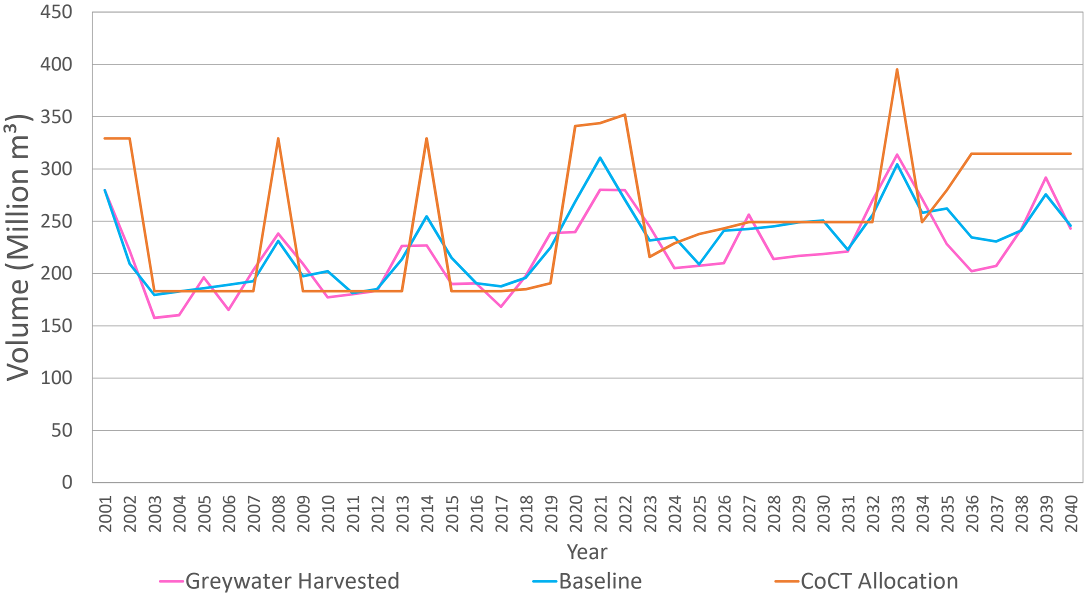


Figure 7.29: Scenario 3: The Impact of Greywater Reuse on the Municipal Water Demand

The 2017/2018 potable water tariff costs for basic domestic water in the City of Cape Town reach up to R26.25 per m^3 without taxes and penalties for high rates of consumption. What is more, the potable water for industrial use is higher at close to R60 per m^3, with large penalties for consumption over restricted allocation (Reddick and Fundikwa, 2018). Based on scenario assumptions and simulation results the cost to the consumer associated with alternative sources of water extracted from waste streams are becoming more economically aligned with municipal water sources.

Subsequently, water is a requirement for the health and well-being of the City, with economic value in the commercial and industrial sector. For the model the total saving on municipal water sources achieved through the utilisation of greywater is conservative. Several households practice greywater harvesting principles using the bucket system to store and reuse captured greywater. Thus, the cost is likely to be overestimated, while the yield may be significantly higher. The cost is estimated as a per annum expenditure, increasing the implementation of formal systems over the simulation period.

However, greywater only serves as a supplementary source for non-potable usage, which does not address the totality of municipal water consumption. Potable water sources, especially in industry, carry high economic value as it is essential to operation. Hence, alternative sources of potable water is considered. Traditionally, municipal sanitation services are responsible for the transfer of wastewater to central wastewater treatment plants, where water can be treated to near potable quality through specialised and sophisticated treatment processes for reuse in industry.

However, high water dependent businesses with extensive water requirements may consider a decentralised alternative. Although the capital and operating cost of decentralised wastewater treatment plants to supplement water requirements are high, the potential benefit may prove to outweigh the costs. Continual tariff increases and further restrictions with reduced water allocation, serve as additional drivers for the uptake of private effluent plants in industry.

Scenario 4: Decentralised Wastewater Supplement

The 2017 GreenCape Market Intelligence Report investigated the case for private treatment of wastewater for high water users in industry. The case included a cost comparison to evaluate the economic feasibility of generating potable quality water from wastewater at decentralised facilities. The case found that the repayment period for the investigated decentralised wastewater treatment facilities is five years, due to lower sanitation and water tariff payments.

For the case, the reuse of water is estimated at 65%, with the annual treatment capacity of 365 000 m^3 per facility (Bronkhorst, Pengelly, et al., 2017). As water is a direct risk to the majority of businesses, the installation of decentralised wastewater treatment plants become an attractive option. To refine the model based on findings from the GreenCape report, a single case study was conducted to extrapolate further information and data from a real-world application. The study brought to light several limitations and requirements associated with the operation of a decentralised wastewater treatment system. The model has been refined to incorporate the requirement for additional inputs, such as groundwater and municipal treated effluent, as a result of system losses.

Barriers to the uptake of these facilities include the high capital cost, health risks and plant area requirement. Consequently, the model simulated the introduction of ten private wastewater treatment plants every ten years, with the first initiated plants introduced in 2018. Subsequently, the potential potable water generation rise from zero to approximately 10 million m^3 by 2040.

The cost of ten decentralised potable quality wastewater treatment plants in the City of Cape Town for 2019 is captured in Table 7.17. 2019 results are used, as the impact of implementing the first 10 decentralised wastewater systems only present in 2019. The associated yield is based on the per plant capacity of 365 000 m^3 per annum with the *Fraction Supplemented* set at 1 (100%). However, the water supply stress is above 1, which indicates that the treated effluent subsidising the municipal water is not sufficient to address the supply deficit in 2019.

Table 7.17: Scenario 4: Comparative Cost and Benefit

Parameter	**Yield** (m^3)	**Cost** (Rand)	**URV** (R/m^3)	**Water Supply Stress**
Industrial Reuse Plant Capacity	3.47 million m^3 per annum	R76.3 million	R22/m^3	1.12

The reuse of wastewater, reduces the amount of effluent diverted to the City's centralised wastewater treatment works. The model accounts for the reduced volume of sewage entering the municipal reticulation system. According to the financial model in the 2017 GreenCape Market Intelligence Report, the capital cost per facility is approximated at R40 million, with operating cost at R2,37 million per year. Additional cost include the per unit treatment cost of R10 per m^3 (R3.65 million). Thus the unit cost of R22 per m^3 is based on the costing model for the utilisation of decentralised effluent plants in industry.

The reduction in *Total Municipal Resource Demand*, reduce abstraction from raw water resources. This influences the dam level, resulting in lowered restriction levels, consequently increasing consumption. The oscillating behaviour is evident in Figure 7.30, illustrating the impact of intervention actions on water consumption behaviour.

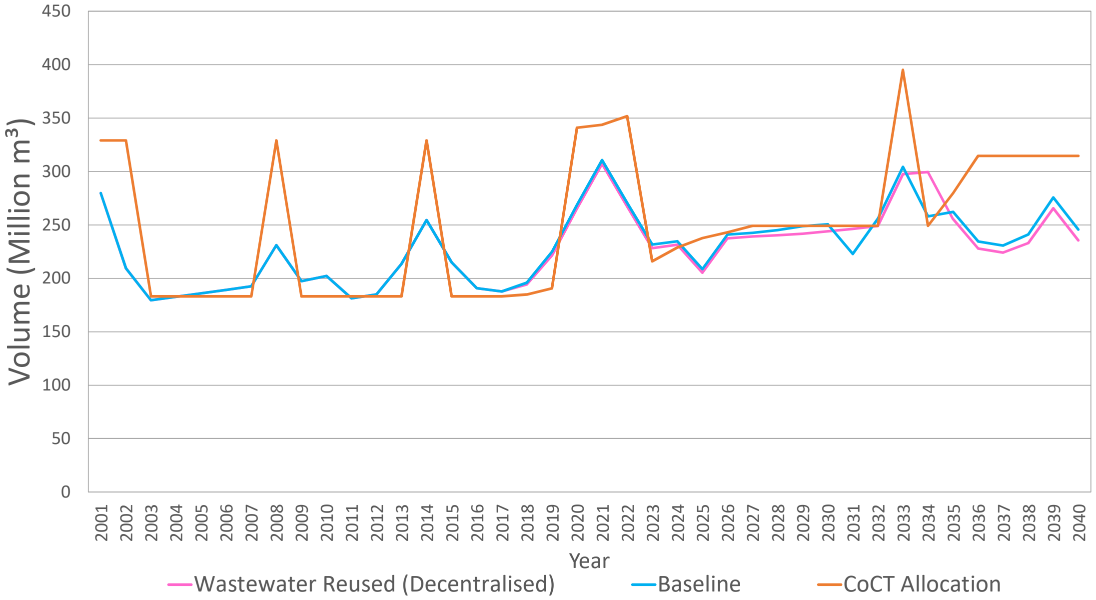


Figure 7.30: Scenario 4: The Impact of Supplementing Decentralised Wastewater on the Municipal Water Demand

To further the evaluation of policy alternatives for future scenarios, the combination of several interventions are investigated. These combinations serve as a separate scenario future for improving water availability in the City of Cape Town.

7.5 Scenario 5: Combined Intervention

Evaluating the combined impact of several intervention scenarios provide decision-makers with insight into the behavioural response of the urban water system. These interventions are combined to supplement both domestic and industrial municipal water consumption.

The total implementation of alternative scenarios to collectively reduce the pressure on the municipal water system and therefore, water supply stress, is illustrated in Figure 7.31. The graph compares the planned yield increase to potential policy alternatives for retaining and reusing water streams in the urban water system.

The results in Figure 7.32 indicates a potential saving of 37 million m^3 in 2020 against baseline consumption, however the savings differ and decrease as time progress. The 2020 values are used to ensure the inclusion of decentralised wastewater treatment facilities' yield and the model oscillation.

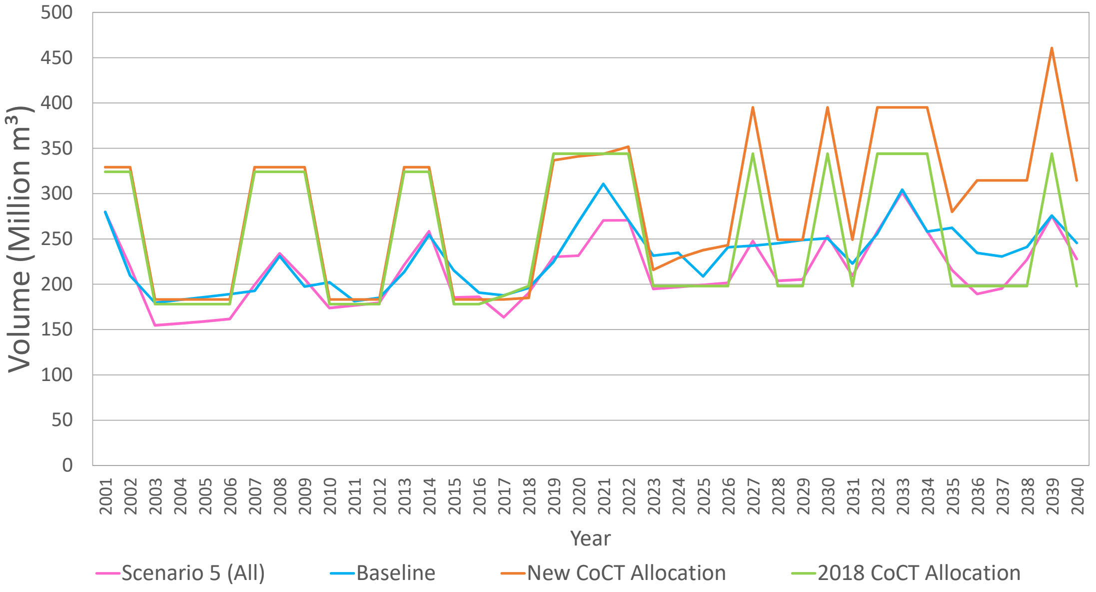


Figure 7.31: Scenario 5: The Impact of Combined Alternatives on the Total Municipal Demand

The saving is more than sufficient based on the 20 million m^3 increase planned over the 2018/2019 period. However, as the demand for industrial and domestic water requirements grow over the simulation period, subsequently the spare capacity declines.

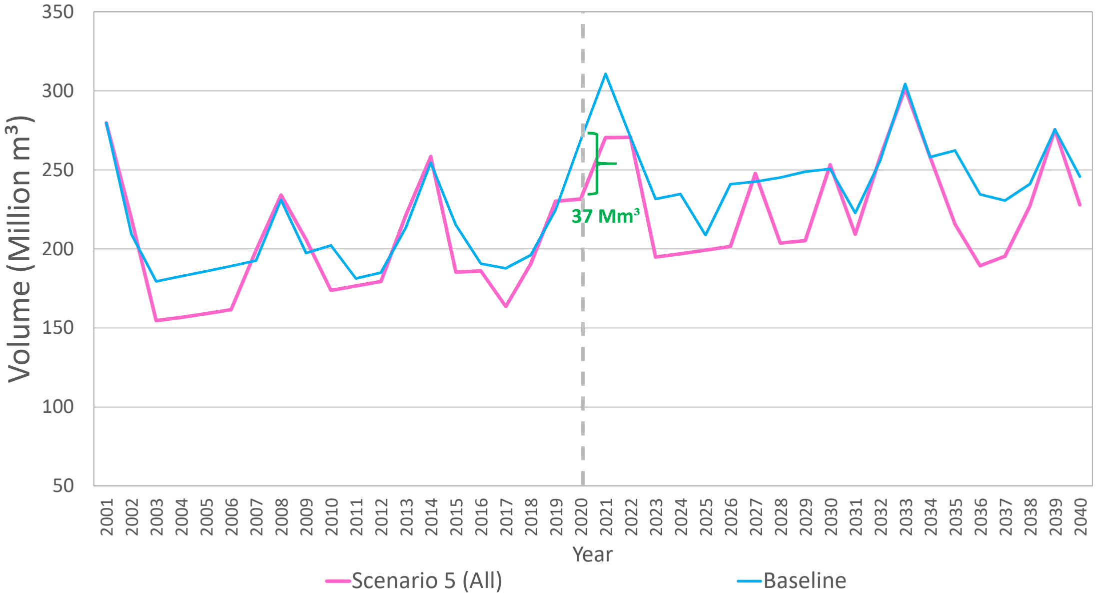


Figure 7.32: Comparison of Total Municipal Demand for Baseline Scenario 1 and Scenario 5

Consequently, additional yield and water sources are required to avoid water supply deficits in the City of Cape Town. Even though urban water waste streams and the retention of alternative sources serve as suitable substitutions to scarce raw water sources.

Due to the dynamic behaviour of the urban water system and the response to water demand, the water supply stress experienced in the City is not linear. The displayed behaviour is oscillatory in nature, responding to unconstrained and constrained allocation of water resources. This response is inherent to the baseline behaviour in Scenario 1, where water restrictions determine the water allocation to the City of Cape Town.

The water supply stress experienced in the urban water system is taken as the fraction of demand over available yield, which varies over the simulation period. The increase in system yield for the City of Cape Town accounts for the new planned augmentation initiatives set out in the committed and adaptable water programmes. Subsequently, a value less than 1 indicates an excess in yield, reducing water scarcity experienced in the city. For water supply stress values above 1, the deficit in supply place strain on the available water sources. This behaviour is illustrated in Figure 7.33, which also shows the oscillating behaviour of the system. It is also apparent from the results that the increase in augmentation schemes as time progress reduces the water supply stress in the urban water system.

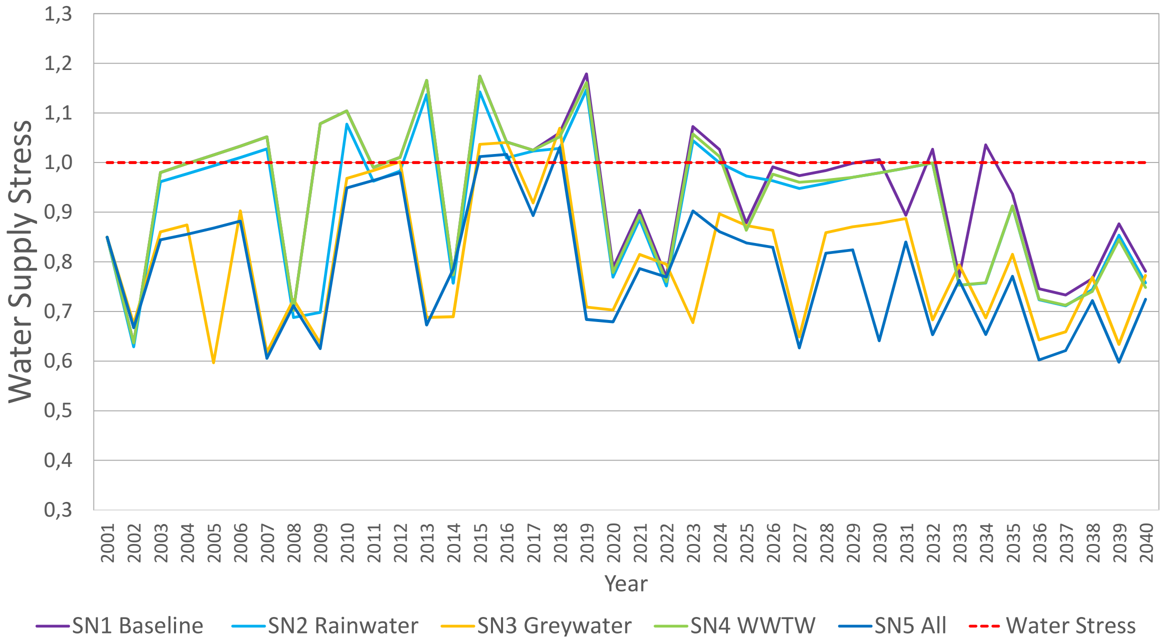


Figure 7.33: Scenario 5: Water Supply Stress

The comparison of alternative future scenarios provide further insight into the system response when extracting value from several water streams simultaneously in the urban water system.

7.6 Result Comparison

Due to the dynamic behaviour of the system, the cost and yield comparison for the future scenarios are based on 2018/2019 values and quantities. Scenario 1 incorporates constrained water allocations and water restrictions as part of the City's demand management initiatives. However, it is assumed that the implementation of restricted allocations in the model is strictly adhered to by both industry and domestic users. This is not a complete representation of real-world behaviour. Nevertheless, it is assumed that the model response is sufficient.

The 2018 water programme plan to add an additional yield of 20 Mm^3 per annum in 2018, at a capital cost of R1,51 billion with a further R671 million per annum operating cost. The cost of maintaining current reticulation infrastructure and demand management is not incorporated in the cost comparison to simplify the evaluation of possible future alternatives.

Scenario 2 investigated the potential use of both industry and domestic harvested rainwater to substitute non-potable water demand. Although the generated yield is taken conservatively, this source of water serves to provide a relatively consistent yield, with low operation and maintenance costs. Due to the conservative nature of the evaluation, the cost were found to be extensive, at R250 per m^3. Realistically, this value can be reduced with changes in assumptions. The 2018 rainwater harvested for both industry and domestic systems amounts to 6.15 million m^3.

The reuse of greywater, generated by several potable water use activities, is investigated as a potential alternative water source in Scenario 3. Although the cost of sophisticated greywater systems are higher than rainwater harvesting systems, the potential yield is greater. The total greywater generated depend on the total potable water consumed by both industry and domestic users. Thus, the yield varies from year to year. For consistency, the price per m^3 is used based on the 2018 simulated results, which is estimated at R75 per m^3. For 2018 the total greywater yield for non-potable usage is totalled to 28.6 million m^3 at a cost of R2 145 million.

To supplement potable water demand in industry, the utilisation of private decentralised wastewater facilities are evaluated in Scenario 4. Barriers include health risks, space requirement, system losses and capital costs. However, the benefit is water assurance for economic and operational growth. The model simulated the implementation of ten facilities in 2018, with ten more in 2028 and 2038. Each facility serves to treat and provide 365 000 m^3 per annum. The yield added in 2018 equals 3.47 million m^3 at a cost of R22 per m^3, totalling to R76.3 million.

The combined benefit of implementing several alternative water sources, extracted from waste streams in the urban water system is explored in Scenario 5. This scenario found that a saving of approximately 37 million m^3 per annum in municipal water consumption can be achieved through the total implementation of all alternative waste reuse sources and retention of water streams. Subsequently, the combined alternative does not result in equal costs and yields as per individual simulated scenarios. This is due to the dynamic nature of the system, responding to the demand and supply patterns inherent in the system.

The scenario comparison with regards to achieved per annum yield and cost factors are summarised in Table 7.18.

The cost and yield values used in the comparison table are estimations based on assumptions made from literature. No actual costing structure for municipal implementation of alternative water streams are available for the City of Cape Town. Nevertheless, these estimations are sufficient for the purpose of the model and can be refined with actual values or costing.

Table 7.18: Comparison of Scenario Benefit and Cost

Scenario	**Yield** (m^3)	**Cost** (Rand)	**URV** (R/m^3)	**Water Supply Stress**
Scenario 1	20 million m^3	R 2 181 million	R109/m^3	1.2
Scenario 2	6.15 million m^3	R 1 538 million	R250/m^3	1.1
Scenario 3	28.6 million m^3	R 2 145 million	R75/m^3	0.7
Scenario 4	3.47 million m^3	R 76.3 million	R22/m^3	1.12
Scenario 5	37 million m^3	R 3 952 million	R105/m^3	0.67

The system dynamics model for the urban water system serves to provide insight into the behaviour and causal links in the complex urban water system. Investigating the response of the modelled system in relation to developed future scenarios provides insight and understanding. Thus, the decision making for policy implementation and evaluation is supported through the exploration and refinement of scenarios and model structure.

7.7 Conclusion

Information and data from literature studies and available public documentation regarding the water shortages in urban cities are used as the basis on which potential future scenarios are developed. Water management, legislation and planned programmes are assessed to identify potential water streams for reuse and retention in the urban City of Cape Town. Therefore, scenario development revolves around the value extraction from water streams, to ultimately zero water system waste and minimise raw water abstraction.

To compare and evaluate the cost and benefit of each constructed scenario, a baseline is established. The baseline scenario is modelled and simulated to incorporate the City's demand management interventions and augmentation plans. What is more, the baseline is set as the first scenario, which provide decision-makers with a point of reference, against which alternative scenarios are measured and compared.

The scenario development investigated the utilisation of rainwater harvesting, greywater reuse and decentralised wastewater treatment respectively. These alternative scenarios aim to serve as supplementing sources of water to alleviate the total municipal demand and reduce water supply stress in the urban City. The final scenario simulates the combined impact of utilising all modelled supplementary sources from identified water streams simultaneously.

It was found that the model responds in an oscillatory manner, reacting to the reduced water scarcity, thus increasing allocations. The rise in consumption results in water supply stress rising and water demand interventions increasing, reducing urban consumption. Ultimately, the scenario development and exploration phase serve to expand stakeholder thinking, allow for reflection on outcomes, while providing clarity or confirmation on certain aspects of the urban water system model.

Chapter 8

Conclusions and Recommendations

> *"Once we shift our paradigmatic perspective to recognise that nature system is a complex and dynamic social-ecological system, it is evident that we need to think regarding coupled systems in which change is large-scale, often non-linear, frequently fast and sometimes irreversible."* – Young and Steffen (2009)

The aim of this chapter is to provide recommendations and insight based on findings and results from the previous chapters. The goal of the research study is to provide decision support to policymakers for the evaluation of regulations aimed at sustainably alleviating water stress in the City of Cape Town. More specifically, evaluating regulation intent on extracting value from water streams within the urban water system, to serve as potential water sources for the City.

8.1 Summary of Research Results

Water scarcity is a global occurrence, worsened by the continual growth in population, urbanisation and economic activities. Urban cities are becoming more water stressed as the demand for water continues to grow. Subsequently, traditional water supply augmentation and demand management initiatives are no longer sufficient for addressing the continuous increase in demand, the growing water pollution and the unequal distribution of urban water sources.

It is evident from literature that an integrated water management approach is a suitable alternative for addressing water scarcity in urban cities. Hence, alternative sources of water from waste streams are incorporated in the total management approach. For integrated management, water policies and legislation serve to address water shortages in urban cities through laws and guidelines. These regulatory documents stipulate how demand management, water conservation, augmentation schemes and the retention, reuse and reduction of water streams in the urban water system are implemented.

Several methods for policy evaluation and testing are investigated to identify a suitable approach to evaluate regulatory documents aimed at ensuring sustainable and equitable water for the future in the City of Cape Town. System dynamics is a modelling approach proven to assist decision-makers in the policy environment. The modelling tool allows for the construction of the complex and dynamic urban water system model, using directional links to connect system parameters. Mathematical equations are used to represent the behaviour of the system variables, while causal loops connect the interacting and directional behaviour among system elements.

Once the constructed model is validated and it is ascertained that the model is fit for purpose, adjustments are made to the model for scenario testing. Scenarios for future water systems in the City of Cape Town are evaluated, using these adjusted system dynamics model structures. The dynamic structures assist with identifying likely behavioural responses, represented as graphical system parameter graphs. Multiple simulation runs with varying parameters serve to provide insight and understanding into the behaviour and reaction of the urban water system.

Five scenarios were developed and tested, with the first scenario serving as the baseline against which the other four alternative scenarios are compared. The use of harvested rainwater, the reuse of greywater and the reuse of wastewater for potable usage are investigated as individual intervention scenarios. Finally, the fifth future scenario investigates the combined intervention response to water supply shortages in the City of Cape Town.

Decision-makers can use the simulation results to analyse and interpret the information and system behaviour for evaluating and testing various policy alternatives, aimed at extracting value from water streams within the urban water system. Subsequently, the value extracted from these water streams are tested for its ability to address water scarcity in the City of Cape Town through the reuse, retention and usage reduction of water sources. Recommendations are made based on findings, shortcomings and results obtained from the model and scenario testing and evaluation.

8.1.1 Business as Usual

The business as usual scenario investigates the model's response to several demand management and water conservation initiatives currently employed in the City of Cape Town. Findings include the growing water supply deficit in response to reduced demand management and water conservation activities. Thus, water restrictions serve as the major contributor to the behaviour of the urban water system.

Without demand management intervention, the total industrial and domestic consumption far exceeds the City of Cape Town's available water resources. Therefore, city consumption patterns have a direct influence on the available water supply. Without restrictions and measures to constrain water allocation, the simulation indicates that the Western Cape Water Supply System (WCWSS) will be depleted.

However, during constrained water allocation and restricted usage, the volume of revenue water sold is severely diminished. This reduction in municipal income is substituted through changes in the tariff structure. Stepped tariffs and punitive cost are used to facilitate the conservation of water in the City, using incremental charges based on the volume of water usage. As a result of demand management activities, the cost per volume is increased during reduced water sales to compensate for revenue lost. However, the increase in cost to the consumer inhibits investment and therefore, economic growth and employment opportunities within the City.

It is recommended that the City of Cape Town Municipality evaluate alternative revenue sources to meet the shortfall in income. Thus, finding a more drought resilient approach to substituting the nearly R2 billion revenue loss as a result of a significant drop in water sales. Increasing user tariffs may have detrimental social, political and economic results. A thorough feasibility study in relation to costing, funding and water demand management interventions is suggested.

As a result of rising costs and the declining availability of surface water resources, national and provincial regulation aims to regulate the consumption, whilst diversifying the water yield for the City of Cape Town. Providing residents and industry with the ability to reuse and retain water streams in the urban water system may serve to be mutually beneficial. Incentive schemes, changes in tariff structure for water and sanitation services, provision of alternative sources and educational programmes are some of the suggested routes identified in literature that government can evaluate to address water scarcity.

Furthermore, it is recommended that demand management activities continue to constrain wasteful consumption of scarce resources. Educational campaigns have changed water use behaviour in the City of Cape Town, curbing the responsive increase in demand with lowered water restrictions, as conservation becomes inherent to consumption behaviour. In addition, the continual management of water pressure and loss in the reticulation system is also recommended to curb the loss of treated water through leaks and faulty connections. However, additional interventions are required to address the growing demand in the urban city, which include the reuse and retention of alternative water sources.

8.1.2 Rainwater Harvesting

Due to urban build-up, strong rainfall result in excessive amounts of runoff. With severe rainfall, runoff can result in urban flooding which cause major infrastructure damage in the City, harm natural ecosystems and ingress into sewage systems. Subsequently, urban runoff is a risk to the City's economy, health and environment. The filtration into aquifers are also hindered by paved and built-up areas, limiting the recharge of natural resources.

Harvesting rainwater in urban cities not only provide water assurance to households and industry, but capture runoff to ultimately reduce stormwater runoff. However, during peak rainfall, rainwater harvesting is limited to the storage capacity only attenuating peak flows to an extent. Changes in urban design carry the potential to divert, store and filtrate urban runoff further. The benefit associated with implementing rainwater harvesting systems to capture rainwater runoff may extend further than providing a supplementing water source for non-potable usage.

The sophistication and application of rainwater harvesting systems vary. Basic structures can capture rainwater from rooftops with minimum adjustments or changes to the households or industry structures. Larger more sophisticated systems may include filters, internal plumbing, pumps and meters. Therefore, system cost may differ significantly based on the sophistication and requirements of the rainwater harvesting system.

Traditionally, harvested rainwater has been predominantly used as a water source for irrigation, however it is recommended that guidelines and legislation shift the application of this retained water stream to indoor usage. Direct plumbing to household or industry facilities can channel captured water to non-potable uses, such as toilet flushing. Subsequently, reducing the total demand for municipal water. In the case, where water serve to supplement the total usage, the loss in revenue based water sales should be evaluated.

Alternatively, retained water may serve as an additional source of water, improving the standard of living in households and industry. The increase in sewage, based on metered consumption, should also be considered as the inflow is potentially adding additional pressure to the reticulation system. This is unlikely to be the case in drought periods, when the metered water consumption is significantly lower than the reticulation design capacity. Furthermore, the additional inflow may prove to be beneficial to the movement of sewage in the system during constrained use periods.

It is recommended that subsidies and pay-back initiatives for funding the installation of rainwater harvesting systems be investigated. These incentives or repayment loans may further benefit the fixed monthly income assurance, whilst alleviating pressure on scarce water resources. These fixed charges to households may serve to reduce the financial impact of volumetric changes in demand.

The model assumes the capacity of rainwater harvesting systems, on which the water return is tested and evaluated. Therefore, the scenario evaluation found that conservatively the system can return its capacity in non-potable water per annum. It is likely that the volume retained and used will be at least double the system capacity per annum in the real-world. However, it should be taken into account that rainwater harvesting is dependent on annual rainfall events influenced by changes in climate. Therefore, it is important to explore other alternative sources, such as the reuse of greywater, to further alleviate the total municipal water demand.

8.1.3 Reuse Greywater

The reuse of greywater in domestic households, as a non-potable substitute for flushing toilets, is encouraged by the City of Cape Town through various promotional and educational campaigns. The effectiveness of reusing water from baths, showers and wash basins, as an alternative to municipal water for non-potable demands, is tested in Scenario 3.

Chapter 7.3.3 investigates the impact and behaviour of the urban City in response to the utilisation of greywater, to substitute non-potable water functions. Based on the preference to reuse greywater for toilet flushing and the discouragement of irrigation, this waste stream is predominantly aimed at supplementing indoor demands. Changes in model variables relating to the reuse of generated greywater is simulated.

It is evident that the quantity of greywater generated depends directly on the amount of water consumed by users. Therefore, the supplementing supply ensues change in the consumption behaviour of both industry and domestic users. This corresponding pattern of behaviour between generated greywater and domestic demand is elaborated on in Chapter 7.3.3.

The total saving achieved through the reuse of greywater is substantial in relation to other alternatives. However, the total reuse in households are reduced during unconstrained conditions when water supply is sufficient. The model does not address this change in behaviour, only the change in distribution of potable and non-potable water consumption. What is more, greywater is not to be stored for periods longer than 24 hours, unless treated. Therefore, sophisticated systems with internal plumbing connections are preferred for greywater reuse, to reduce the health risk and unpleasant odours.

It is recommended, that a similar approach to rainwater harvesting incentive and funding programmes be investigated. Furthermore, there is no formal legislation addressing the reuse and management of greywater specifically however, guidelines and warnings are issued by the City of Cape Town. Due to the lack of national regulation guiding the use and management of greywater in domestic households and industry, it is recommended that the implementation of potential legislation be included in the evaluation.

The scenario development for the reuse of greywater as a water source to reduce water supply stress in the City is based on several assumptions. These assumptions assume usage patterns, the fraction of households and industries adopting the use of greywater and the fraction of greywater generated. In addition, it is assumed that due to the high cost, sophisticated greywater systems are shared among several households to assure inflow, supply and affordability. The behaviour and response of the model in relation to assumptions should be considered as part of the recommended evaluation.

The majority of the municipal water demand is attributed to potable water requirements, which leads to the investigation and evaluation of alternative potable water sources. Literature found that smaller, decentralised wastewater treatment facilities have proven to be effective in supplementing the potable water requirements in industry.

8.1.4 Decentralised Wastewater Treatment

Water assurance for economic activities in industry is essential to the economic and social sustainability of the City. Alternative sources of water for supplementing the municipal water allocation to industry are investigated. Although centralised treated effluent from municipal sources are supplied to industry, the use is primarily limited to irrigation and other non-potable functions.

Wastewater in industry is identified as a potential value stream, which through specialised treatment processes can be reused as potable quality water. Although the direct potable reuse alternatives are investigated for municipal use, the installation of private decentralised systems are gaining popularity. Italy, Japan and South Africa (Durban), have already successfully implemented smaller decentralised wastewater treatment plants.

Subsequently, the research study investigates the impact and behaviour of the urban water system in response to added and substituted water sources from decentralised wastewater treatment facilities. Scenario 4 simulate several iterations to determine model response to changes in variables relating to the fraction of wastewater treated and reused.

Further model assumptions and parameters are derived from case study findings, which indicate the requirement for additional input sources to decentralised treatment plants. It was found that wastewater produced on-site does not serves as sufficient input to meet production requirements. The shortfall is due to operation and consumption losses within the system, such as irrigation, evaporation and leaks. Groundwater abstracted on-site and municipal treated effluent have been identified as feasible inputs into the decentralised wastewater treatment plant. Consequently, the system is dependent on centralised inputs to produce the adequate quantity of potable quality water for consumption requirements.

It is recommended that the financial viability and municipal cost recovery for private wastewater treatment facilities be incorporated into the feasibility studies. Input and information from local projects, in addition to global initiatives, should be used to support further investigation. Additional value can be extracted from this waste stream, as a potential source of nutrients and energy for reuse. The downstream impact of reduced effluent flow from industry is another consideration that should be included in future feasibility studies, as centralised treated effluent is used to recharge aquifers.

It is unlikely that individual interventions will be implemented without the consideration of several alternatives. Thus, the final recommendation relates to the total impact of implementing several intervention actions simultaneously.

8.1.5 Combined Intervention

Simulation results indicate that a combination of various interventions aimed at reducing water scarcity in the City, through the reuse of waste streams, result in an effective reduction in municipal water demand. Several alternative sources of water is added to the urban water system, substituting and adding to the consumption of municipal water resources.

The causal links among system variables influence the direct and indirect behaviour of the complex system. Consequently, the simulation results indicate several changes in behavioural response to iterative implementation of scenarios. Chapter 7.5 elaborates on the dynamic behaviour of the total municipal demand in relation to added supply interventions.

The oscillating behaviour of the system in response to various inputs confirms the dynamic behaviour expected of an urban water system. Therefore, it is recommended that the management initiatives through policy should be evaluated for response over an extended period of time, due to the unpredictable nature of the complex water system. Especially with several intervention actions implemented simultaneously.

As water revenue accounts for approximately 10% of the City's revenue income, a decline in water sales as a result of water shortages will decrease the available funding for essential water infrastructure and services. The situation is worsened by the high cost of new augmentation projects and crisis management. Therefore, the City should consider the combined use of internal water streams to reduce water supply stress in the region as simulated for Scenario 5.

Furthermore, water carries economic value, presenting new opportunities for business development and investment. It is suggested that the City consider global collaboration and funding from initiatives such as the World Bank's Water Scarce City programmes to improve the City of Cape Town's water management approach and resilient against climate change. Therefore, the financial feasibility and opportunities for economic growth should be evaluated for implementing a combination of decentralised water saving initiatives in the City.

8.2 System Barriers and Limitations

The 2017 GreenCape Market Intelligence Report found that several barriers limit the uptake of new technologies and strategies aimed at improving water resource management. These barriers include the lack of awareness, regulatory hurdles, capital requirements and insufficient technical support.

Furthermore, negative perceptions of recycled or reused water and the large initial capital investments required are some of the barriers to adopting reuse strategies. The regulatory and policy restriction on water quality for food and beverage industries and the limited incentives for implementing water reuse systems are also hindering factors to the adoption rate of industries entering the reuse market.

What is more, the ongoing drought conditions drive the increased investment in the water sector due to the strain on water resources and economic losses. Subsequently, the opportunity to diversify water sources and to address the risk of supply deficit have increased considerably. Emergency augmentation projects and the fast-tracking of planned supply options require evaluation measures to test the feasibility of planned alternatives.

Public perception, down-stream losses, ecological impacts and operating costs are factors influenced by the intervention actions. These actions may severely impact the success of the water initiatives. The system dynamics modelling tool allows for relatively easy and timely evaluation of the modelled system's response and behaviour to changes in input.

However, the narrowed use of feedback loops in the system dynamics model, in comparison to the conceptual causal loop diagrams, may limit the representation of the model. Detailed investigation into subsystem models and refinement of parameter linkage and behaviour may serve to include necessary feedback loops. To refine the model subsystems, uniquely related case studies serve to provide valuable input and validity to the sector in which the research is applied.

The evaluation and testing of identified barriers towards the implementation of circular economy principles, allows policy development to timeously investigate, confirm and identify possible system reactions. These barriers include the consumer usage patterns, which may change in response to the implementation of alternative water sources, such as treated effluent. Therefore, barriers and limitations identified in the uptake of alternative sources, extracted from water waste streams, can be investigated using simple system dynamics models and scenario development.

The model results aim to assist the decision making process by providing insight into the probable behavioural reactions of the system. Hence, system and model barriers and limitations can be addressed accordingly to ultimately reduce water scarcity in urban cities.

8.3 Knowledge Contribution

Recent years have shown an increase in utilising system dynamics models to quantitatively evaluate policy alternatives in the water sector. Prominent studies in the water sector using system dynamics include water management investigations and applications conducted in several countries, including Singapore, China and Korea. In addition, studies in South Africa although limited, include system dynamics water models aimed at transitioning to a green economy, addressing municipal water supply and demand dilemmas as well as investigating associated cost and electricity usage for water supply alternatives.

However, limited research has been done to address water scarcity in urban regions in South Africa utilising alternative sources of water, derived from within the urban water system. The dissertation made several theoretical and practical contributions, to address the gap in literature dealing with water shortages in the urban City of Cape Town.

8.3.1 Theoretical Contributions

The research study made the following theoretical contributions:

1. Defined the urban water roles for the City of Cape Town within the circular economy context. The water roles served as subsystems for the dynamic urban water system model.

2. Water requirements within the urban City of Cape Town were categorised according to the water quality demanded. The distribution of potable and non-potable water requirements for industry and domestic consumptions during constrained and unconstrained water allocations were also stipulated. Allocation constraints are based on the level of water restrictions implemented as part of the water demand management interventions, which change in accordance with average WCWSS dam levels.

3. Identified several alternative water sources derived from waste streams and unretained water resources within the City of Cape Town's urban water system and their behaviour links to municipal water demand. Rainwater harvesting, greywater reuse and potable quality treated effluent were identified as potential sources of water supply to supplement municipal water resources. Although, stormwater harvesting is also identified as a potential source of water, albeit indirectly to recharge aquifers, it is not a focal point of the investigation.

4. A decision support model capable of representing the urban water system holistically for the City of Cape Town was constructed using system dynamics modelling.

5. The behavioural response of the system to simultaneous intervention actions within the water supply, demand and water waste management factions were investigated using scenario based simulations. The resulting behaviour is presented in graphs, stipulating the parameter response over the modelled time frame.

6. Using insights gained from a singular applicable case study in the City of Cape Town, an industry based decentralised wastewater treatment plant model was constructed. The sub-model provided insight into the challenges and value such systems represent and allowed for the exploration of the feasibility of utilising on-site reclamation plants to address water shortage in urban regions.

8.3.2 Practical Contributions

The research study made the following practical contributions:

1. The constructed model supports policy evaluation and decision making, by providing insight and understanding into the system behaviour and response to intervention actions. The results reflect the expected oscillating and growing consumption behaviour for both industry and domestic users in response to available water resources and demand management interventions.
2. The constructed model serves as a base model for the City of Cape Town's urban water system on which further research can be build for in-depth analysis.
3. Identified the requirement for municipal treated effluent, potable water and groundwater, which serve as external input to the on-site decentralised wastewater systems, in the event that the system is unable to produce an adequate quantity of potable quality water to meet internal demand.
4. Allowed for decision-makers to adjust input variables and evaluate the corresponding behavioural changes and system response of the urban water system for the City of Cape Town. Furthermore, the constructed model allows for adjustments and refinements to be made for future investigation or adaptations.

Although several theoretical and practical contributions have been made by the dissertation, various future endeavours can continue to add to the field of knowledge.

8.4 Future Research Recommendations

The model introduced several water streams with the potential to alleviate water scarcity in urban cities. Although, each of the identified sources have been investigated and sub-models have been refined, in-depth analysis and case studies for each alternative is not incorporated in the study. Subsequently, several detailed studies can add to the constructed model to improve the usability and accuracy of model results.

It is proposed that the model be expanded to include elements of a spatially explicit approach. This approach should allow for the investigation of changes and impacts on water sources in relation to urbanisation, precipitation and climate patterns. The hybrid model approach may further allow for the expansion, exploration and validation of system behaviour in response to investigated scenarios by combining landscape maps and simulation results such as urban population.

In addition to the expansion of the urban water system model, other research opportunities arise from the research. The cost structure and influence of changing tariffs on the socio-economic balance in urban cities are not addressed in the research study. Future research can incorporate the detailed causal impact of changing water tariffs, revenue-based water consumption and subsidies for private water sources. Further investigation should link water shortages, economic investment opportunities and migration in urban cities. Other water system aspects identified in literature and during the development of the system dynamics model, include the unknown elements and impacts on revenue generation in response to alternative water supplies.

Recommendations are made to utilise subsidies and repayment schemes as a source of fixed revenue income, to improve budget balancing and cost planning in the municipality. The suggestion stems from the causal relationship between water tariffs and consumption patterns. Furthermore, future studies into the impact of privatising water supply and the cost implication of additional sewage in urban cities can broaden the scope of the model.

The impact on the equitable and sustainable distribution of water through privatisation and the policies regulating these sources may bring to light several new insights. Drought stricken countries such as China and India are hindered by the financial impact and water losses caused by the privatisation of water sources. While Israel faces the risk of a monopolistic market structure for privatised desalination plants. However, future studies may serve to investigate the cause of these risks and the policies that address them.

The risk related to climate variances in the water sector cascades through environmental, agriculture, urban and energy systems. This may lead to higher food prices, unaffordable water, economic decline and migration spikes. It is recommended that future model expansions investigate the impact of seasonality and climate variance on water security in urban cities. As precipitation is directly influenced by changes in climate, the impact is translated to the available runoff into dams and aquifers.

Additional investigation into the extraction of secondary value from water waste streams, such as energy and nutrients, may serve as an alternative approach to the research study. The model boundary can expand or shift to include additional value streams in the urban water system.

Furthermore, future studies may serve to address the limitations and model shortcomings discussed in Chapter 5.8.6 to improve and expand the model usefulness and accuracy. Hence, accurate and refined historical data and specialist input can improve the representation of the model. Several future studies are suggested to improve, refine, or add to the urban water system model. Ultimately, expanding the techniques and the body of knowledge aimed at sustainably assuring water resources for the future.

8.5 Final Conclusion

It is evident that the current approach to water management in the City of Cape Town will not be able to assure equitable and sustainable water supply to the City for much longer. Although several efforts are being made to increase the yield of the water system, while reducing the water demand through restrictions and conservation efforts. Drought periods are becoming longer with lower rainfalls, thus the reliance on surface water as the predominant source of water carry the risk of water assurance for the region.

Several scenarios are investigated to provide insight into the water system's response to the reuse and retention of water streams as alternative sources of water. The results of the simulated model scenarios found that without current demand and conservation efforts, the demand far exceed the planned yield for the water system. Demand will continue to grow in the urban City as a result of urbanisation, rise in population and economic growth. Subsequently, wastewater and greywater will continue to increase directly proportional to the growth in total urban water demand.

Waste streams are identified as potential substitutes and additions to traditional water supply, to serve as either potable or non-potable water sources. Domestic and industry consumption should, however continue to be monitored and curbed through demand management interventions. The investigation provides decision-makers with insight into the response and behaviour of the urban water system. These insights and findings aim to assist the development and evaluation of policies regulating the allocation, usage and discharge of water sources for urban consumption.

Finally, the constructed model serves as the basis on which future studies, in the water sector, may be build to address water scarcity in urban cities equitably and sustainably. Subsequently, the study emphasise the importance of reusing and retaining water streams in the urban water system to minimise the input of raw water resources. Hence, the research study provides a means of evaluating policy alternatives aimed at extracting value by retaining, reusing and reducing consumption from the urban water system to alleviate water scarcity in the City of Cape town, while ensuring economic, social and environmental sustainability.

Appendix A

Literature Review Sources

The aim of this Appendix is to catalogue the literature sources used to conduct the research study, providing transparency and clarity on how the literature review was conducted. This includes the literature sources for the case study research.

A.1 Literature Sources

The database of searched and reviewed sources for the research study are summarised in the tables below. These tables are set in accordance with themes searched in literature based on selected keywords. Furthermore, these searches included all publication types in the English language over the time period from 2000 to 2018.

Table A.1 refers to the literature extracted to address the water scarcity theme investigated in Chapter 2.2.

Table A.1: Literature Sources: Water Scarcity

No	Title	Author	Year	Modelling Tools
1	The impact of water scarcity on economic development initiatives	Blignaut and van Heerden	2009	CGE Model Water Rationing
2	A Review of Water Scarcity Indices and Methodologies	Brown and Matlock	2011	Water Stress Indices
3	Four billion people facing severe water scarcity	Mekonnen and Hoekstra	2016	Blue water scarcity

Table A.2 refers to methods and approaches found in literature aimed at addressing and evaluating urban water systems and water resource management for sustainability in water scarce areas. The literature supports the evaluation of urban water systems in Chapter 2.3.

Table A.3 refers to the literature supporting circular economy principles in the water sector aimed at ensuring sustainable water systems and economic growth through optimising value extraction and improving efficiency as discussed in Chapter 2.4.

Table A.2: Literature Sources: Evaluating Urban Water Systems

No	Title	Author	Year	Modelling Tools
1	Strategic decision making for urban water reuse application: A case from Thailand	Sa-nguanduan and Nititvattananon	2011	Decision Making System (DMS) with Criteria
2	Estimating the potential water reuse based on fuzzy reasoning	Almeida et al.	2013	Fuzzy Logic, DSS Simulation
3	Evaluation of urban water resource security under urban expansion using a system dynamics model	Chang et al.	2015	Systems Dynamics
4	Hierarchical distance-based fuzzy approach to evaluate urban water supply systems in a semi-arid region	Yekta et al.	2015	MCDM Fuzzy Logic
5	Modelling transitions in urban water systems	Rauch et al.	2017	System Dynamics Integrated Modelling
6	Life-cycle energy impacts for adapting an urban water supply system to droughts	Lam et al.	2017	Decision Support System Optimiser (DSSO)
7	System dynamics approach for simulating water resources of an urban water system with emphasis on sustainability of groundwater	Ghasemi et al.	2017	Systems Dynamics
8	Systems thinking and modelling for sustainable water resources management and agricultural development in the Volta River Basin, West Africa	Kotir	2017	Systems Thinking Systems Dynamics
9	A dynamic model for exploring water-resource management scenarios in an inland arid area: Shanshan County, Northwestern China	Chen et al.	2017	IWRM Systems Dynamics

The articles in Table A.4 are based on findings and literature on water systems and management in South Africa. Keywords searched in the Scientific Electronic Library Online South Africa include *Urban Water System, Management, Cycle, Policy.*

Table A.3: Literature Sources: Circular Economy in the Water Sector

No	Title	Author	Year	Modelling Tools
1	Optimizing Circular Economy Planning and Risk Analysis Using System Dynamics	Xu et al.	2010	System Dynamics, Multi-Objective Programming
2	Towards a national circular economy indicator system in China: an evaluation and critical analysis	Geng et al.	2011	Circular Economy Indicators
3	Introducing a Circular Economy: New Thinking with New Managerial and Policy Implication	Esposito et al.	2018	Systems Thinking Sustainability

Table A.4: Literature Sources from Scielo SA: Urban Water Systems

No	Title	Author	Year	Approach
1	Integrated water resource management in complex systems: how the catchment management strategies seek to achieve sustainability and equity in water resources in South Africa	Pollard and du Toit	2008	IWRM Sustainability
2	Environmental life cycle assessments for water treatment processes a South African case study of an urban water cycle	Friedrich et al.	2009	Life Cycle Assessment Water Treatment
3	Options for improving water use efficiency under worsening scarcity evidence from the middle olifants sub-basin in SA	Walter et al.	2011	IWRM
4	Life-cycle assessments in the South African water sector: a review and future challenges	Buckley et al.	2011	Life Cycle Assessment
5	Assessing urban water sustainability in South Africa - not just performance measurement	Carden and Armitage	2013	Assessment Sustainability

A.2 South African Water Policies

Several regulations and supporting documentation address various aspects of the total urban water system. The evaluation of public water regulation in South Africa and the City of Cape Town allowed for the construction of Table A.5 The table sets out the application and reach of each policy, both locally and nationally. Although the documentation addresses a specific resource in the urban water system, it does not necessarily allow for the consumption or use of that resource for domestic or industrial purposes. Furthermore, not all policies and regulations are included in the tables as document inclusion is limited to support the scope of the research investigation. Desalinated water is only addressed in the National Water Bill (NO 34 of 1998).

Table A.5: The Application of National and Regional Water Policies in South African

Document	**Water Quality**	**Surface/ Ground Water**	**Rain-water**	**Water Usage**	**Waste-Water Reuse**	**Grey-Water**	**Storm-water**
The National Constitution	✓			✓			✓
Water Supply and Sanitation Policy White Paper (1994)	✓	✓					
Water Service Act (No 108 of 1997)	✓			✓			
National Water Act (No 36 of 1998)	✓	✓	Rev ✓		Rev ✓		
National Water Bill (No 34 of 1998)	✓	✓					✓
Management of Urban Stormwater Impacts Policy (2009)							✓
Groundwater Strategy (2010)	✓	✓					
Public Works Design Guidelines (PW 2011/1)					✓		
National Water Resource Strategy II (2013)	✓			✓			
WCWDM Strategy and Review (2016)	✓	✓		✓			
CoCT Water Service By-law (2003)	✓			✓			
Stormwater Management By-law (2005)							✓
CoCT Water By-law (2010)	✓	✓		✓		✓	
CoCT Water By-law (2018)	✓	✓	✓	✓	✓	✓	
Treated Effluent By-law (2015)	✓				✓		
Wastewater and Industrial Effluent By-law (2013)							✓
CoCT Water Demand Management and Strategy (2016)	✓	✓	✓	✓	✓	✓	
Guidelines for Alternative Water System CoCT (2019)	✓	✓	✓	✓	✓	✓	✓

A.3 Case Study Research

The articles in Table A.6 are based on findings and literature on case studies conducted to investigate the reuse of treated effluent to address water scarcity in the region. Key words searched in the University of Stellenbosch library database include *urban, water scarcity, case study, treated wastewater.* The literature supports the case study research conducted in Chapter 6.

Table A.6: Case Studies Addressing Urban Water Scarcity and the Reuse of Wastewater

No	Title	Author	Journal
1	Use of treated wastewater for managed aquifer recharge in highly populated urban centres: a case study in Addis Ababa, Ethiopia	Abiye et al.	Environmental Geology Volume 58 (1), 2009
2	Urban water management strategies based on a total urban water cycle model and energy aspects - Case study for Tel Aviv	Duong et al.	Urban Water Journal Volume 8 (2) 2011
3	A Critical Review on the End Uses of Recycled Water	Chen et al.	Critical Reviews in Environmental Science and Technology Volume 43 (14), 2013
4	Urban wastewater reclamation for industrial reuse: An LCA case study	Pintilie et al.	Journal of Cleaner Production Volume 139, 2016
5	Mitigation options for future water scarcity: A case study in Santa Cruz Island and Indonesia	Reyes et al.	Water Journal Volume 9, 2017
6	Nationwide simulation of water, energy, and food nexus: Case study in South Korea and Indonesia	Wicaksono and Kang	Journal of Hydro-Environment Research Volume 22, 2019

A more refined search limits the results to local applications. Subsequently, the articles in Table A.7 are based on findings and literature on case studies conducted to investigate the reuse of treated effluent to address water scarcity in South Africa and neighbouring countries. Keywords searched in the University of Stellenbosch library database and Google Scholar include *urban, water scarcity, case study, treated wastewater, South Africa, re-use.*

Technical presentations and electronic articles relating to the Old Mutual blackwater filtration plant in Pinelands are documented in Table A.8.

Table A.7: Local Case Studies Addressing Urban Water Scarcity and the Reuse of Wastewater

No	Article Title	Author	Journal
1	Unconventional Water Supply Options in South Africa	Smakhtin et al.	Water International Volume 26 (3), 2001
2	Context driven policy design in urban water management: A case study of Windhoek Namibia	Sjomander et al.	Urban Water Journal Volume 2 (3) 2005
3	Environmental life cycle assessment for water treatment processes - A South African case study of an urban water cycle	Friedrich et al.	Water SA Volume 35 (1) 2008
4	Religious, philosophical and environmentalist perspectives on potable wastewater reuse in Durban, South Africa	Zoe Wilson and Bill Pfaff	Desalination Volume 228 2008
5	Treated wastewater reuse in South Africa: Overview potential and challenges	Adewumi et al.	Resource, Conservation and Recycling Volume 55 (2), 2010
6	Four decades of water recycling in Atlantis (WC, South Africa): past, present and future	Bugan et al.	Water SA Volume 42 (4) 2016

Table A.8: Technical Data and Information Sources: Mutualpark Blackwater Filtration Plant in Pinelands, City of Cape Town

No	Title	Author	Year
1	Reducing Water Use in Offic Parks: Old Mutual	Adila Cassim	2018
2	Old Mutual Aims for Net Zero Water	Christy Borman	2018
3	Mutualpark: Water Net Zero	Khiyam Fredericks	2018
4	Old Mutual net zero water implementation plan on onsite water sewage treatment	Khiyam Fredericks	2018

Appendix B

Model Quantification and Equations

Appendix B support the data and source collection for model development in Chapter 4 and Chapter 5. This appendix serve as the source document for the quantification of the model, capturing the equations used to dynamically link variables in the system dynamics model. The appendix is structure to replicate the outline of Chapter 5 for ease of use. The final section of the appendix quantifies and captures the equations for the case study model in Chapter 6.

B.1 Dynamic Modelling

No equations in this section.

B.2 Quantitative Data Extraction

No equations in this section.

B.3 Stock-and-Flow Diagrams

No equations in this section.

B.4 Water as a Resource

The sub-models and equations for water resources follows in corresponding sequence to Chapter 5 for ease of reference:

1. Surface Water Supply Sub-Model
2. Groundwater Supply Sub-Model
3. Alternative Water Supply Sub-Model
4. Total Water Supply Sub-Model

B.4.1 Surface Water Supply

The capacity of WCWSS dams depend on the increase in dam capacity under the assumption that depreciation of dams are balanced by maintenance and repair activities in Equation B.4.1.

$$\begin{aligned}\text{WCWSS Dam Capacity} = &\int_{2001}^{2040} (\text{Increase Dam Capacity})\,\mathrm{d}t \\ &+ \text{ Initial Dam Capacity}\end{aligned} \tag{B.4.1}$$

Model equations for *Raw Water* as part of the Surface Water Supply sub-model.

WCWSS Dam Capacity = INTEG(Increase in Dam Capacity) + Initial Dam Capacity (Unit: Mcubed)

Initial Dam Capacity = 7.68e+008 (Unit: Mcubed)

Increase Dam Capacity = IF THEN ELSE(WCWSS Dam Capacity < Dam Capacity Limit, WCWSS Dam Capacity Increase + Investment Increase in WCWSS Dams, 0) (Unit: Mcubed/Year)

Dam Capacity Limit = 9.25e+008 (Unit: Mcubed)

WCWSS Dam Capacity Increase = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Look up for Dam Capacity = ([(2001,0)-(2040,2e+008)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,1.3e+008), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Investment Increase in WCWSS Dams = WITH LOOKUP (Time) (Unit: Mcubed/Year)

Look up Dam Capacity Investment = ([(2001,0)-(2040,3e+007)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,2.3e+007), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Dam Level = WCWSS Raw Water/WCWSS Dam Capacity (Unit: Dmnl)

Spillage = IF THEN ELSE(WCWSS Raw Water>WCWSS Dam Capacity, (WCWSS Raw Water - WCWSS Dam Capacity), 0)* 1/Year (Unit: Mcubed/Year)

1/Year = 1 (Unit: 1/Year) This variable serves as an unit conversion for the model parameters.

WCWSS Raw Water = INTEG(Raw Water Into Dams+Raw Water Transferred In -Potable Water Treatment -Raw Water Decrease) + Initial WCWSS Raw Water (Unit: Mcubed)

Raw Water Into Dams = Adjustment Inflow +Filtration Rate from Groundwater +Runoff per Year

Filtration Rate from Groundwater = 0 (Unit: Mcubed/Year)

Runoff per Year = Catchment Area * Precipitation Conversion * Precipitation over Catchment Area (Unit: Mubed/Year)

Precipitation over Catchment Area = Precipitation Lookup*(1-Climate Change Impact) (Unit: Millimetre/Year)

Climate Change Impact = Climate Change Lookup*Climate Change Time Lookup (Unit: Dmnl)
Comment: Change due to climate change

Precipitation Lookup = WITH LOOKUP (Time) (Unit: Millimetre/Year)

Lookup Precipitation = ([(2001,0)-(2040,800)], (2001,595), (2002,521), (2003,371), (2004,544), (2005,517), (2006,436), (2007,680), (2008,628), (2009,525), (2010,369), (2011,348), (2012,466), (2013,655), (2014,516), (2015,348), (2016,382), (2017,283), (2018,697), (2019,487), (2020,550), (2021,706), (2022,422), (2023,516), (2024,441), (2025,376), (2026,595), (2027,521), (2028,376), (2029,544), (2030,517), (2031,436), (2032,680), (2033,628), (2034,525), (2035,369), (2036,348), (2037,466), (2038,655), (2039,516), (2040,348))
Source: 2018 Water Outlook Report.

Precipitation Conversion = 1/1000 (Unit: Mcubed/(Millimetre*Msquare))

Catchment Area = Catchment Lookup+Initial Catchment Area (Unit: Msquare)

Initial Catchment Area = 7.135e+008 (Unit: Msquare)

Catchment Lookup = WITH LOOKUP (Time) (Unit: Msquare)

Look up Catchment = ([(2001,0)-(2040,2e+008)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,1.427e+008), (2010,1.427e+008), (2011,1.427e+008), (2012,1.427e+008), (2013,1.427e+008), (2014,1.427e+008), (2015,1.427e+008), (2016,1.427e+008), (2017,1.427e+008), (2018,1.427e+008), (2019,1.427e+008), (2020,1.427e+008), (2021,1.427e+008), (2022,1.427e+008), (2023,1.427e+008), (2024,1.427e+008), (2025,1.427e+008), (2026,1.427e+008), (2027,1.427e+008), (2028,1.427e+008), (2029,1.427e+008), (2030,1.427e+008), (2031,1.427e+008), (2032,1.427e+008), (2033,1.427e+008), (2034,1.427e+008), (2035,1.427e+008), (2036,1.427e+008), (2037,1.427e+008), (2038,1.427e+008), (2039,1.427e+008), (2040,1.427e+008))

Initial WCWSS Raw Water = 5.467e+008 (Unit: Mcubed)
Source: Estimation, based on 70% dam level in 2001 as per the 2018 Water Outlook

Report.

Raw Water Transferred In = 0 (Unit: Mcubed/Year)

Raw Water Decrease = Irrigation Allocation+Other Urban Allocation+Raw Water Losses+WRYM Evaporation+Filtration Rate to Groundwater (Unit: Mcubed/Year)

Filtration Rate to Groundwater = 0 (Unit: Mcubed/Year)

Other Urban Allocation = Lookup Urban Allocation (Unit: Mcubed/Year)

Lookup Urban Allocation = WITH LOOKUP(Constrained/ Unconstrained) (Unit: Mcubed/Year)

Look up Urban Allocation = ([(0,1e+007)-(1,3e+007)], (0,2.3e+007), (1,1.3e+007))

Constrained/ Unconstrained = Restriction Conversion to Un/Constrained (Unit: Dmnl)
Comment:
1 for Constrained
0 for UNconstrained

Restriction Conversion to Un/Constrained = IF THEN ELSE(Restriction Level>3, 1, 0) (Unit: Dmnl)

Lookup Irrigation Allocation = WITH LOOKUP(Constrained/ Unconstrained) (Unit: Mcubed/Year)

Look up Irrigation Allocation = ([(0,0)-(1,2e+008)], (0,1.44e+008), (1,5.8e+007))

Irrigation Allocation = 0*Lookup Irrigation Allocation+Irrigation Allocation Restriction (Unit: Mcubed/Year)

Irrigation Allocation Restriction = Allocation*(1-Restriction Agriculture Lookup) (Unit: Mcubed/Year)

Allocation = 1.44e+008 (Unit: Mubed/Year)

Restriction Agriculture Lookup = WITH LOOKUP(Restriction Level) (Unit: Mubed/Year)

Look up Restriction Agriculture Lookup = ([(1,0)-(7,0.7)], (1,0.1), (2,0.2), (3,0.3), (4,0.4), (5,0.5), (6,0.6), (7,0.65))

WRYM Evaporation = Evaporation Lookup (Unit: Mubed/Year)

Evaporation Lookup = WITH LOOKUP(Time) (Unit: Mubed/Year)

Look up Evaporation = ([(2001,6e+007)-(2040,7e+007)], (2001,6.15e+007), (2002,6.15e+007), (2003,6.15e+007), (2004,6.15e+007), (2005,6.15e+007), (2006,6.15e+007), (2007,6.15e+007), (2008,6.15e+007), (2009,6.75e+007), (2010,6.75e+007), (2011,6.75e+007), (2012,6.75e+007), (2013,6.75e+007), (2014,6.75e+007), (2015,6.75e+007), (2016,6.75e+007), (2017,6.75e+007), (2018,6.75e+007), (2019,6.75e+007), (2020,6.75e+007), (2021,6.75e+007), (2022,6.75e+007), (2023,6.75e+007), (2024,6.75e+007), (2025,6.75e+007), (2026,6.75e+007), (2027,6.75e+007), (2028,6.75e+007), (2029,6.75e+007), (2030,6.75e+007), (2031,6.75e+007), (2032,6.75e+007), (2033,6.75e+007), (2034,6.75e+007), (2035,6.75e+007), (2036,6.75e+007), (2037,6.75e+007), (2038,6.75e+007), (2039,6.75e+007), (2040,6.75e+007))

Raw Water Losses = 0 (Unit: Mubed/Year)
This parameter is used and adjusted to calibrate the model behaviour to improve the accuracy with which the model represents the real world system.

Potable Water Treatment = MIN((Reticulation Losses + Potable Consumption), Water Treatment Capacity) (Unit: Mubed/Year)

Reticulation Losses = Fraction of Reticulation Losses * Potable Consumption (Unit: Mubed/Year)

Water Treatment Capacity = 5.8e+008 (Unit: Mubed/Year)

Fraction of Reticulation Losses = 0.09 (Unit: Dmnl)
Source: Real losses (leaks, burst pipes and faulty meters)

Potable Surface Water = INTEG(Potable Water Treatment - Potable Consumption - Reticulation Losses) + 0 (Unit: Mubed)

Potable Consumption = Domestic Demand + Total Industrial Demand (Unit: Mubed/Year)

B.4.2 Groundwater Supply

Groundwater Abstraction Capacity = INTEG(Increase in Groundwater Abstraction Capacity) + Initial Groundwater Abstraction Capacity (Unit: Mcubed)

Initial Groundwater Abstraction Capacity = 0.26*4.06e+008 (Unit: Mcubed)
Source: Berg-Olifants WMA UGEP (Adams et al., 2017)

As the City of Cape Town is largely positioned within the Berg-Olifants WMA, the UGEP for the WMA is used as the as the total groundwater abstraction limit for both drought, normal and wet years.

Lookup Groundwater UGEP = WITH LOOKUP (Constrained/ Unconstrained) (Unit: Mcubed/Year)

Look up Groundwater UGEP = ([(0,2e+008) - (1,5e+008)], (0,4.06e+008), (1,2.56e+008))
Source: State of Environment Outlook Report for the Western Cape Province 2014 - 2017

UGEP Limit = Lookup Groundwater UGEP (Unit: Mcubed/Year)

Increase in Groundwater Abstraction Capacity = IF THEN ELSE (UGEP Gap > Increase in GW Abstraction Capacity, Increase in GW Abstraction Capacity, UGEP Gap)

(Unit: Mcubed/Year)

UGEP Gap = UGEP Limit - Groundwater Abstraction Capacity * (1/Year) (Unit: Mcubed/Year)

Increase in GW Abstraction Capacity = GW Abstraction Capacity Increase Lookup (Unit: Mcubed/Year)

GW Abstraction Capacity Increase Lookup = WITH LOOKUP(Time) (Unit: Mcubed/Year)

LOOKUP GW Abstraction Capacity Increase = ([(2001,0)-(2040,2e+007)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,1.2775e+007), (2020,9.125e+006), (2021,1.643e+007), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,1.825e+007), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Available Groundwater Supply = Groundwater Abstraction Capacity * (1/Year) (Unit: Mcubed/Year)

Groundwater Utilised CoCT = Available Groundwater Supply*Fraction of Groundwater Utilised (Unit: Mcubed/Year)

Fraction of Groundwater Utilised = 1 (Unit: Dmnl)

Fraction Groundwater Recharge = 0.3 (Unit: Dmnl)
Assumption: 30% recharge required for sustainable groundwater supply.

Recharge Requirement = (Industrial Groundwater Abstraction +Available HH Groundwater) * Fraction Groundwater Recharge(Unit: Mcubed/Year)

Decentralised Groundwater Recharge Requirement = Available HH Groundwater * Fraction Groundwater Recharge (Unit: Mcubed/Year)

Available HH Groundwater = Annual Groundwater Usage per HH * Total No Formal Housing * Fraction of HH Boreholes (Unit: Mcubed/Year)

Fraction of HH Boreholes = 0.02 (Unit: Dmnl)
Source: Fraction of households who are able to afford private boreholes. (Nel et al., 2018)

Annual Groundwater Usage per HH = 40 (Unit: Mcubed/(Household*Year))
Source: National Water Service Act limits the household usage of groundwater to 400 m^3 per year per hectare, with the assumption that households who can afford boreholes are estimated at 1000 m^2.

Groundwater Available Per Capita = Available HH Groundwater/Urban Population (Unit: Mcubed/(Year*People))

Total Industrial Groundwater Requirement DPR = Fraction from Borehole * Industrial

Reuse Plant Capacity * "1/Year" (Unit: Mcubed/Year)

Industrial Groundwater = Groundwater Usage per Hectare * Size of Industrial Site*Industries Utilising Groundwater (Unit: Mcubed/Year)

Groundwater Usage per Hectare = 400 (Unit: Mcubed/(Ha*Year))

Industries Utilising Groundwater = 5000 (Unit: Industries)

Size of Industrial Site = 0.5 (Unit: Ha/Industries)

B.4.3 Alternative Water Supply

Alternative sources of water include retained rainwater, reused greywater and desalinated seawater. The alternative sources are strongly aligned with the identified waste streams in the urban water systems.

Rainwater and Stormwater Harvesting

Volume of Stored Rainwater = INTEG (Rainwater Entering Tanks - Rainwater Consumption) + 0 (Unit: Mcubed)
Assumption: The assumption is made that the initial volume in the collective rainwater tanks are set to zero for the simulation.

Rainwater Entering Tanks = MIN(("1/Year" * Storage Capacity for Rainwater Harvesting), (Potential Rainwater Stock)) (Unit: Mcubed/Year)

Storage Capacity for Rainwater Harvesting = Avg Capacity of Rainwater Tank * Total HH with Rainwater Tanks * Per HH Conversion (Unit: Mcubed)

Potential Rainwater Stock = Precipitation Conversion * Precipitation over Catchment Area * Roof Runoff Coefficient * Total HH Roof Catchment Area (Unit: Mcubed/Year)

Roof Runoff Coefficient = 0.9 (Unit: Dmnl)
Source: GreenCape Water Market Intelligence Report 2018

Precipitation over Catchment Area = Precipitation Lookup*(1-Climate Change Impact) (Unit: Millimetre/Year)

Precipitation Conversion = 1/1000 (Unit: Mcubed/(Millimetre*Msquare))

Avg Rainfall = 490 (Unit: Millimetre/Year)

Climate Change Impact = Climate Change Lookup * Climate Change Time Lookup (Unit: Dmnl)

Climate Change Time Lookup = WITH LOOKUP (Time)(Unit: Dmnl)

Climate Change Time look up = ([(2001,0)-(2040,1)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,1), (2017,1), (2018,1), (2019,1), (2020,1), (2021,1), (2022,1), (2023,1), (2023.66,1), (2025,1), (2026,1), (2027,1), (2028,1), (2029,1), (2030,1), (2031,1), (2032,1), (2033,1), (2034,1), (2035,1), (2036,1), (2037,1), (2038,1), (2039,1), (2040,1))

Climate Change Lookup = WITH LOOKUP (Time)(Unit: Dmnl)

Climate Change Lookup look up = ([(1,0)-(3,0.2)], (1,0), (2,0.02), (3,0.1))

Total HH Roof Catchment Area = Avg Size of HH Roof * Total HH with Rainwater Tanks (Unit: Msquare)

Informal HH with Rainwater Tanks = Fraction of IFHH with Rainwater Tanks* Total No Informal Housing (Unit: Household)

Fraction of IFHH with Rainwater Tanks = 0.01 (Unit: Dmnl)

Formal HH with Rainwater Tanks = Fraction of FHH with Rainwater Tanks *Total No Formal Households (Unit: Household)

Fraction of FHH with Rainwater Tanks = 0.5 (Unit: Dmnl)

Total HH with Rainwater Tanks = Informal HH with Rainwater Tanks + Formal HH with Rainwater Tanks (Unit: Household)

Avg Size of HH Roof = 50 (Unit: Msquare/Household)
Source: GreenCape Water Market Intelligence Report 2018

Avg Capacity of Rainwater Tank = 5 (Unit: Mcubed)
Source: GreenCape Water Market Intelligence Report 2018

Per HH Conversion = 1 (Unit: 1/Household)

Rainwater Consumption = Volume of Stored Rainwater * 1/Year (Unit: Mcubed/Year)

Rainwater available per Capita = (Volume of Stored Rainwater * "1/Year") / Urban Population (Unit: Mcubed/ (Year*People))

Spillage to Stormwater Harvesting = IF THEN ELSE(Potential Rainwater Stock > Storage Capacity for Rainwater Harvesting * "1/Year", Potential Rainwater Stock - Storage Capacity for Rainwater Harvesting * "1/Year", 0) (Unit: Mcubed/Year)

Peak Flow Events - Refill Tanks = 1 (Unit: Dmnl)

Volume of Industrial Stored Rainwater = INTEG(Rainwater Entering Industry Tanks - Industry Rainwater Consumption) + 0 (Unit: Mcubed)

Rainwater Entering Industry Tanks = MIN(("1/Year" * Storage Capacity for Industry Rainwater Harvesting) ,Potential Industrial Rainwater Stock) (Unit: Mcubed/Year)

Potential Industrial Rainwater Stock = (Industry Roof Runoff Coefficient* Precipitation Conversion* Precipitation over Catchment Area* Total Industry Roof Catchment Area) + 0* (Avg Rainfall*Industry Roof Runoff Coefficient* Precipitation Conversion* Total Industry Roof Catchment Area) (Unit: Mcubed/Year)

Total Industry Roof Catchment Area = Avg Size of Industry Roof * Total Industries with Rainwater Tanks (Unit: Msquare)

Avg Size of Industry Roof = 500 (Unit: Msquare/Industries)

Industry Roof Runoff Coefficient = 0.9 (Unit: Dmnl)

Industry Spillage to Stormwater Harvesting = IF THEN ELSE (Potential Industrial Rainwater Stock > "1/Year"* Storage Capacity for Industry Rainwater Harvesting, Potential Industrial Rainwater Stock -"1/Year"* Storage Capacity for Industry Rainwater Harvesting, 0) (Unit: Mcubed/Year)

Storage Capacity for Industry Rainwater Harvesting = Avg Capacity of Industrial Rainwater Tank *Per Industry Conversion *Total Industries with Rainwater Tanks * "Peak Flow Events - Refill Tanks" (Unit: Mcubed)

Avg Capacity of Industrial Rainwater Tank = 100 (Unit: Mcubed)

Per Industry Conversion = 1 (Unit: 1/Industries)

Total Industries with Rainwater Tanks = 1000 (Unit: Industries)

Industry Rainwater Consumption = Volume of Industrial Stored Rainwater * 1/Year (Unit: Mcubed/Year)

Potential Industrial Rainwater Supplement = Industry Rainwater Consumption (Unit: Mcubed/Year)

The collective stored volume of harvested rainwater that provides an alternative source of supply for non-potable uses, is the stock in Equation B.4.2, that is increased when rainwater enters the tank, and decreases when consumed by households.

$$\begin{aligned}\text{Volume of Stored Rainwater} &= \int_{2001}^{2040} (\text{Rainwater Entering Tanks} - \\ &\quad \text{Rainwater Consumption})\,, \mathrm{d}t + 0\end{aligned} \tag{B.4.2}$$

The water harvested in the rainwater tanks are suitable for non-potable uses such as irrigation, laundry, cleaning and toilet flushing. Consequently, the rainwater harvested supply serves as a supplement to non-potable urban requirements.

Desalinated Seawater

Capacity of Desalinated Water = INTEG(Increase in Desalination Capacity) + 0 (Unit:

Mcubed)

Increase in Desalination Capacity = Desalination Capacity Increase Due to Investment (Unit: Mcubed/Year)

Desalination Capacity Increase Due to Investment = WITH LOOKUP (Time) (Unit: Mcubed/Year)

Desalination Capacity Lookup = ([(2001,0)-(2040,5e+009)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,5.84e+006), (2019,0), (2020,7.3e+006), (2021,4.38e+009), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Desalinated Potable Water Supply = Capacity of Desalinated Water * 1/Year (Unit: Mcubed/Year)

2019 Strategy Desalination Increase = WITH LOOKUP (Time) (Unit: Mcubed/Year)

2019 Desalination Look up = ([(2001,0)-(2040,5e+007)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,2.555e+006), (2019,0), (2020,2.555e+006), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,1.825e+007), (2027,0), (2028,0), (2029,0), (2030,3.65e+007), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

B.4.4 Total Water Supply

The total current and planned potable water resources for the WCWSS as per the reconciliation report is represented by the urban water system model for comparison. These yields are based on planned augmentation projects to provide sufficient water resources to the WCWSS customers, of which the City of Cape Town is the majority user.

Total WC Potable Supply Yield = (Desalinated Yield + Potable Groundwater Yield + Potable Reuse Yield + WCWSS Dam Yield) * "1/Year" (Unit: Mcubed/Year)

WCWSS Dam Yield = INTEG(Increase in Dam Yield) + 4.4e+008 (Unit: Mcubed)

Increase in Dam Yield = WCWSS Dam Yield Increase per Annum (Unit: Mcubed/Year)

WCWSS Dam Yield Increase per Annum = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Dam yield look up = ([(2001,0)-(2040,2e+008)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,8e+007), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,2.3e+007), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,1.1e+008), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Potable Reuse Yield = INTEG(Increase in Potable Reuse Yield) (Unit: Mcubed)

Increase in Potable Reuse Yield = Increase in Reuse Yield per Annum (Unit: Mcubed/Year)

Increase in Reuse Yield per Annum = WITH LOOKUP (Time) (Unit: Mcubed/Year)

Reuse yield look up = ([(2001,0)-(2040,8e+007)],(2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,4e+007), (2023,0), (2024,4e+007), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Potable Groundwater Yield = INTEG(Increase in Potable Groundwater Yield) + 0 (Unit: Mcubed)

Increase in Potable Groundwater Yield = Increase in Potable Groundwater Yield per Annum (Unit: Mcubed/Year)

Increase in Potable Groundwater Yield per Annum = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Groundwater yield look up = ([(2001,0)-(2040,8e+007)],(2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,2e+007), (2025,0), (2026,3e+007), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

Desalinated Yield = INTEG(Increase in Desalinated Yield) + 0 (Unit: Mcubed)

Increase in Desalinated Yield = Increase in Desalinated Yield per Annum (Unit: Mcubed/Year)

Increase in Desalinated Yield per Annum = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Desalinated yield look up = ([(2001,0)-(2040,2e+008)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,5e+007), (2029,0), (2030,0), (2031,5e+007), (2032,0), (2033,5e+007), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0)
)

The new water programme set out in the 2019 Cape Town Water Strategy report is modelled for comparison (CoCT, 2019a).

New Water Plan Yield = "1/Year"* (CoCT Desalination Yield +CoCT Groundwater Yield +CoCT Reuse Yield +CoCT Surface Water Yield) (Unit: Mcubed/Year)

CoCT Surface Water Yield = INTEG(Surface water Increase) + 0 (Unit: Mcubed)

Surface water Increase = Surface Water Augmentation (Unit: Mcubed/Year)

Surface Water Augmentation = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Surface Water Augmentation look up = ([(2001,0)-(2040,2e+008)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,1.5e+007), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,3.65e+007), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

CoCT Groundwater Yield = INTEG(Groundwater Increase) + 8.03e+006 (Unit: Mcubed)

Groundwater Increase = Groundwater Augmentation (Unit: Mcubed/Year)

Groundwater Augmentation = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Groundwater Augmentation look up = ([(2001,0)-(2040,2e+007)],(2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,1.2775e+007), (2020,0), (2021,9.125e+006), (2022,1.6425e+007), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,1.825e+007), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

CoCT Reuse Yield = INTEG(Reuse Increase) + 0 (Unit: Mcubed)

Reuse Increase = Water Reuse Augmentation (Unit: Mcubed/Year)

Water Reuse Augmentation = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Water Reuse Augmentation look up = ([(2001,0)-(2040,3e+007)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,2.6e+007), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,1.095e+007), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

CoCT Desalination Yield = INTEG(Desalination Increase) + 0 (Unit: Mcubed)

Desalination Increase = Desalination Augmentation (Unit: Mcubed/Year)

Desalination Augmentation = WITH LOOKUP(Time) (Unit: Mcubed/Year)

Desalination Augmentation look up = ([(2001,0)-(2040,4e+007)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,5.83e+006), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,1.8e+007), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,3.65e+007), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

B.5 Model as a Product Input

The City of Cape Town consumes 64% of the total allocated WCWSS yield, of which 70% is attributed to domestic usage and 30% to industrial usage. The following sub-models are built and described in the section:

1. Domestic User Sub-Model
2. Industry Users Sub-Model
3. Consumption Patterns Sub-Model
4. Water Demand Management Sub-Model
5. Total Water Demand Sub-Model

B.5.1 Domestic Users

The domestic user sub-model incorporates various variables to identify the total domestic water demand on the urban water system, both potable and non-potable water.

Urban Population

Urban Population (Unit: People) is the first stock for the domestic user sub-model with the integration Equation B.5.1. The population growth rates and initial values are derived from several public reports and census data.

$$\begin{aligned}\text{Urban Population} = &\int_{2001}^{2040} (\text{Population Growth - Population Decline})\, \mathrm{d}t \\ &+ \text{ Initial Population}\end{aligned} \tag{B.5.1}$$

Sources for population and household data:

1. *Statistics South Africa: Census 2001 and 2011*
2. *Statistics South Africa: Community Survey 2016*
3. *Western Cape Socio-Economic Profile 2016*
4. *2017 City of Cape Town Annual WSDP Performance and Water Services Audit Report*
5. *Trends in Western Cape Urbanisation 2017 (Available: http://docs.sbs.co.za/3%20-%20PietvanZyl.pdf)*

Urban Population = INTEG(Population Growth-Population Decline) + Initial Population (Unit: Population)

Initial Population = 2 892 243 People (Unit: Population)
Source: 2001 Census - City of Cape Town

Population Growth = Urban Population * Population Growth Rate
(Unit: People/Year)

Population Growth Rate = WITH LOOKUP(Time) (Unit: People/Year)

Population Growth Rate Look up: ([(2001,0)- (2040,0.03)], (2001,0.026), (2002,0.026), (2003,0.026), (2004,0.026), (2005,0.026), (2006,0.026), (2007,0.026), (2008,0.026), (2009,0.026), (2010,0.026), (2011,0.023), (2012,0.023), (2013,0.023), (2014, 0.00742), (2015,0.00742), (2016,0.00742), (2017,0.00742), (2018,0.00742), (2019,0.00742), (2020,0.00742), (2021,0.00742), (2022,0.00742), (2023,0.00742), (2024,0.00742), (2025,0.00742), (2026,0.00742), (2027,0.00742), (2028,0.00742), (2029,0.00742), (2030,0.00742), (2031,0.00742), (2032,0.00742), (2033,0.00742), (2034,0.00742), (2035,0.00742), (2036,0.00742), (2037,0.00742), (2038,0.00742), (2039,0.00742), (2040,0.00742)) (Unit: 1/Year)

Comment: *Time* is an inherent time-based variable within the VENSIM program that runs per time step over the selected simulation period.

Population Decline = Urban Population * Population Decline Rate (Unit: People/Year)

Population Decline Rate = 0 (Unit: 1/Year)

Urban Households

The average household size is showing an continual decline, as a result of several social influences. The declining values of average household size is based on census and annual socio-economic reports which are included in the model variable *Avg People per Household*.

Avg People per Household = LOOKUP WITH (Time)

Avg People per Household Look up: ([(2001,2)-(2040,4)], (2001,3.9), (2002,3.86), (2003,3.82), (2004,3.78), (2005,3.74), (2006,3.7), (2007,3.66), (2008,3.62), (2009,3.58), (2010,3.54), (2011,3.5), (2012,3.425), (2013,3.35), (2014,3.275), (2015,3.2), (2016,3.188), (2017,3.1764), (2018,3.165), (2019,3.153), (2020,3.141), (2021,3.129), (2022,3.118), (2023,3.106), (2024,3.094), (2025,3.082), (2026,3.071), (2027,3.059), (2028,3.047), (2030,3.024), (2031,3.012), (2032,3), (2033,3), (2034,3), (2035,3), (2036,3), (2037,3), (2038,3), (2039,3), (2040,3)) (Unit: People/Household)

Total No Households = Urban Population * Avg People per Household (Unit: Household)

Total No Formal Housing = Fraction Formal HH * Total No Households (Unit: Household)

Total No Informal Housing = Fraction Informal HH * Total No Households (Unit: Household)

Total No Backyard Dwellers = Fraction Backyard Dwellers * Total No Households (Unit: Household)

Fraction Formal HH = 0.802 (Unit: Dmnl)

Fraction Informal HH = 0.13 (Unit: Dmnl)

Fraction Backyard Dwellers = 0.068 (Unit: Dmnl)

B.5.2 Industry Users

The industrial users are the collective term for commercial, municipal and industrial sectors in the City of Cape Town that accounts for 30% of water consumption in the urban City.

CoCT Industrial Allocation Growth = INTEG(Increase CoCT Industrial Allocation) + Initial Industrial Allocation (Unit: Mcubed)

Initial Industrial Allocation = 3.24e+008*Fraction of Industrial Demand *Mcubed (Unit: Mcubed)
Comment: 3.24e+008 m^3 is the unconstrained allocation to the CoCT from the WCWSS as per the 2018 Water Outlook Report.

Fraction of Industrial Demand = 0.3 (Unit: Dmnl)

Increase CoCT Industrial Allocation = CoCT Industrial Allocation Growth*(GDP Rate) (Unit: Mcubed/Year)

GDP Rate = Economic Growth Scenario * Rate Included Lookup (Unit: 1/Year)

Rate Included Lookup = WITH LOOKUP(Time) (Unit: Dmnl)

GDP Rate look up = ([(2001,0)-(2040,30)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,1), (2018,1), (2019,1), (2020,1), (2021,1), (2022,1), (2023,1), (2024,1), (2025,1), (2026,1), (2027,1), (2028,1), (2029,1), (2030,1), (2031,1), (2032,1), (2033,1), (2034,1), (2035,1), (2036,1), (2037,1), (2038,1), (2039,1), (2040,1))
Comment: GDP growth is only accounted for from 2017.

Economic Growth Scenario = WITH LOOKUP(Select Economic Growth Rate) (Unit: 1/Year)
Comment:
1 - Recession 1.5%
2 - Recovery 2.7%
3 - Trend 3.9%

Economic growth lookup = ([(1,0)-(3,0.04)], (1,0.015), (2,0.027), (3,0.039))

Select Economic Growth Rate = USER INPUT (Unit: 1/Year)

CoCT Industrial Allocation Growth Constrained = INTEG(Increase CoCT Industrial Allocation Constrained) + Initial Industrial Allocation Constrained (Unit: Mcubed)

Initial Industrial Allocation Constrained = 1.78e+008 *Fraction of Industrial Demand *Mcubed (Unit: Mcubed)
Comment: 1.78e+008 m^3 is the constrained allocation to the CoCT from the WCWSS as per the 2018 Water Outlook Report.

Increase CoCT Industrial Allocation Constrained = CoCT Industrial Allocation Growth Constrained*GDP Rate (Unit: Mcubed/Year)

B.5.3 Consumption Patterns

Domestic Consumption

Per Capita Non-Potable Demand = Fraction of Non-Potable Water PCD * Per Capita Consumption Limit (Unit: Mcubed/(People*Year))

Fraction of Non-Potable Water PCD = Non-Potable Fraction Conversion (Unit: Dmnl)

Per Capita Potable Demand = Fraction of Potable Water PCD * Per Capita Consumption Limit (Unit: Mcubed/(People*Year))

Fraction Potable Water PCD = Potable Fraction Conversion (Unit: Dmnl)

Total per Capita Domestic Demand = Per Capita Non-Potable Demand +Per Capita Potable Demand (Unit: Mcubed/(Year*People))

Domestic Demand = Total per Capita Demand * Urban Population (Unit: Mcubed/Year)

The industrial sector consumes the remainder of the allocated water from the WCWSS in the City of Cape Town.

Industrial Consumption

Industrial Consumption Limit with Growth = (IF THEN ELSE (Constrained /Unconstrained=1, CoCT Industrial Allocation Growth Constrained, CoCT Industrial Allocation Growth)) *1/Year (Unit: Mcubed/Year)

Industrial Consumption Growth Restriction = (1/Year *CoCT Industrial Allocation Growth *(1-Restriction Industrial Lookup)) /Industrial Consumption Efficiency +Baseline ZERO supplement (Unit: Mcubed/Year)

Industrial Consumption Efficiency = 0.9 (Unit: Dmnl)

Non-Potable Industrial Demand with Growth = Industrial Consumption Growth Restriction *Fraction of Non-Potable Industrial Demand (Unit: Mcubed/Year)

Fraction of Non-Potable Industrial Demand = 0.3 (Unit: Dmnl)

Potable Industrial Demand with Growth = Fraction of Potable Industrial Demand *Industrial Consumption Growth Restriction +Potable Water Requirement DPR +1*Baseline ZERO supplement (Unit: Mcubed/Year)

Fraction of Potable Industrial Demand = 0.7 (Unit: Dmnl)

B.5.4 Water Demand Management

Restrictions

Restriction Level = IF THEN ELSE(Dam Level>0.8, 0, IF THEN ELSE(Dam Level>0.65, 1, IF THEN ELSE(Dam Level>0.6, 2, IF THEN ELSE(Dam Level>0.55, 3, IF THEN ELSE(Dam Level>0.45 ,4,IF THEN ELSE(Dam Level>0.35, 5, IF THEN ELSE(Dam Level>0.25, 6, IF THEN ELSE(Dam Level<0.26,7, 7)))))))) (Unit: Dmnl)

Comment: These restriction levels can be adjusted to investigate the impact on demand management in relation to restriction level triggers.

Avg Dam Level = (WCWSS Raw Water/WCWSS Dam Capacity) (Unit: Dmnl)

Restriction Industrial Lookup = WITH LOOKUP(Restriction Level) (Unit: Dmnl)

Restriction Industrial Look up = ([(0,0)-(7,0.5)], (0,0), (1,0.1), (2,0.2), (3,0.3), (4,0.35), (5,0.4), (6,0.45), (7,0.5))

Alternative Restriction Industrial Look up = ([(0,0)-(7,0.5)], (0,0), (1,0), (2,0), (3,0.1), (4,0.15), (5,0.2), (6,0.45), (7,0.5))

The difference in restriction levels result in a significant deviation in water supply stress. Figure B.1 shows that the strict water restrictions for industrial consumption results in more moderated behaviour in comparison to restriction only applied during constrained water allocations (Restriction level 3 and above).
Restriction Agriculture Lookup = WITH LOOKUP(Restriction Level) (Unit: Dmnl)

Restriction Agriculture Look up = ([(0,0)-(7,0.7)], (0,0), (1,0.1), (2,0.2), (3,0.3), (4,0.4), (5,0.5), (6,0.6), (7,0.65))

Restriction Conversion = IF THEN ELSE (Restriction Level=1, 0, IF THEN ELSE (Restriction Level=2, 0, IF THEN ELSE (Restriction Level=3, 1, IF THEN ELSE (Restriction Level=4, 2, IF THEN ELSE (Restriction Level=5, 3, IF THEN ELSE (Restriction Level=6, 3, 4)))))) (Unit: Dmnl)

Restriction Conversion to Un/Constrained = IF THEN ELSE(Restriction Level>3, 1, 0)+1*Baseline ZERO supplement (Unit: Dmnl)

Domestic Demand

Restriction Conversion to Consumption Limit = WITH LOOKUP(Restriction Level) (Unit: Mcubed/(Year*People))

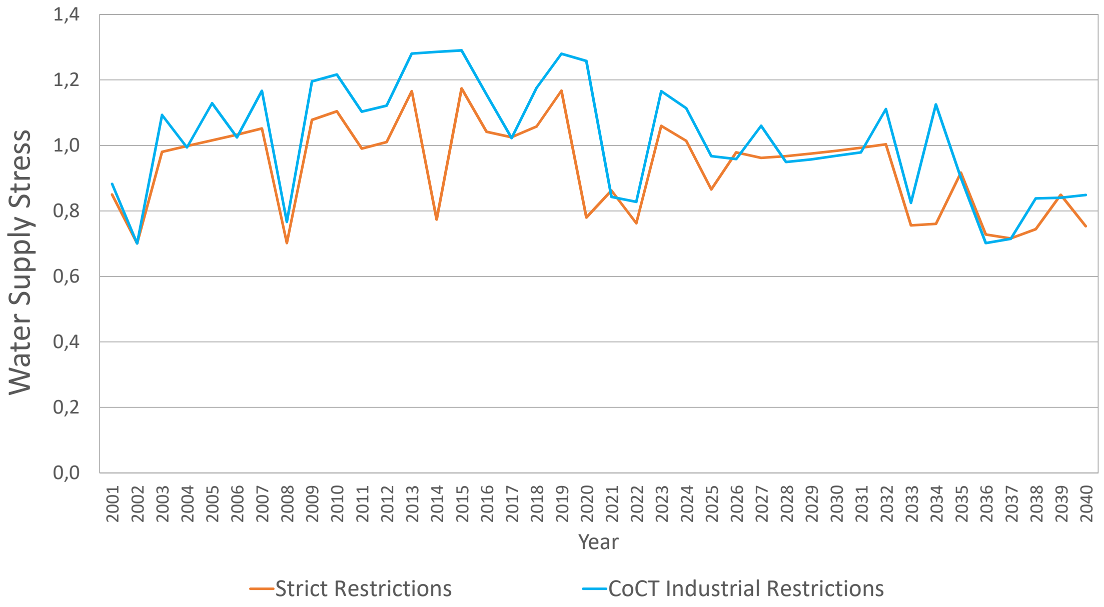


Figure B.1: Impact of Industrial Water Restriction on Water Supply Stress (Scenario 4)

Restriction Level Look up = ([(0,0)-(7,90)], (0,88.33), (1,79.497), (2,70.66), (3,61.83), (4,36.5), (5,31.755), (6,31.755), (6.5,18.25), (7,9.125))
Comment: Water consumption is based on the 242 l per day per capita usage average under no restriction.

Per Capita Consumption Limit = Restriction Conversion to Consumption Limit/Consumption Efficiency (Unit: Mcubed/(People*Year))

Consumption Efficiency = 0.9 (Unit: Dmnl)
Input: The fraction is based on the level of intervention, penalties and eduction actions implemented.

Calibrate Domestic Usage = 0.8 (Unit: Dmnl)
Comment: The calibration fraction dampens the responsiveness of consumption behaviour against imposed restriction levels.

Other Restrictions

Constrained/Unconstrained = Restriction Conversion to Un/Constrained (Unit: Dmnl)

Lookup CoCT Allocation = WITH LOOKUP(Constrained/Unconstrained) (Unit: Mcubed/Year)

CoCT Allocation look up = ([(0,1e+008)-(1,4e+008)], (0,3.24e+008), (1,1.78e+008))

Lookup Urban Allocation = WITH LOOKUP (Constrained/Unconstrained) (Unit: Mcubed/Year)

Urban Allocation Look up = ([(0,1e+007)-(1,3e+007)], (0,2.3e+007), (1,1.3e+007))

Other Urban Allocation = Lookup Urban Allocation (Unit: Mcubed/Year)

Lookup Irrigation Allocation = WITH LOOKUP (Constrained/Unconstrained) (Unit: Mcubed/Year)

Irrigation Allocation Look up = ([(0,0)-(1,2e+008)], (0,1.44e+008), (1,5.8e+007))

Irrigation Allocation Restriction = Allocation* (1-Restriction Agriculture Lookup) (Unit: Mcubed/Year)

Irrigation Allocation = 0*Lookup Irrigation Allocation +Irrigation Allocation Restriction (Unit: Mcubed/Year)

Allocation = 1.44e+008 (Unit: Mcubed/Year)

B.5.5 Total Water Demand

The total water demand in the urban water system is divided between potable and non-potable demand from both industry and domestic consumers.

Total CoCT Potable Water Yield = Fraction of WC Supply to CoCT * Total WC Potable Supply Yield (Unit: Mcubed/Year)

Fraction of WC Supply to CoCT = 0.64 (Unit: Dmnl)
Source: 2018 Water Outlook Report, distribution of WCWSS water allocation.

Total Municipal Resource Demand = Domestic Demand + Total Industrial Demand (Unit: Mcubed/Year)

Total Domestic Demand

Domestic Demand = Total per Capita Demand *Urban Population (Unit: Mcubed/Year)

Total per Capita Demand = IF THEN ELSE (Gap in Per Capita Non-Potable Demand>0, (Per Capita Potable Demand +Per Capita Non -Potable Demand -Non-Potable Domestic Demand Supplement per Capita), Per Capita Potable Demand) (Unit: Mcubed/(Year*People))

Gap in Per Capita Non-Potable Demand = Per Capita Non-Potable Demand - Non-Potable Domestic Demand Supplement per Capita (Unit: Mcubed/(Year*People))

Per Capita Non-Potable Demand = "Fraction of Non-Potable Water PCD"*Per Capita Consumption Limit (Unit: Mcubed/(Year*People))

Non-Potable Domestic Demand Supplement per Capita = (Rainwater available per Capita)*Baseline ZERO supplement +(Groundwater Available Per Capita) +(Indoor Greywater Generated Per Capita)*Baseline ZERO supplement +(Per Capita Greywater)*Baseline ZERO supplement
Comment: The equation is set to represent the baseline scenario.

Total Industry Demand

Total Industrial Demand = Potable Industrial Demand with Growth +Non-Potable Industrial Demand with Growth -IF THEN ELSE (Gap in Non-Potable Industrial Demand>0, Non-Potable Industrial Demand Supplemented, Non-Potable Industrial Demand with Growth) -IF THEN ELSE (Gap in Potable Industrial Demand>0, Potable Industrial Demand Supplemented, Potable Industrial Demand with Growth) (Unit: Mcubed/Year)

Gap in Non-Potable Industrial Demand = Non-Potable Industrial Demand with Growth -Non-Potable Industrial Demand Supplemented (Unit: Mcubed/Year)

Non-Potable Industrial Demand Supplemented = Baseline ZERO supplement *(Municipal Treated Effluent for Reuse)+Baseline ZERO supplement*(Industrial Greywater Generated with Growth)+Baseline ZERO supplement *(Potential Industrial Rainwater Supplement)+Baseline ZERO supplement *(Industrial Greywater for Reuse) +(Industrial Groundwater +Reused in Industry) (Unit: Mcubed/Year)
Comment: The equation is set to represent the baseline scenario.

Gap in Potable Industrial Demand = Potable Industrial Demand with Growth-Potable Industrial Demand Supplemented (Unit: Mcubed/Year)

(Potential Industrial Potable Water Supplement *Fraction Supplemented) *Baseline ZERO supplement (Unit: Mcubed/Year
Comment: The equation is set to represent the baseline scenario.

B.6 Water as a Waste Stream

Globally, several waste streams in urban water systems are used as alternative sources of water supply, to alleviate the demand on the constrained raw water resources. The following sub-models are built and described in the section:

1. Wastewater Treatment Works Sub-Model
2. Retain, Reuse and Reduce Sub-Model
3. Water Waste Management Sub-Model

B.6.1 Wastewater Treatment Works

The centralised municipal wastewater treatment plants is an essential part of the water management system, responsible for the discharge and treatment of wastewater generated by the urban water consumers in the City of Cape Town. The capacity of the City of Cape Town Wastewater Treatment Works (WWTW) represents the stock in Equation B.6.1 (Unit: Mcubed).

$$\begin{aligned}\text{Wastewater Treatment Works Capacity} &= \int_{2001}^{2040} (\text{Increase WWTW Capacity})\, \mathrm{d}t \\ &+ \text{Initial WWTW Capacity}\end{aligned} \tag{B.6.1}$$

The initial capacity of the WWTW in the City of Cape Town according to the State of Cape Town Report for 2001 indicated a capacity of 564 million litres per day.

Initial WWTW Capacity = 5.64e+008 * Conversion l/day to Mcubed/Year (Unit: Mcubed)

Conversion l/day to Mcubed/Year = 365/1000 (Unit: Mcubed)

Wastewater Treatment Works Capacity = INTEG(Increase WWTW Capacity) + Initial WWTW Capacity (Unit: Mcubed)

Increase WWTW Capacity = Added WWTW Capacity (Unit: Mcubed/Year)

Added WWTW Capacity = WWTW Capacity Lookup + Added Capacity Through Investment (Unit: Mcubed/Year)

Added Capacity Through Investment = WITH LOOKUP (Time) (Unit: Mcubed/Year)

Added Capacity Look up = ([(2001,0)-(2040,50)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,45), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,20), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,25), (2040,0))

WWTW Capacity Lookup = WITH LOOKUP (Time) (Unit: Mcubed/Year)

WWTW Capacity Look up = ([(2001,0)-(2040,30)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,20), (2008,25), (2009,0), (2010,0), (2011,0), (2012,0), (2013,4), (2014,0), (2015,0), (2016,2), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,2), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,2), (2040,0))

Gap Between WWTW Capacity and Wastewater Received = WWastewater Treatment Works Capacity *1/Year -Wastewater Input to WWTW (Unit: Mcubed/Year)

Wastewater Input to WWTW = Domestic Wastewater Generated+Generated Industrial Wastewater +(Domestic WW from Alternative Source +Industrial WW from Alternative Source + Stormwater Ingress) *Baseline ZERO supplement -WW from CoCT to OM (Unit: Mcubed/Year)

Domestic Wastewater Generated = Domestic Demand *Fraction of Wastewater Generated (Unit: Mcubed/Year)

Fraction of Wastewater Generated = 0.7 (Unit: Dmnl)
Source: The fraction of sewage charged per metered water consumption.

Domestic WW from Alternative Source = Fraction of Wastewater Generated *(Groundwater Available Per Capita +Rainwater available per Capita) *Urban Population (Unit: Mcubed/Year))

Generated Industrial Wastewater = Fraction of Industrial Wastewater Generated *Total Industrial Demand +((1-Fraction Supplemented) *Potential Industrial Potable Water Supplement) *Fraction of Industrial Wastewater Generated -Fraction of Industrial Wastewater Generated *Potable Water Requirement DPR (Unit: Mcubed/Year)

Industrial WW from Alternative Source = Fraction of Industrial Wastewater Generated *(Potential Industrial Rainwater Supplement +Industrial Groundwater) (Unit: Mcubed/Year)

WW from CoCT to OM = 0 (Unit: Mcubed/Year)

Stormwater Ingress = 0 (Unit: Mcubed/Year)

Municipal Effluent Capacity

The capacity of the City of Cape Town Wastewater Treatment Works (WWTW) to generate potable quality treated effluent is represents by the stock in Equation B.6.2 (Unit: Mcubed).

$$\text{Municipal Effluent Capacity} = \int_{2001}^{2040} (\text{Increase CoCT Effluent Capacity})\, dt + 52742500 \tag{B.6.2}$$

Increase CoCT Effluent Capacity = Added CoCT Effluent (Unit: Mcubed)

Added CoCT Effluent = CoCT Capacity Increase Lookup (Unit: Mcubed)

CoCT Capacity Increase Lookup = WITH LOOKUP(Time) (Unit: Mcubed)

CoCT Capacity Increase Look up = ([(2001,0)-(2040,4e+007)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,8.76e +006), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,0), (2019,0), (2020,0), (2021,0), (2022,4e +007), (2023,0), (2024,4e +007), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))

CoCT Treated Available for Reuse = MIN (1/Year *Municipal Effluent Capacity, Fraction of CoCT Treated Effluent for Reuse *Wastewater Input to WWTW) (Unit: Mcubed/Year)
Comment: The equation is an alternative Calculation based on WWTW Treated Effluent Capacity.

Fraction of CoCT Treated Effluent for Reuse = 0.1 (Unit: Dmnl)
Comment: Percentage of wastewater reused as treated effluent in the City of Cape Town is taken as 10 %.

Utilised CoCT Treated Effluent = MIN(CoCT Treated Available for Reuse,Total CoCT Treated Effluent Requirement DPR) (Unit: Mcubed/Year)

WW to Environment = Wastewater Input to WWTW -Utilised CoCT Treated Effluent (Unit: Mcubed/Year)

WW Discharged Marine Outfalls = MIN(Marine Outfall Capacity, WW to Environment) (Unit: Mcubed/Year)

Marine Outfall Capacity = 2.0075e+007 (Unit: Mcubed/Year)

Discharge to Nature = WW to Environment -WW Discharged Marine Outfalls (Unit: Mcubed/Year)

Municipal Treated Effluent for Reuse = (Fraction of CoCT Treated Effluent for Reuse *Wastewater Treatment Works Capacity *1/Year) -Total CoCT Treated Effluent Requirement DPR+ 0*Municipal Effluent Capacity (Unit: Mcubed)
Comment: The equation is an alternative Calculation based on WWTW Capacity.

Treated Effluent for Reuse = INTEG(Increase Treated Effluent Stock-Decrease Treated Effluent Stock) + 0 (Unit: Mcubed)
Comment: The equation is an alternative that calculates treated effluent for reuse as a fraction of wastewater input into the City of Cape Town WWTW facility.

Increase Treated Effluent Stock = CoCT Treated Available for Reuse (Unit: Mcubed/Year)

Decrease Treated Effluent Stock = Treated Effluent for Reuse (Unit: Mcubed/Year)

Reused in Industry = 1/Year *Decrease Treated Effluent Stock -Recharge Requirements -Total CoCT Treated Effluent Requirement DPR (Unit: Mcubed/Year)

Recharge Requirements = 0 (Unit: Mcubed/Year)
Comment: The recharge requirements can be derived from the aquifer recharge requirements.

B.6.2 Retain, Reuse and Reduce

To reduce waste in the system, behavioural alterations are required, of which retaining water in the system, reusing water and reducing the demand for water resources are central to minimising system wastage in a circular water economy.

Domestic Greywater Reuse

Domestic Greywater per Capita = INTEG(Domestic Greywater Inflow-Domestic Greywater Used) + 0 (Unit: Mcubed/People)

Domestic Greywater Inflow = Fraction Greywater Captured*(Fraction Potable Water PCD*Total per Capita Demand)*Fraction of Capita Using Greywater (Unit: Mcubed/(Year*People))

Fraction of Capita Using Greywater = 0.5 (Unit: Dmnl)

Fraction Greywater Captured = 0.5 (Unit: Dmnl)

Domestic Greywater Used = Domestic Greywater per Capita *1/Year (Unit: Mcubed/(Year*People))

Per Capita Greywater = Domestic Greywater Used (Unit: Mcubed/(Year*People))

Industry Greywater Reuse

Industrial Greywater Stock = Generated Industrial Greywater-Industrial Greywater Used + 0 (Unit: Mcubed)

Generated Industrial Greywater = Total Industrial Demand*Fraction of Potable Industrial Demand*Fraction of Industrial Greywater Generated*Fraction of Industry Utilising Greywater Systems (Unit: Mcubed/Year)

Fraction of Industrial Greywater Generated = 0.3 (Unit: Dmnl)

Fraction of Industry Utilising Greywater Systems = 0.7 (Unit: Dmnl)

Fraction of Potable Industrial Demand = 0.7 (Unit: Dmnl)

Industrial Greywater Generated with Growth = Fraction of Industrial Greywater Generated *(Fraction of Potable Industrial Demand *Industrial Consumption Growth Restriction) *Fraction of Industry Utilising Greywater Systems (Unit: Mcubed/Year)

Industrial Greywater Used = Industrial Greywater Stock (Unit: Mcubed)

Industrial Greywater for Reuse = 1/Year *Industrial Greywater Used (Unit: Mcubed/Year)

Stormwater Harvesting

Spillage to Stormwater Harvesting = IF THEN ELSE (Potential Rainwater Stock >Storage Capacity for Rainwater Harvesting *1/Year, Potential Rainwater Stock -Storage Capacity for Rainwater Harvesting *1/Year, 0) (Unit: Mcubed/Year)

Decentralised Wastewater Treatment Plant

Industrial Reuse Plant Capacity = INTEG (Increase in Industrial Reuse Plant Capacity) + Initial Industrial Reuse Plant Capacity (Unit: Mcubed)

Initial Industrial Reuse Plant Capacity = 0 (Unit: Mcubed)

Increase in Industrial Reuse Plant Capacity = Number of Industrial Reuse Plants Added *Yearly Industrial Treatment per Facility (Unit: Mcubed/Year)

Yearly Industrial Treatment per Facility = 365000 (Unit: Mcubed/(Year*Plants))

Number of Industrial Reuse Plants Added = Industrial Reuse Plants Added Lookup (Unit: Plants)

Industrial Reuse Plants Added Lookup = WITH LOOKUP (Time) (Unit: Plants)

Industrial Reuse Plants Look up = ([(2001,0)-(2040,30)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,10), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,10), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,10), (2039,0), (2040,0))

Total CoCT Treated Effluent Requirement DPR = Industrial Reuse Plant Capacity* 1/Year *Fraction CoCT Treated Effluent (Unit: Mcubed/Year)

Potable Water Requirement DPR = 1/Year *Fraction from Municipal *Industrial Reuse Plant Capacity (Unit: Mcubed/Year)

Total Industrial Groundwater Requirement DPR = Fraction from Borehole *Industrial Reuse Plant Capacity *1/Year (Unit: Mcubed/Year)

Total Produced Decentralised Treated Effluent = Industrial Reuse Plant Capacity *Fraction from Filtration *1/Year (Unit: Mcubed/Year)

Potential Industrial Potable Water Supplement = 1/Year *Industrial Reuse Plant Capacity *Fraction of Wastewater Transformed (Unit: Mcubed/Year)

Fraction of Wastewater Transformed = 0.95 (Unit: Dmnl)

Wastewater Generated from Treated Effluent = Fraction for Re-treatment *Potential Industrial Potable Water Supplement (Unit: Mcubed/Year)
Comment: This equation represent the calculation of wastewater generated prior to case study inputs.

Fraction for Re-treatment = 0.65

Industrial Wastewater used On-site = Fraction of On-site OM Wastewater *Potential Industrial Potable Water Supplement (Unit: Mcubed/Year)
Comment: This equation represent the calculation of wastewater generated after case study inputs.

B.6.3 Total Water Waste Management

No equations in this section.

B.7 Simulation Model

The measurement indices for the urban water system model is supported by various model structures and equations, which are elaborated on in Appendix C.

B.8 Model Validation

The adaptation to model structure and equations for the validation process and sensitivity analysis. Thus, the baseline for model restriction level is set as:

IF THEN ELSE(Avg Dam Level>0.8, 0, IF THEN ELSE(Avg Dam Level>0.65, 1, IF THEN ELSE(Avg Dam Level>0.6, 2, IF THEN ELSE(Avg Dam Level>0.55 , 3, IF THEN ELSE(Avg Dam Level>0.45 ,4,IF THEN ELSE(Avg Dam Level>0.35, 5, IF THEN ELSE(Avg Dam Level>0.25, 6, IF THEN ELSE(Avg Dam Level <0.26,7, 7))))))))

To test the impact of lowering the trigger for restriction implementation by 5%, the run *RestrictionLower5* is set up as follows:

Restriction Level = IF THEN ELSE(Avg Dam Level>0.8, 0, IF THEN ELSE(Avg Dam Level>0.60, 1, IF THEN ELSE(Avg Dam Level>0.55, 2, IF THEN ELSE(Avg Dam Level>0.50 , 3, IF THEN ELSE(Avg Dam Level>0.40 ,4,IF THEN ELSE(Avg Dam Level>0.30, 5, IF THEN ELSE(Avg Dam Level>0.20, 6, IF THEN ELSE(Avg Dam Level <0.15,7, 7))))))))

Increasing the restriction trigger by 5% from the initial run, *RestrictionHigher5*, results in the following parameter quantification:

Restriction Level = IF THEN ELSE(Avg Dam Level>0.8, 0, IF THEN ELSE(Avg Dam Level>0.7, 1, IF THEN ELSE(Avg Dam Level>0.65, 2, IF THEN ELSE(Avg Dam Level>0.6 , 3, IF THEN ELSE(Avg Dam Level>0.5 ,4,IF THEN ELSE(Avg Dam Level>0.4, 5, IF THEN ELSE(Avg Dam Level>0.3, 6, IF THEN ELSE(Avg Dam Level <0.3,7, 7))))))))

The primary influencing parameters in the urban water system include the potable consumption, allocation to other urban areas and irrigation demands as well as the reticulation losses within the system. Potable consumption is directly influenced by domestic and industrial demand, which respond to restrictions and conservation requirements.

B.9 Case Study

OM Storage Tanks = INTEG(Borehole Water Entering +Treated WW Entering -OM Potable Water Consumed -Over Capacity) + 0 (Unit: Mcubed)

Over Capacity = IF THEN ELSE (OM Storage Tanks> OM Storage Tank Capacity, ((OM Storage Tanks -OM Storage Tank Capacity) *1/Year), 0) (Unit: Mcubed/Year)

OM Storage Tank Capacity = 167900 (Unit: Mcubed)
Source: Tank Capacity 460 m^3 * 365 = 167900 m^3

Borehole Water Entering = MIN(OM Borehole Water, OM Borehole Water Capacity) (Unit: Mcubed/Year)

OM Borehole Water = Fraction OM Borehole Water *OM Annual Consumption (Unit: Mcubed/Year)

Fraction OM Borehole Water = 0 (Unit: Dmnl)

OM Groundwater Recharge Requirement = Borehole Water Entering *Fraction Groundwater Recharge (Unit: Mcubed/Year)

OM Potable Water Consumed = OM Storage Tanks (Unit: Mcubed/Year)

OM Water Requirement = OM Annual Consumption-OM Potable Water Consumed (Unit: Mcubed/Year)

OM CoCT Potable = OM Water Requirement (Unit: Mcubed/Year)

Water Entering OM System = OM CoCT Potable+OM Potable Water Consumed (Unit: Mcubed/Year)

Fraction from Municipal = OM CoCT Potable/OM Annual Consumption (Unit: Dmnl)

OM Annual Consumption = OM Demand*(1-OM Water Saving Intervention) (Unit: Mcubed/Year)

OM Water Saving Intervention = OM Water Saving Intervention LOOKUP + Intervention (Unit: Dmnl)

OM Water Saving Intervention LOOKUP = WITH LOOKUP(Time) (Unit: Dmnl)

OM Water Saving Intervention Look up = ([(2001,0)-(2040,0.5)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0.3), (2017,0.3), (2018,0.3), (2019,0.35), (2020,0.3), (2021,0.3), (2022,0.3), (2023,0.3), (2024,0.3), (2025,0.3), (2026,0.4), (2027,0.3), (2028,0.3), (2029,0.3), (2030,0.3), (2031,0.3), (2032,0.3), (2033,0.3), (2034,0.3), (2035,0.3), (2036,0.3), (2037,0.3), (2038,0.3), (2039,0.35), (2040,0.3))

Intervention = 0.3 (Unit: Dmnl)

OM Consumption = Fraction Consumption*OM Annual Consumption (Unit: Mcubed/Year)

Fraction Consumption = 0.53 (Unit: Dmnl)

OM Losses = OM Annual Consumption*Fraction Losses (Unit: Mcubed/Year)

Fraction Losses = 0.07 (Unit: Dmnl)

OM Irrigation = OM Annual Consumption*Fraction Irrigation (Unit: Mcubed/Year)

Fraction Irrigation = 0.3 (Unit: Dmnl)

OM Evaporation = Fraction Evaporation*OM Annual Consumption (Unit: Mcubed/Year)

Fraction Evaporation = 0.1 (Unit: Dmnl)

OM Demand = 180000 (Unit: Mcubed/Year)

Treated WW Entering = MIN((OM CoCT Treated Effluent +OM Wastewater Produced +(Fraction OM Runoff Used *Annual OM Roof Runoff)-OM Process Losses), (OM Treatment Plant Capacity *"1/Year")) (Unit: Mcubed/Year)

OM Wastewater Produced = WW from CoCT +OM Consumption *Fraction of OM WW (Unit: Mcubed/Year)

Fraction of OM WW = 0.97 (Unit: Dmnl)

OM Process Losses = Fraction Process Losses *OM Storage Tanks (Unit: Mcubed/Year)

OM CoCT Treated Effluent = Fraction of Treated Effluent*OM Annual Consumption (Unit: Mcubed/Year)

Fraction of Treated Effluent = 0.25 (Unit: Dmnl)

Throughput = Treated WW Entering /(OM Treatment Plant Capacity *1/Year) (Unit: 1)

OM Treatment Plant Capacity = INTEG(Increase OM WWTW Capacity) +1 (Unit: Mcubed)

Increase OM WWTW Capacity = OM WWTW Capacity Added (Unit: Mcubed/Year)

OM WWTW Capacity Added = Lookup OM WWTW Capacity (Unit: Mcubed/Year)

Lookup OM WWTW Capacity = WITH LOOKUP (Time) (Unit: Mcubed/Year)

Look up = ([(2001,0)-(2040,300000)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,0), (2010,0), (2011,0), (2012,0), (2013,0), (2014,0), (2015,0), (2016,0), (2017,0), (2018,237250), (2019,0), (2020,0), (2021,0), (2022,0), (2023,0), (2024,0), (2025,0), (2026,0), (2027,0), (2028,0), (2029,0), (2030,0), (2031,0), (2032,0), (2033,0), (2034,0), (2035,0), (2036,0), (2037,0), (2038,0), (2039,0), (2040,0))
Comment: 237 250 m^3 per annum capacity is based on the 650 m^3 per day capacity of the installed blackwater filtration plant in 2018.

WW from CoCT = 0 (Unit: Mcubed/Year)

Fractions for Model Refinement

Fraction from Filtration = Treated WW Entering/OM Annual Consumption (Unit: Dmnl)

Fraction CoCT Treated Effluent = OM CoCT Treated Effluent /OM Annual Consumption (Unit: Mcubed/Year)

Fraction from Borehole = Borehole Water Entering/OM Annual Consumption

Appendix C

System Dynamics Models: Scenario Testing

This appendix serves as the model illustration for tested scenarios in Chapter 7.3. The model quantification and mathematical equations are available in Appendix B.

C.1 Scenario 1: Business as Usual

To establish the baseline for the model, several parameters were adapted to exclude intervention actions. These adaptations are indicated with **red arrows**, although the equations and relationship may vary for connected variables for alternative scenarios. The following figures and equations represent the system dynamics model for the City of Cape Town urban water system.

C.1.1 Baseline

The fixed allocation at 324 million m^3 replace the *Lookup CoCT Allocation* based on constrained and unconstrained conditions. Refer to Figure C.1 and Table C.1.

Lookup CoCT Allocation = WITH LOOKUP(Constrained/ Unconstrained)

Look up = ([(0,1e+008)-(1,4e+008)],(0,3.24e+008),(1,1.78e+008))

Industrial

Industrial Consumption Limit with Growth = (IF THEN ELSE("Constrained/ Unconstrained"=1, CoCT Industrial Allocation Growth Constrained, CoCT Industrial Allocation Growth))*"1/Year"

Industrial Consumption Growth Restriction = ("1/Year"*CoCT Industrial Allocation Growth*(1-Restriction Industrial Lookup))/Industrial Consumption Efficiency

Industrial Consumption Efficiency = 0.9

Domestic

Consumption Efficiency = 0.9

Per Capita Consumption Limit = (Restriction Conversion to Consumption Limits/Consumption Efficiency)*Baseline ZERO supplement + 88.33

Restriction Conversion to Un/Constrained = IF THEN ELSE(Restriction Level>3, 1, 0)*Baseline ZERO supplement **(Therefore, allocation remains unconstrained)**

Select Economic Growth Rate = WITH LOOKUP (Select Economic Growth Rate)

Select Economic Growth Rate Lookup = ([(1,0)-(3,0.04)],(1,0.015),(2,0.027),(3,0.039))

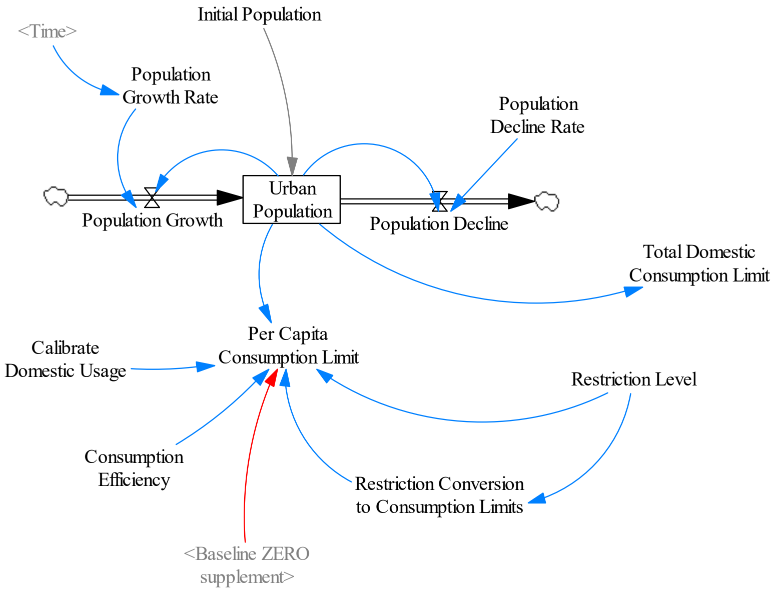


Figure C.1: Scenario 1: CoCT Urban Population and Domestic Demand

Table C.1: Scenario 1: Baseline Parameters

Parameter	**Value**	**Unit**	**Note**
Reused in Industry	Varying	m^3	Input
Industrial Groundwater	Varying	m^3	Input
Groundwater Available per Capita	Varying	m^3	Input

C.1.2 Wastewater Reuse

The baseline model with supplemented non-potable water for industrial consumption from Wastewater Treatment Works (WWTW) incorporates adjustments noted with **red arrows**. The following equations and Figure C.2 illustrates the model changes.

Wastewater Input to WWTW = Domestic Wastewater Generated +Generated Industrial Wastewater +(Domestic WW from Alternative Source +Industrial WW from Alternative

Source + Stormwater Ingress) *Baseline ZERO supplement-WW from CoCT to OM

Fraction of CoCT Treated Effluent for Reuse = 0.05 THEN 0.1

Municipal Treated Effluent for Reuse = Fraction of CoCT Treated Effluent for Reuse*Wastewater Treatment Works Capacity*"1/Year"

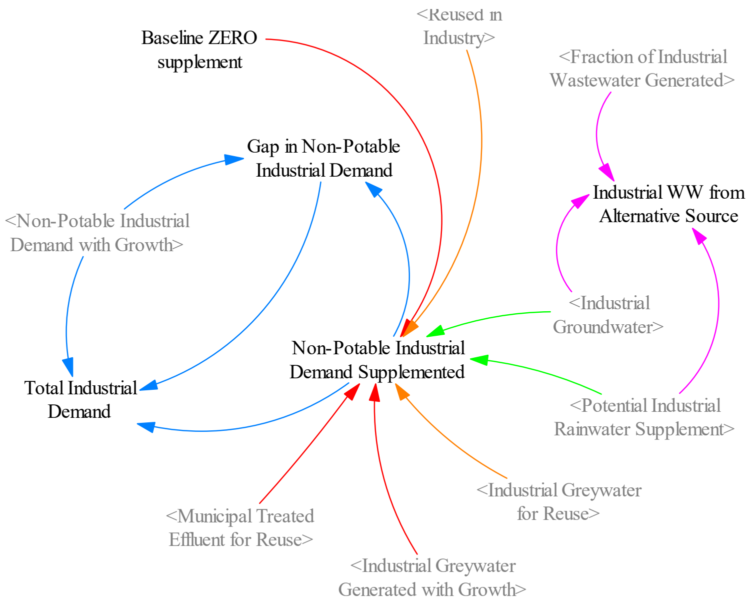


Figure C.2: Scenario 1: WWTW Supplemented Total Municipal Demand

C.1.3 Demand Restrictions

The level of water in the WCWSS dams are used as the measured indicator for restriction requirements. Several levels of restrictions are associated with the set dam levels, which are used to trigger constrained or unconstrained conditions as the water scarcity or abundance change.

This restricted model represents the outcome of strict adherence to water demand restrictions. The following figures were adapted to include the system response to the strict implementation of demand management interventions.

Restriction Conversion to Un/Constrained = IF THEN ELSE(Restriction Level>3, 1, 0)+1*Baseline ZERO supplement)

Per Capita Consumption Limit = (Restriction Conversion to Consumption Limits/Consumption Efficiency)+1*Baseline ZERO supplement

Industrial Consumption Growth Restriction = "1/Year"*CoCT Industrial Allocation Growth*(1-Restriction Industrial Lookup)

Non-Potable Industrial Demand with Growth = Industrial Consumption Growth Restriction*Fraction of Potable Industrial Demand

Potable Industrial Demand with Growth = Fraction of Non-Potable Industrial Demand*Industrial Consumption Growth Restriction

The model quantification and variable equations for the modified *WCWSS Raw Water* stock model based on precipitation, builds on Appendix B.1.1.

Avg Dam Level = WCWSS Raw Water/WCWSS Dam Capacity (Unit: Dmnl)

Raw Water Into Dams = Filtration Rate from Groundwater+Runoff per Year + Adjustment Inflow (Unit: Mcubed/Year)

Adjustment Inflow = 0 TO BE CHANGED FOR CALIBRATION (Unit: Mcubed/Year)

Runoff per Year = Catchment Area * Precipitation Conversion * Precipitation over Catchment Area (Unit: Mcubed/Year)

Precipitation Conversion = 1/1000 (Unit: Mcubed/(Millimetre*Msquare))

Precipitation over Catchment Area = Precipitation Lookup * (1+Precipitation Change) (Unit: Millimetre/Year)

Precipitation Change = 0 CHANGE IN PRECIPITATION PATTERNS (Unit: Dmnl)

Precipitation Lookup = WITH LOOKUP(Time) (Unit: Millimetre/Year)

Precipitation Look up = ([(2001,0)-(2040,800)], (2001,595), (2002,521), (2003,371), (2004,544), (2005,517), (2006,436), (2007,680), (2008,628), (2009,525), (2010,369), (2011,348), (2012,466), (2013,655), (2014,516), (2015,348), (2016,382), (2017,283), (2018,697), (2019,487), (2020,550), (2021,706), (2022,422), (2023,516), (2024,441), (2025,376), (2026,595), (2027,521), (2028,376), (2029,544), (2030,517), (2031,436), (2032,680), (2033,628), (2034,525), (2035,369), (2036,348), (2037,466), (2038,655), (2039,516), (2040,348))

The following applicable models for the baseline scenario include parameters for adjusting consumer patterns using water demand restrictions with precipitation values based on input data as illustrated in Figure C.3 and runoff rates as shown in Figure C.4.
Catchment Area = Catchment Lookup + Initial Catchment Area (Unit: Msquare)

Initial Catchment Area = 7.135e+008 (Unit: Msquare)
Source: 2006 WCWSS Pilot Study Report

Catchment Lookup = WITH LOOKUP(Time) (Unit: Msquare)

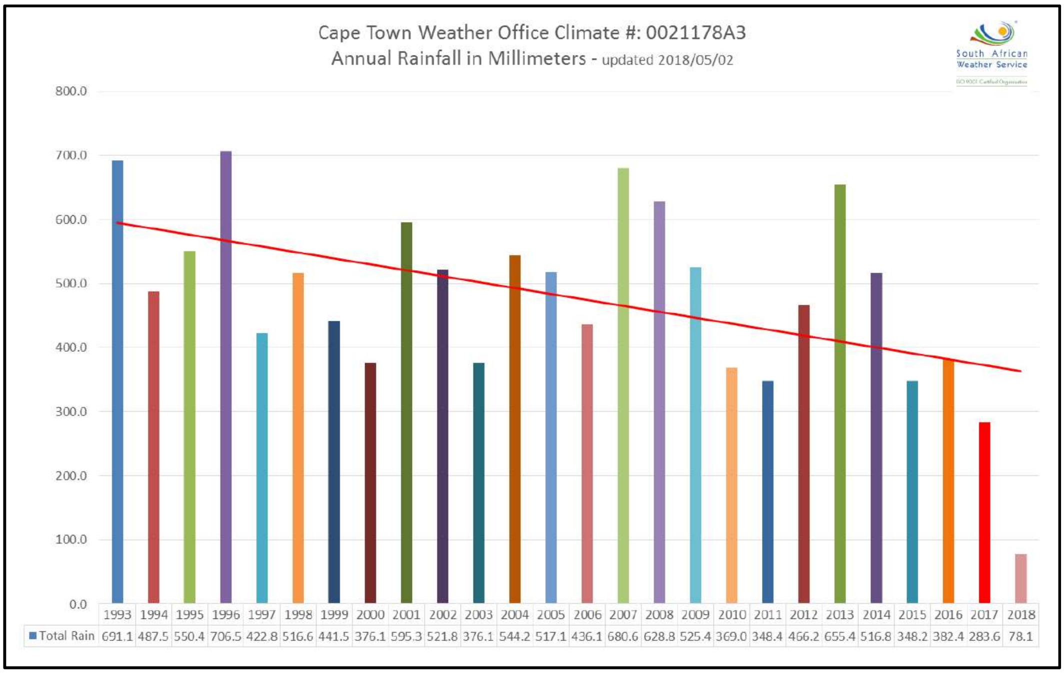


Figure C.3: Scenario 1: Raw Water Input from Precipitation

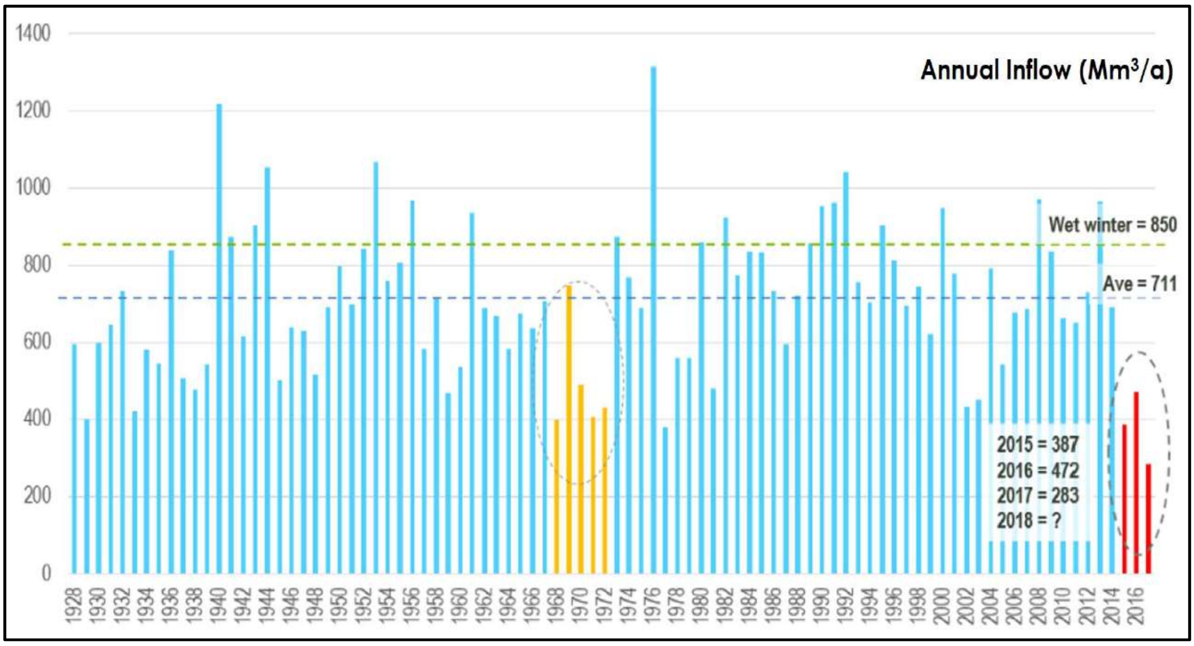


Figure C.4: Scenario 1: Raw Water Input from Annual Runoff

Catchment Look up = ([(2001,0)-(2040,2e+008)], (2001,0), (2002,0), (2003,0), (2004,0), (2005,0), (2006,0), (2007,0), (2008,0), (2009,1.427e+008), (2010,1.427e+008), (2011,1.427e+008), (2012,1.427e+008), (2013,1.427e+008), (2014,1.427e+008), (2015,1.427e+008), (2016,1.427e+008), (2017,1.427e+008), (2018,1.427e+008), (2019,1.427e+008), (2020,1.427e+008), (2021,1.427e+008), (2022,1.427e+008), (2023,1.427e+008), (2024,1.427e+008), (2025,1.427e+008), (2026,1.427e+008), (2027,1.427e+008), (2028,1.427e+008), (2029,1.427e+008), (2030,1.427e+008), (2031,1.427e+008), (2032,1.427e+008), (2033,1.427e+008), (2034,1.427e+008), (2035,1.427e+008), (2036,1.427e+008), (2037,1.427e+008), (2038,1.427e+008), (2039,1.427e+008), (2040,1.427e+008))

Source: 2009 Berg River Augmentation Scheme aim to supply approximately 20% of the city's water supply, thus the catchment area is taken as 20% of the *Initial Catchment Area* in 2009. SA News (Available Online: https://www.sanews.gov.za/south-africa/r15bil-berg-river-dam-supply-20-cape-towns-water)

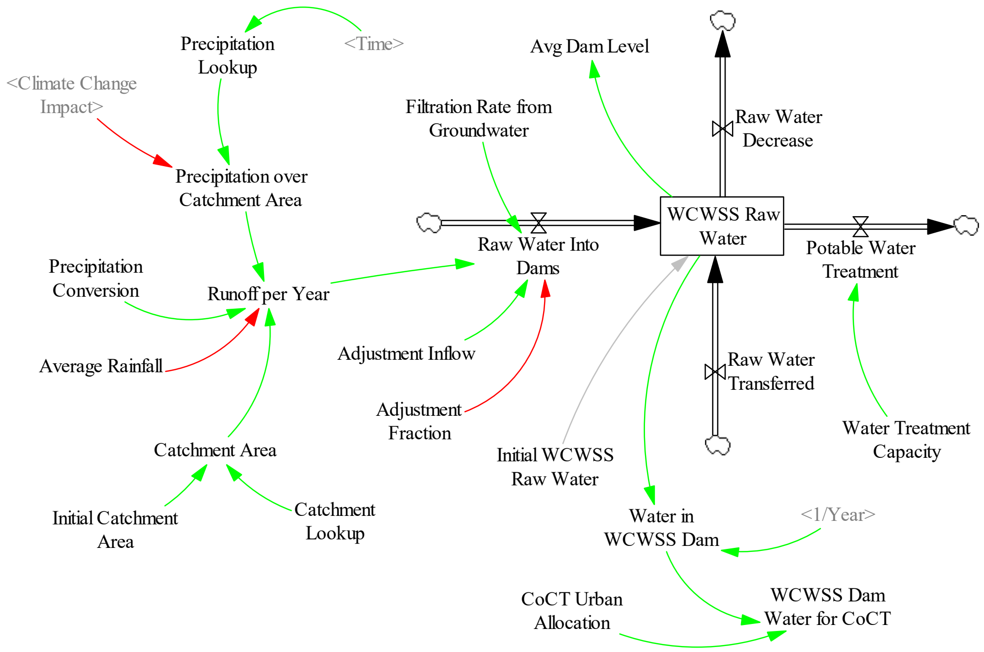


Figure C.5: Scenario 1: Raw Water with Precipitation or Average Annual Rainfall as Inflow Input

C.2 Scenario 2: Rainwater Harvesting

Retain rainwater runoff in storage tanks serve as supplementary non-potable water stock to ultimately reduce total water demand in the urban water system. The retention of this water waste stream, adds non-potable supply, as well as reduce the stormwater runoff and providing a more natural flow into wetlands and estuaries. Adjustments are made to the model to investigate the impact of precipitation on the volume of water entering rainwater harvesting systems.

Average precipitation values based on climate scenarios are compared with provided precipitation levels. These adjustments to parameters are captured and indicated in purple. The following quantification values include:

Rainwater Entering Tanks = MIN((("1/Year" * Storage Capacity for Rainwater Harvesting) - ("1/Year" * Volume of Stored Rainwater)), (Precipitation * Total HH Roof Catchment Area * Roof Runoff Coefficient), (Precipitation over Catchment Area * Total HH Roof Catchment Area * Roof Runoff Coefficient * Precipitation Conversion))

Potential Rainwater Stock = Precipitation Conversion * Precipitation over Catchment Area * Roof Runoff Coefficient * Total HH Roof Catchment Area

Avg Rainfall = 490mm

The model structure for testing the yield and behaviour of the domestic and industrial rainwater harvesting system for the City of Cape Town is shown in Figure C.6. Changes based on tank refills and the the number of entities utilising rainwater harvesting systems can be adjusted and simulated to explore the influence and impact of various parameters within the system.

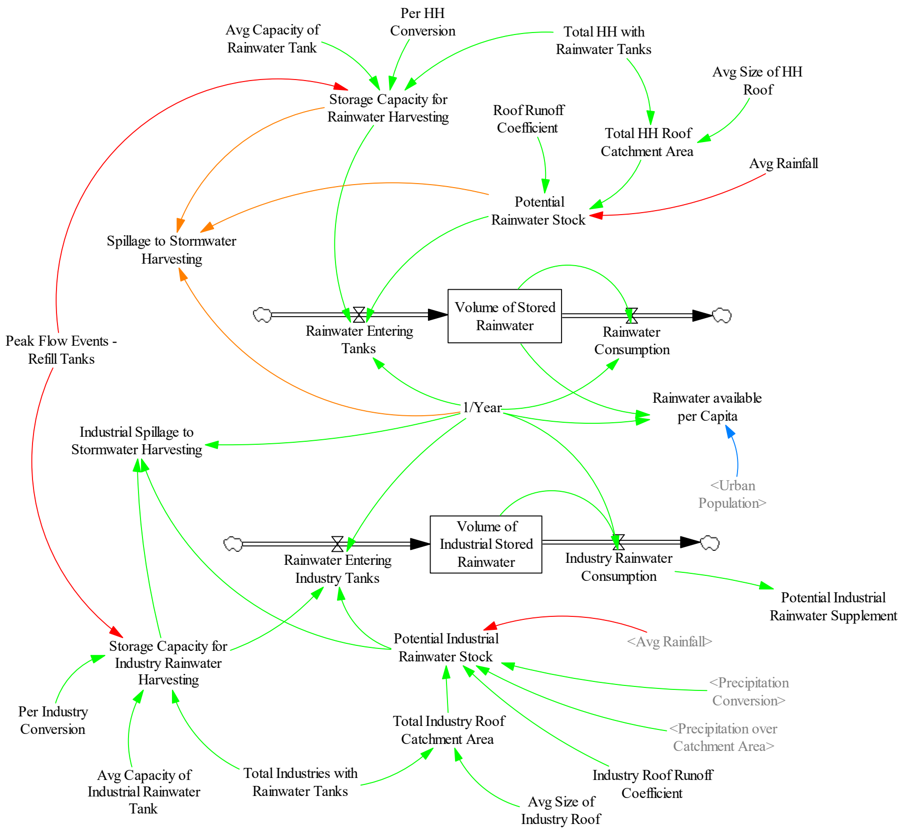


Figure C.6: Scenario 2: Domestic Rainwater Harvesting System

Industrial facilities have extended catchment and storage potential, however, the totality of facilities utilising rainwater harvesting systems to supplement non-potable requirements are not as extensive as the total households utilising these alternative water sources. Assumptions are made and tested with regards to storage capacity, rooftop catchment area and the quantity of industrial facilities utilising rainwater harvesting systems. Table C.2 captures parameter values for Scenario 2.

Table C.2: Scenario 2: Rainwater Harvesting Parameters

Parameter	Value	Unit	Note
Fraction of FHH with Rainwater Tanks	0.5	Dmnl	–
Avg Size of HH Roof	50	m^2	–
Avg Capacity of Rainwater Tank	10	m^3	–
Total Industries with Rainwater Tanks	10 000	Industries	–
Avg Size of Industry Roof	500	m^2	–
Avg Capacity of Industrial Rainwater Tank	100	m^3	–

Stormwater Harvesting

Urban Runoff = CoCT Area *Fraction of Urban Runoff *Urban Built-Up Fraction *Precipitation over Catchment Area*Km Conversion*Precipitation Conversion

Volume of Rainwater Captured = Industry Rainwater Consumption+Rainwater Consumption

The potential of urban runoff is significant, approximately generating equivalent quantities to match urban demand as shown in Figure C.7.

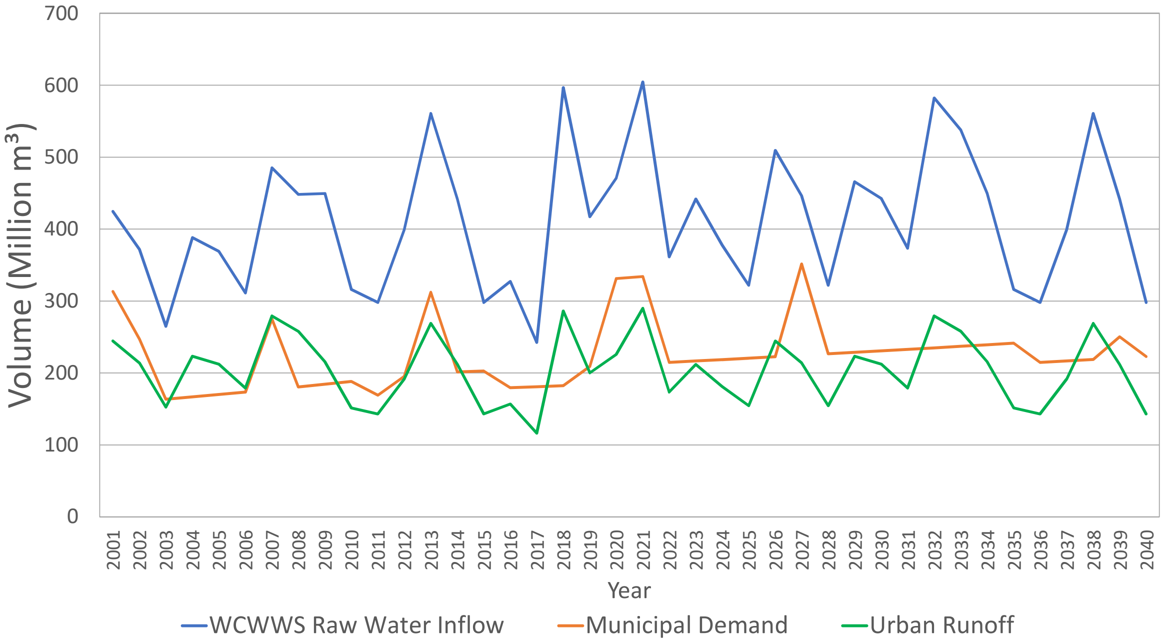


Figure C.7: Scenario 2: Potential Stormwater Runoff and Municipal Demand

Figure C.8 represents the simple system dynamics structure for stormwater runoff.

C.3 Scenario 3: Greywater

Scenario 3 explore the influence and impact of reusing greywater in industry and domestic households. The model structure for industrial greywater is shown in Figure C.9.

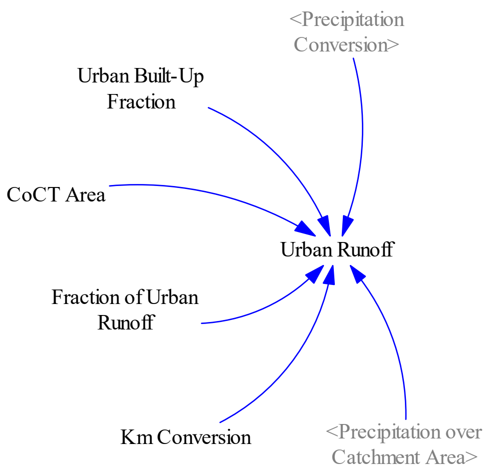


Figure C.8: Scenario 2: Stormwater Runoff Sub-model

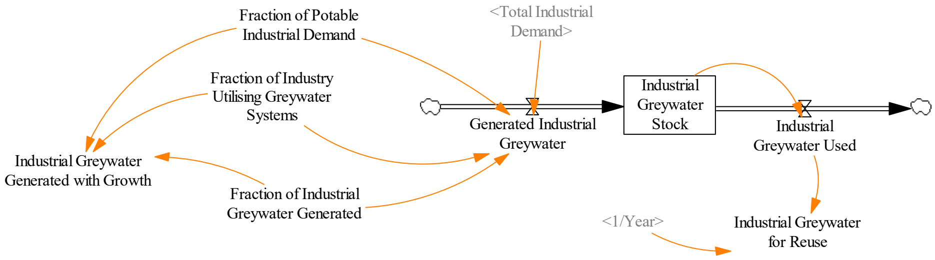


Figure C.9: Scenario 3: Industrial Generated Greywater

The reuse of greywater in domestic households and the influence thereof on the municipal water consumption is explore in Chapter 7. The model structure in Figure C.10 represents the causal links between greywater generating parameters in domestic households.

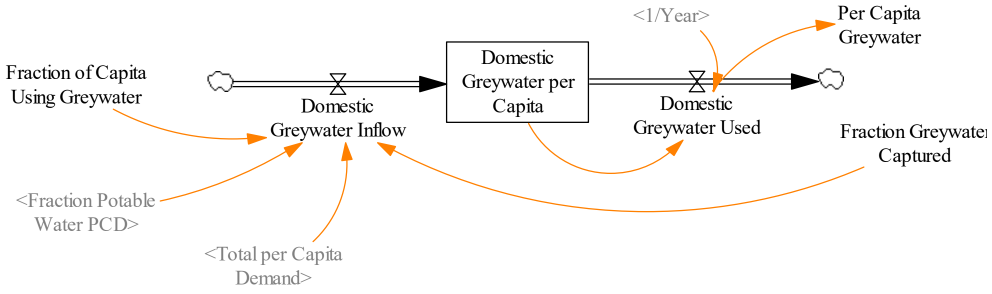


Figure C.10: Scenario 3: Domestic Generated Greywater

C.4 Scenario 4: Decentralise Wastewater Treatment

Scenario 4 investigates the change in consumption patterns in industrial with regards to the implementation of decentralised wastewater treatment plants in industry. The model

Table C.3: Scenario 3: Greywater Reuse Parameters

Parameter	**Value**	**Unit**	**Note**
Fraction of Greywater Captured	0.5	Dmnl	–
Fraction of Capita Using Greywater	0.5	Dmnl	–
Fraction of Industrial Greywater Generated	0.3	Dmnl	–
Fraction of Industry Utilising Greywater Systems	0.7	Dmnl	–

structure for the reuse of treated effluent is shown in Figure C.11.

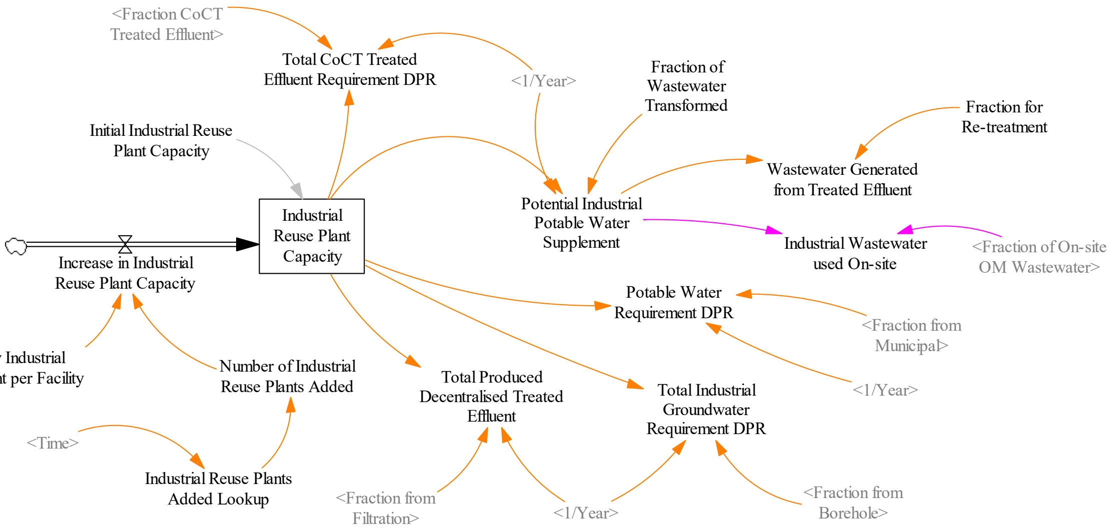


Figure C.11: Scenario 4: Reuse Supply Sub-Model: Industrial Wastewater Reuse

Table C.4: Scenario 4: Decentralised Wastewater Reuse Parameters

Parameter	**Value**	**Unit**	**Note**
Fraction Supplemented	1	Dmnl	–

C.5 Scenario 5: Combined Intervention

The impact on the total municipal water demand for the implementation of several intervention scenarios are captured in Figure C.12.

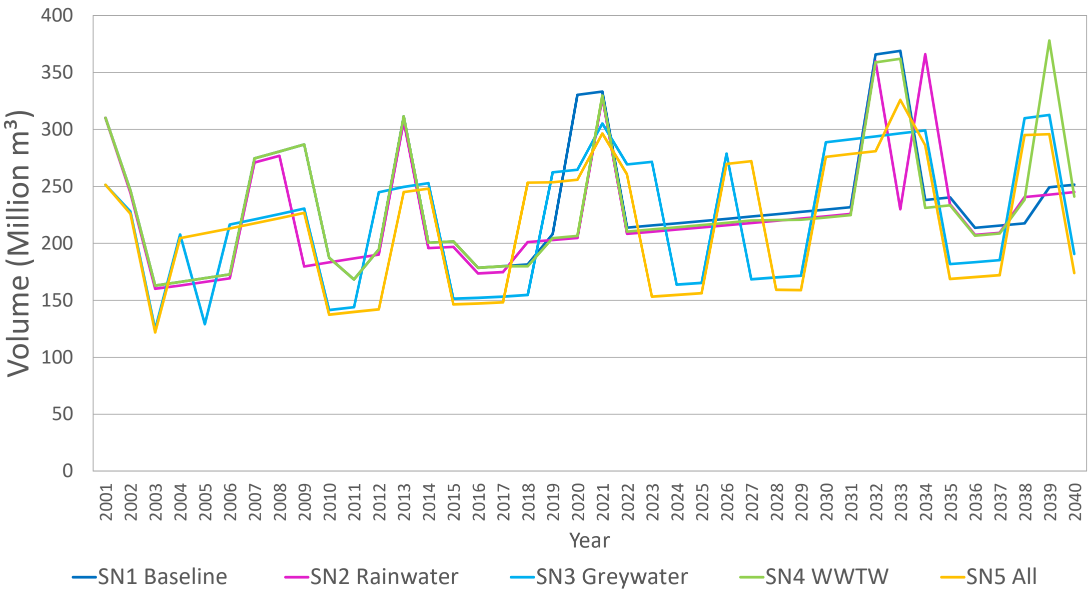


Figure C.12: Scenario 5: Municipal Demand

C.6 Case Study Calibration

To determine the effect of utilising groundwater as a supplementing source to the potable water produced by the Old Mutual blackwater filtration plant, a simulation run with several scenarios are explored. Changing the *Fraction OM Borehole Water*, while fixing the remainder of the variables, allow for the exploration of the likely impact the use of groundwater may have on the production of potable water within the decentralised system.

The following parameters are fixed as per Table C.5.

Table C.5: Fixed Parameters for Old Mutual Groundwater Calibration

Fixed Parameter	**Value**	**Unit**
Fraction OM Runoff Used	0	Dmnl
Fraction of Treated Effluent	0.25	Dmnl
Fraction of OM WW	0.97	Dmnl
Fraction Consumption	0.53	Dmnl

The system dynamics model allows for the exploration of various facets of the water system, including the use of stormwater as a source of input into decentralised wastewater treatment plants. Input parameters into the Old Mutual blackwater filtration plant is fixed at *Fraction OM Borehole Water* set to zero and *Fraction of Treated Effluent* set to 25%. The *Fraction OM Runoff Used* is varied from 0, 0.3 and 0.5 to evaluate the influence of reusing urban runoff on the production of potable quality water on-site. Results in Figure C.13 indicate that utilising urban runoff as an input source into the wastewater treatment plant may serve to address the delta in wastewater produced on-site.

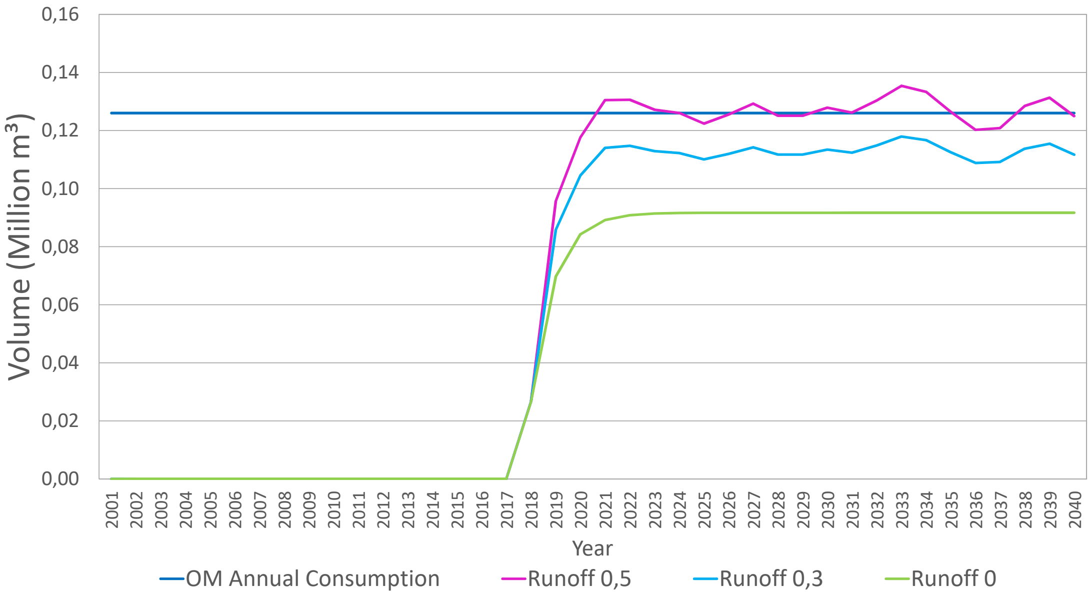


Figure C.13: Mutualpark Urban Runoff to Increase Potable Water Production on Campus

C.7 Model Parameter Settings

The model parameters for the result comparison is captured in Table C.6, Table C.7, Table C.8 and Table C.9. Parameter limits are also indicated. These parameters can be adjusted by decision-makers to test the system responsiveness and the impact on total municipal water requirements as well as water supply stress.

Table C.6: Decision Support Parameters: Water as a Resource

Parameter	**Value**	**Unit**	**Max**	**Min**
Avg Rainfall	490	Millimetre/Year	1800	0
Avg Capacity of Rainwater Tank	10	Mcubed	–	0
Peak Flow Events - Refill Tanks	100	Mcubed	–	0
Filtration Rate to Groundwater	0	Mcubed/Year	–	0
Adjustment Inflow	0	Mcubed/Year	–	0
Raw Water Losses	0	Mcubed/Year	–	0
Avg Size of HH Roof	50	Msquare/Household	–	0
Annual Groundwater Usage per HH	40	Mcubed/Year/Household	–	0
Groundwater Usage per Hectare	400	Mcubed/(Ha*Year)	–	0
Size of Industrial Site	0.5	Ha/Industries	–	0
Industries Utilising Groundwater	5000	Industries	–	0
Total Industries with Rainwater Tanks	10 000	Industries	–	0
Avg Size of Industry Roof	500	Msquare/Industries	–	0
Adjustment Fraction	0	Dmnl	1	0
Fraction of Reticulation Losses	0.09	Dmnl	1	0
CoCT Urban Allocation	0.64	Dmnl	1	0
Fraction of IFHH with Rainwater Tanks	0.01	Dmnl	1	0
Fraction of FHH with Rainwater Tanks	0.5	Dmnl	1	0
Roof Runoff Coefficient	0.9	Dmnl	1	0
Peak Flow Events - Refill Tanks	1	Dmnl	–	1
Industry Roof Runoff Coefficient	0.9	Dmnl	1	0
Fraction of Groundwater Utilised	1	Dmnl	1	0
Fraction Groundwater Recharge	0.3	Dmnl	1	0
Fraction of HH Boreholes	0.02	Dmnl	1	0

Table C.7: Decision Support Parameters: Water as a Product Input

Parameter	**Value**	**Unit**	**Max**	**Min**
Select Economic Growth Rate	1	1/Year	3	1
Population Decline Rate	0	Dmnl	1	0
Calibrate Domestic Usage	0.8	Dmnl	1	0
Consumption Efficiency	0.9	Dmnl	1	0
Fraction Backyard Dwellers	0.068	Dmnl	1	0
Fraction Informal HH	0.13	Dmnl	1	0
Fraction of Formal HH	0.802	Dmnl	1	0
Fraction of Industrial Demand	0.3	Dmnl	1	0
Industrial Consumption Efficiency	0.9	Dmnl	1	0
Fraction of Non-Potable Industrial Demand	0.3	Dmnl	1	0
Fraction of Potable Industrial Demand	0.7	Dmnl	1	0

Table C.8: Decision Support Parameters: Water as a Waste Stream

Parameter	**Value**	**Unit**	**Max**	**Min**
Number of HH per Greywater System	4	Household	–	1
Lifetime of Greywater System	10	Year	20	1
Cost per Dom Greywater System	120 000	Rand	–	1
Fraction of Greywater Captured	0.5	Dmnl	1	0
Fraction of Capita Using Greywater	0.5	Dmnl	1	0
Fraction of Industry Utilising Greywater Systems	0.7	Dmnl	1	0
Fraction of Industrial Greywater Generated	0.3	Dmnl	1	0
Fraction of CoCT Treated Effluent for Reuse	0.1	Dmnl	1	0
Fraction of Wastewater Transformed	0.95	Dmnl	1	0
Fraction for Re-treatment	0.65	Dmnl	1	0
Fraction of Wastewater Generated	0.7	Dmnl	1	0
Fraction of Industrial Wastewater Generated	0.7	Dmnl	1	0

Table C.9: Decision Support Parameters: Old Mutual Blackwater Filtration Plant

Parameter	**Value**	**Unit**	**Max**	**Min**
WW from CoCT to OM	0	Mcubed/Year	–	0
Fraction of Greywater Captured	0.5	Dmnl	1	0
Fraction OM Runoff Used	0	Dmnl	1	0
Fraction of Treated Effluent	0.25	Dmnl	1	0
Fraction of OM WW	0.97	Dmnl	1	0
Fraction Consumption	0.53	Dmnl	1	0
Fraction Losses	0.07	Dmnl	1	0
Fraction Irrigation	0.3	Dmnl	1	0
Fraction Evaporation	0.1	Dmnl	1	0
Fraction of OM WW	0.97	Dmnl	1	0
Fraction Process Losses	0.05	Dmnl	1	0
Fraction OM Borehole Water	0.14	Dmnl	1	0
Fraction of Treated Effluent	0.25	Dmnl	1	0
Intervention	0.3	Dmnl	1	0

Appendix D

System Dynamics Model

The dynamic structures for the sub-models represent the urban water system for the City of Cape Town, using several stocks and flows, summarised in Table D.1.

The model key in Figure D.1 provide context to the colour arrows used.

🟩	Water as a resource	⬛	Stock-and-flow structures
🟦	Water as a product input	🟪	Old Mutual Water Filtration Plant
🟧	Water as a waste stream	🟦	For Future Research
🟥	Model Adjustments	🟪	Alternative model structure

Figure D.1: Model Key

The structures are referenced to represent the following sub-models:

1. Surface Water Supply Sub-Model: Figure D.2
2. Groundwater Supply Sub-Model: Figure D.3
3. Alternative Water Supply Sub-Model: Figure D.4, Figure D.5 and Figure D.6
4. Domestic User Sub-Model: Figure D.7
5. Industrial Users Sub-Model: Figure D.8
6. Consumption Patterns Sub-Model: Figure D.9
7. Water Demand Management Sub-Model: Figure D.7 and Figure D.8
8. Wastewater Treatment Works Sub-Model: Figure D.10
9. Retain, Reuse and Reduce Sub-Model: Figure D.11 and Figure D.12
10. Water Yield and Water Supply Stress Sub-Model: Figure D.13 and Figure D.14
11. Old Mutual Blackwater Filtration Plant Sub-Model: Figure D.15

Table D.1: City of Cape Town Urban Water System Stocks and Flows

Water as a Resource			
No	**Stock**	**Flow In**	**Flow Out**
1	WCWSS Dam Capacity	Increase in Dam Capacity	–
2	WCWSS Raw Water	Raw Water Into Dams Raw Water Transferred	Raw Water Decrease Potable Water Treatment
3	Potable Surface Water	Potable Water Treatment	Potable Consumption Reticulation Losses
4	Groundwater Abstraction Capacity	Increase in Groundwater Abstraction Capacity	–
5	Volume of Stored Rainwater	Rainwater Entering Tanks	Rainwater Consumption
6	Volume of Industrial Stored Rainwater	Rainwater Entering Industry Tanks	Industry Rainwater Consumption
7	Capacity of Desalinated Water	Increase in Desalinated Capacity	–
Water as a User Input			
No	**Stock**	**Flow In**	**Flow Out**
8	Urban Population	Population Growth	Population Decline
9	CoCT Industrial Allocation Growth	Increase CoCT Industrial Allocation	–
10	CoCT Industrial Allocation Growth Constrained	Increase CoCT Industrial Allocation Constrained	–
Water as a Waste Stream			
No	**Stock**	**Flow In**	**Flow Out**
11	Wastewater Treatment Works Capacity	Increase WWTW Capacity	–
12	Municipal Effluent Capacity	*Increase CoCT Effluent* Capacity	–
13	Treated Effluent for Reuse	Increase Treated Effluent Stock	Decrease Treated Effluent Stock
14	Domestic Greywater per Capita	Domestic Greywater Inflow	Domestic Greywater Used
15	Industrial Greywater Stock	Generated Industrial Greywater	Industrial Greywater Used
16	Industrial Reuse Plant Capacity	Increase in Industrial Reuse Plant Capacity	–
16	OM Storage Tanks	Treated WW Entering Borehole Water Entering	Over Capacity OM Potable Water Consumed
17	OM Treatment Plant Capacity	Increase OM WWTW Capacity	–

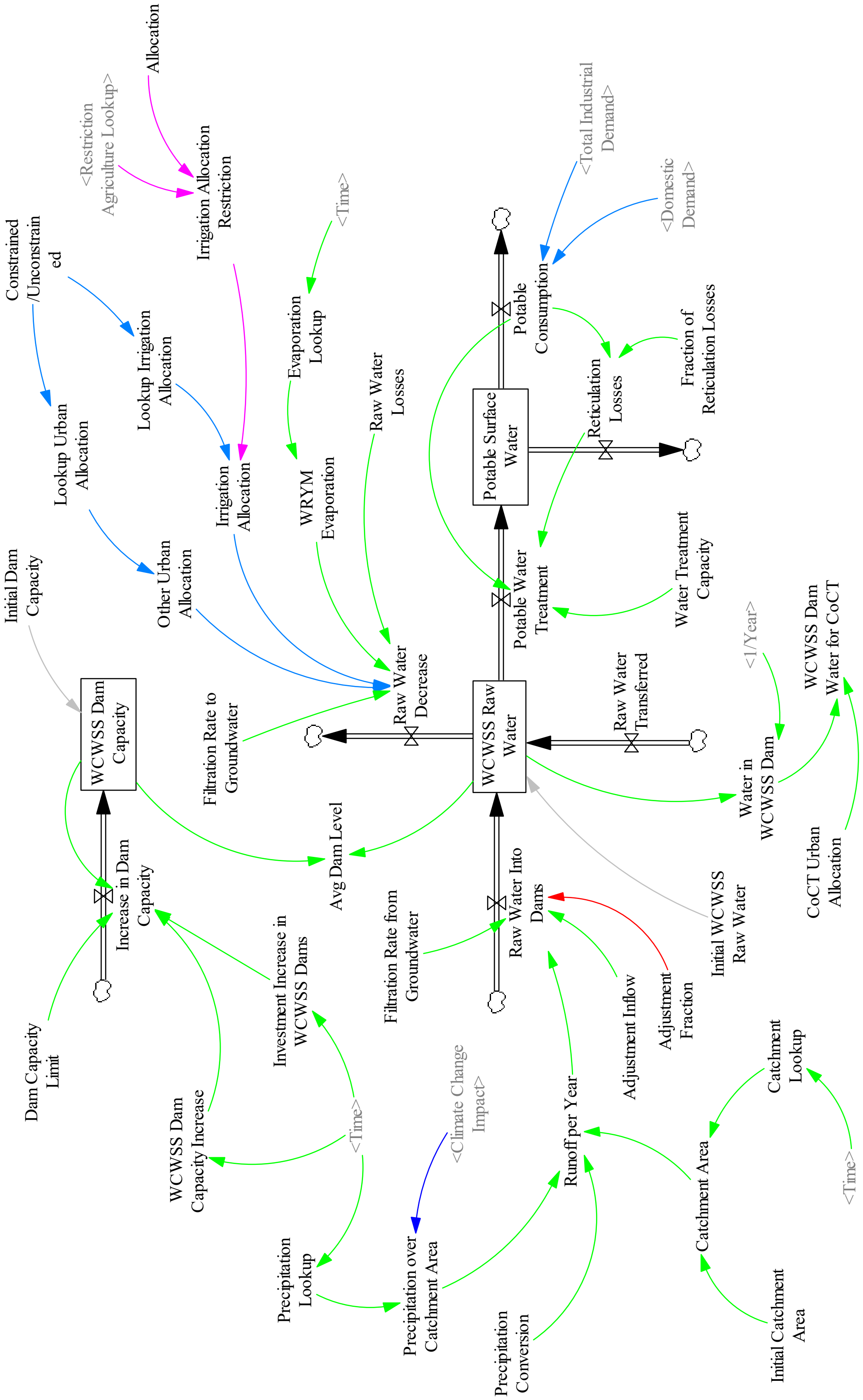


Figure D.2: Surface Supply Water Sub-Model

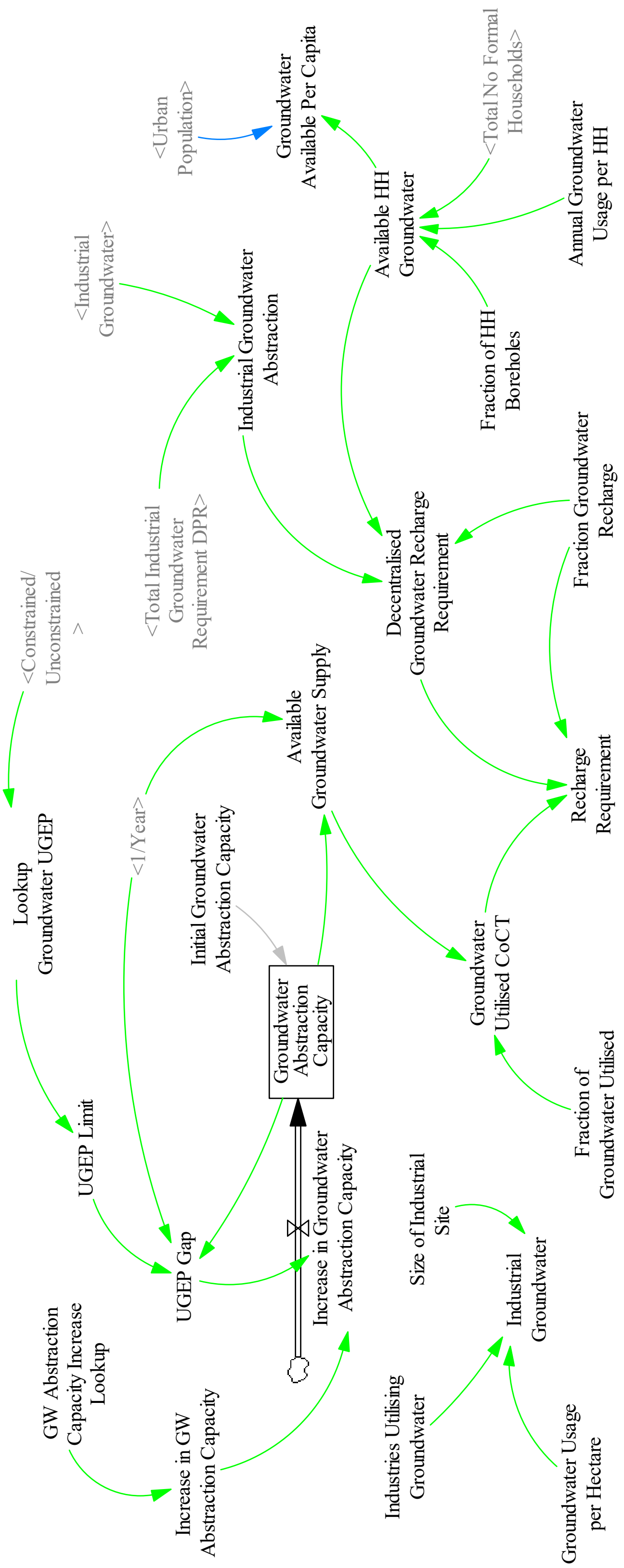


Figure D.3: Groundwater Supply Sub-Model

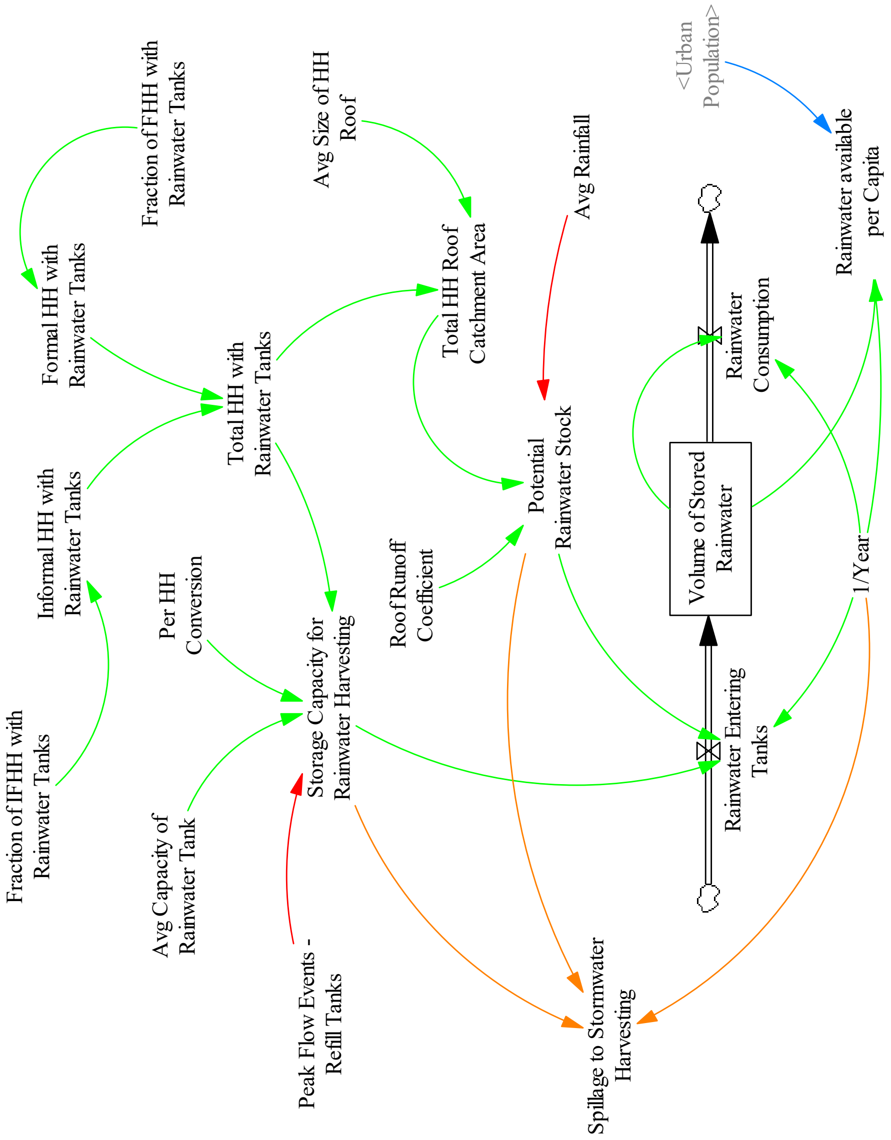


Figure D.4: Alternative Water Supply Sub-Model: Domestic Rainwater

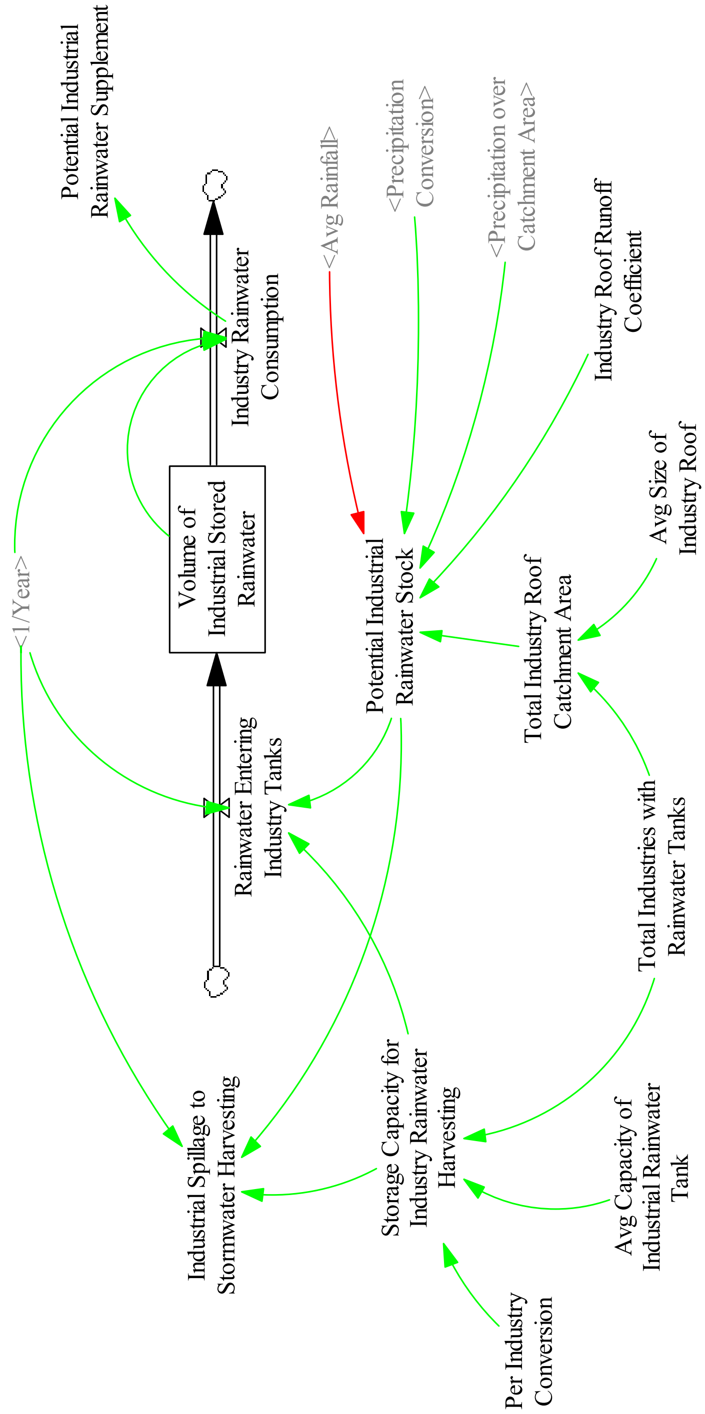


Figure D.5: Alternative Water Supply Sub-Model: Industrial Rainwater

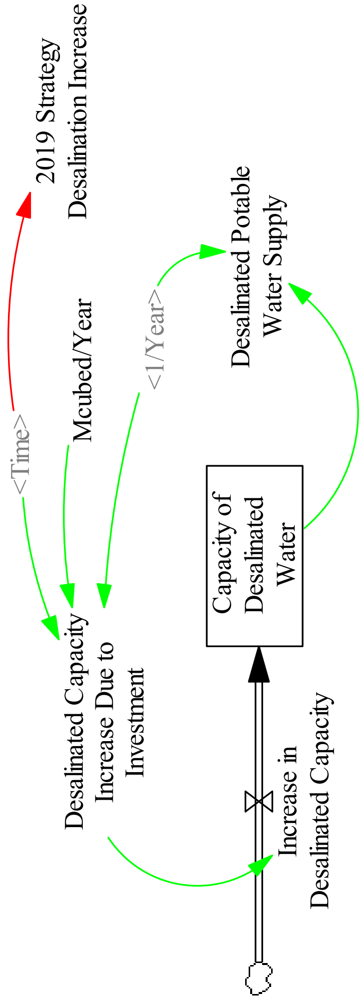


Figure D.6: Alternative Water Supply Sub-Model: Desalination

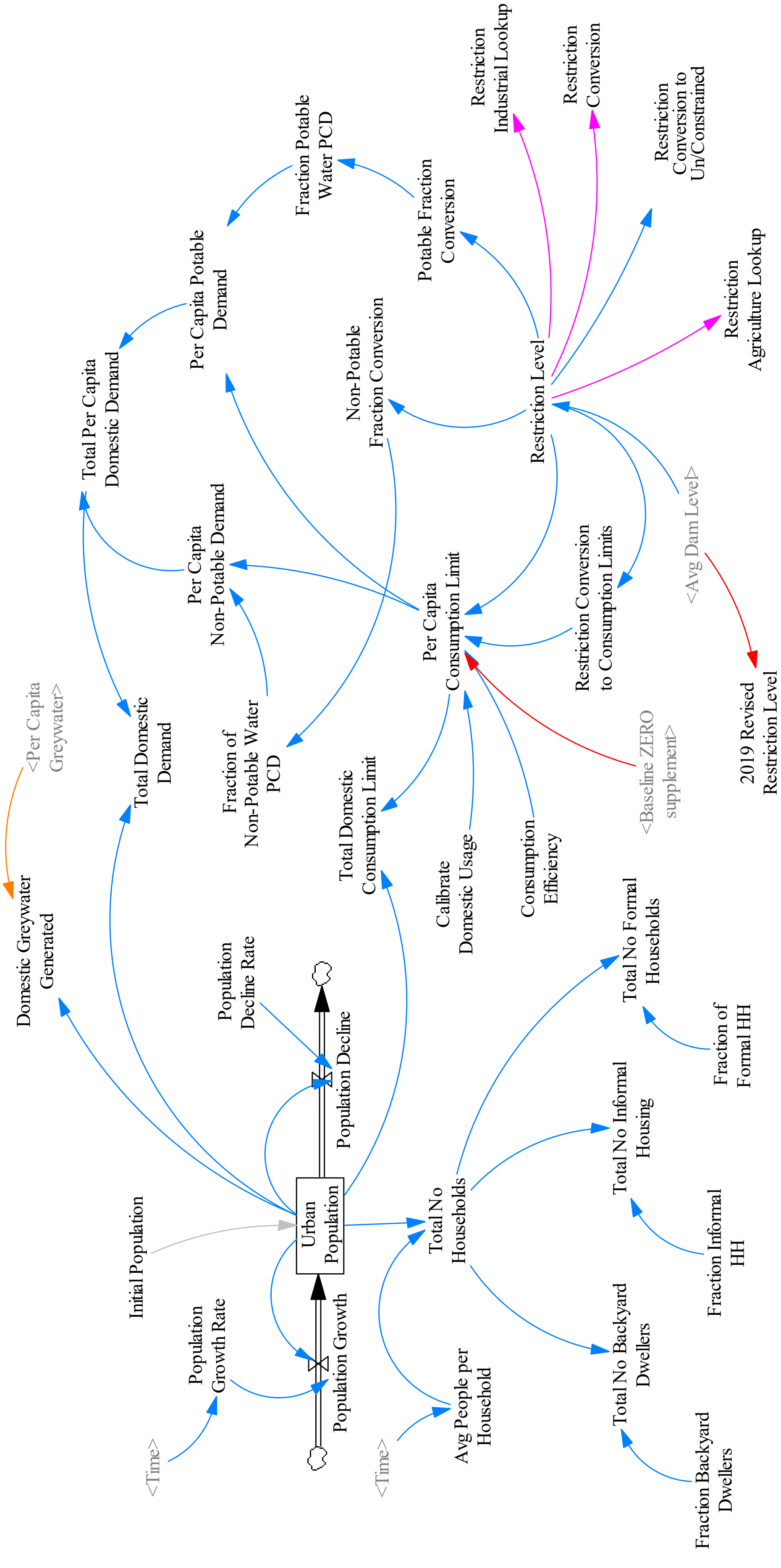


Figure D.7: Domestic Users Sub-Model

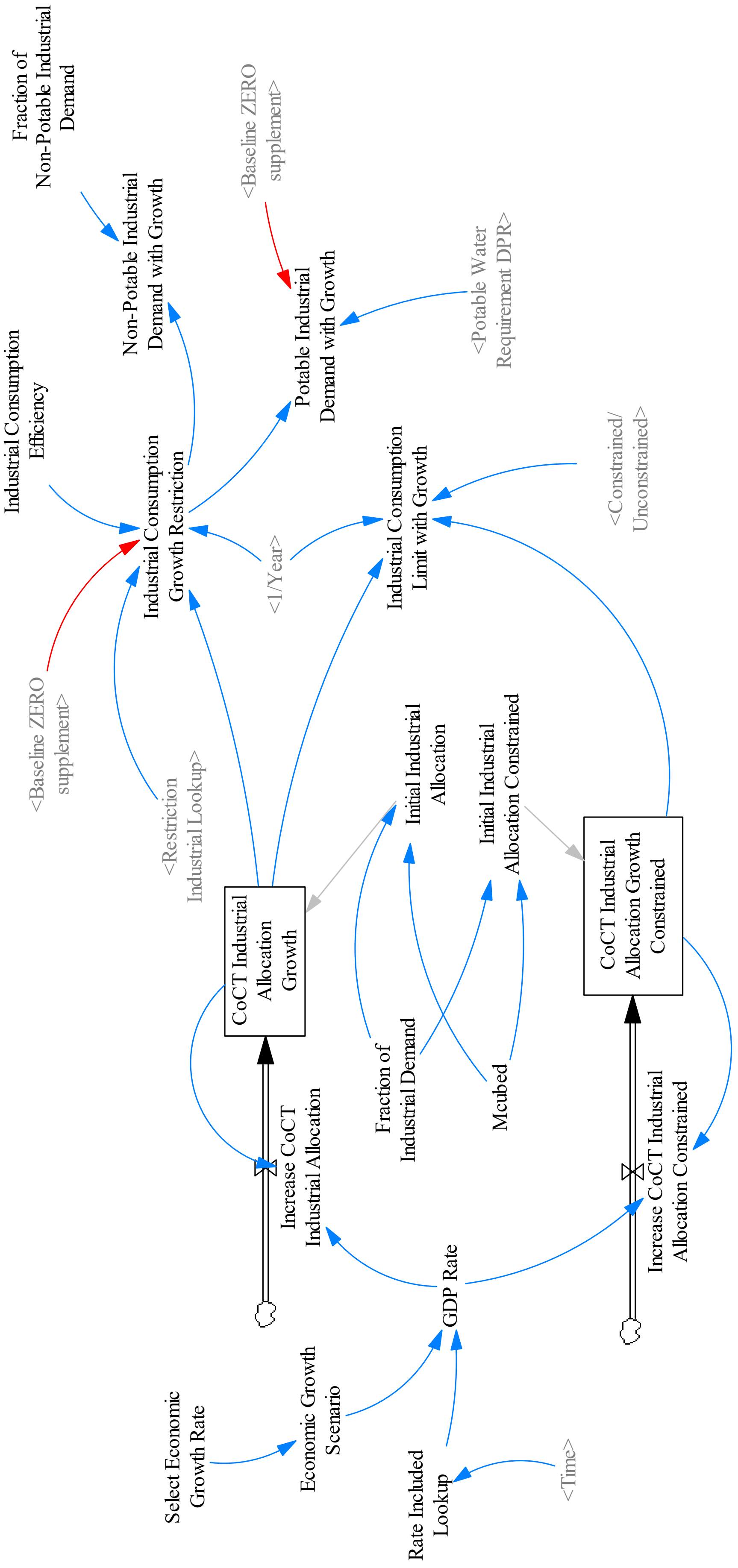


Figure D.8: Industrial Users Sub-Model

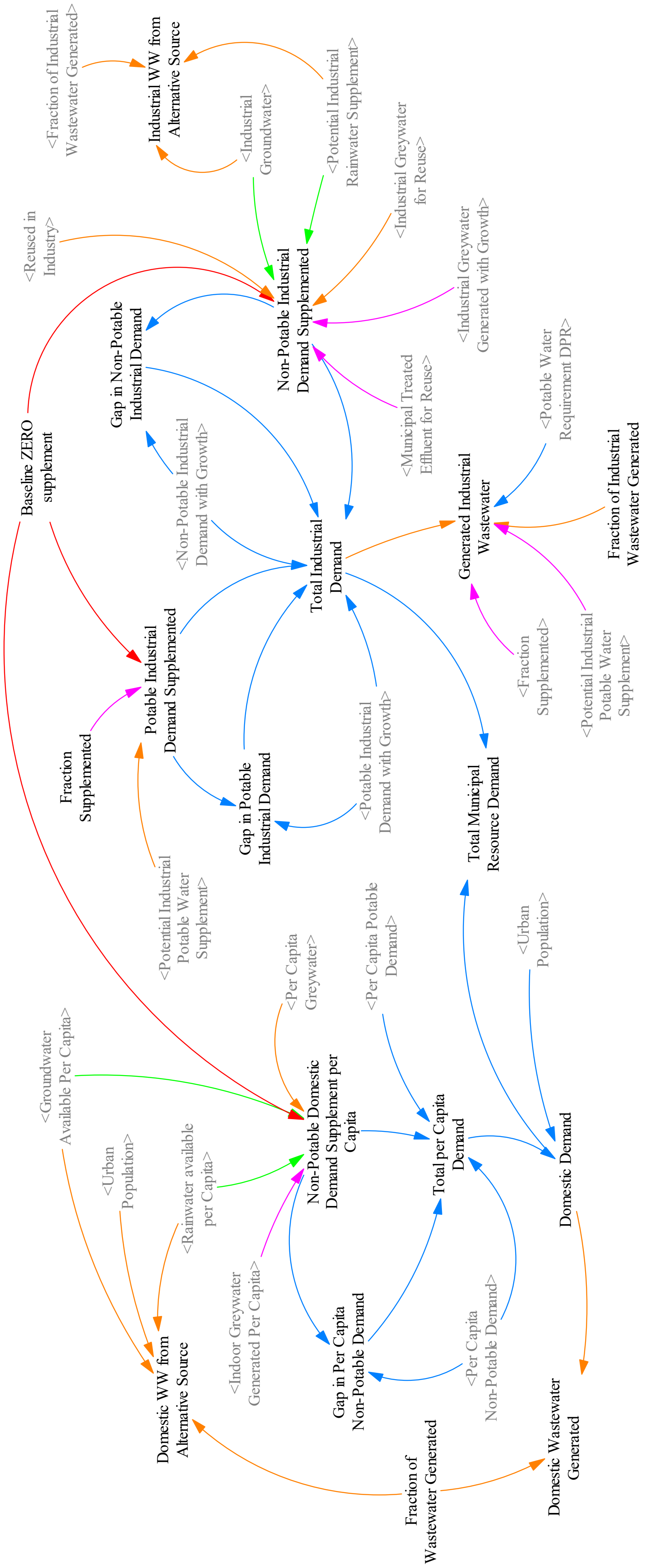


Figure D.9: Consumption Pattern Sub-Model

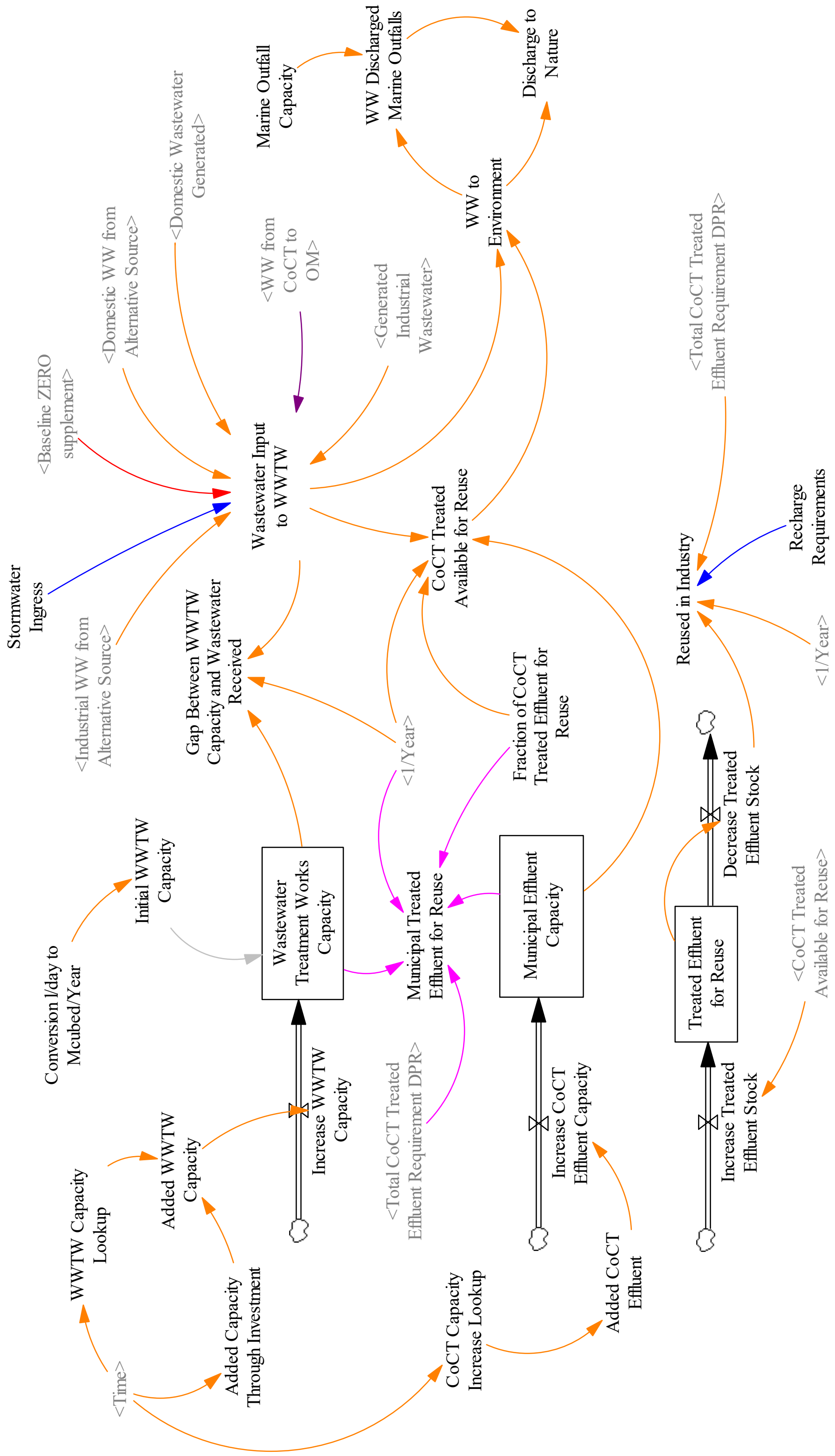


Figure D.10: Wastewater Treatment Works Sub-Model

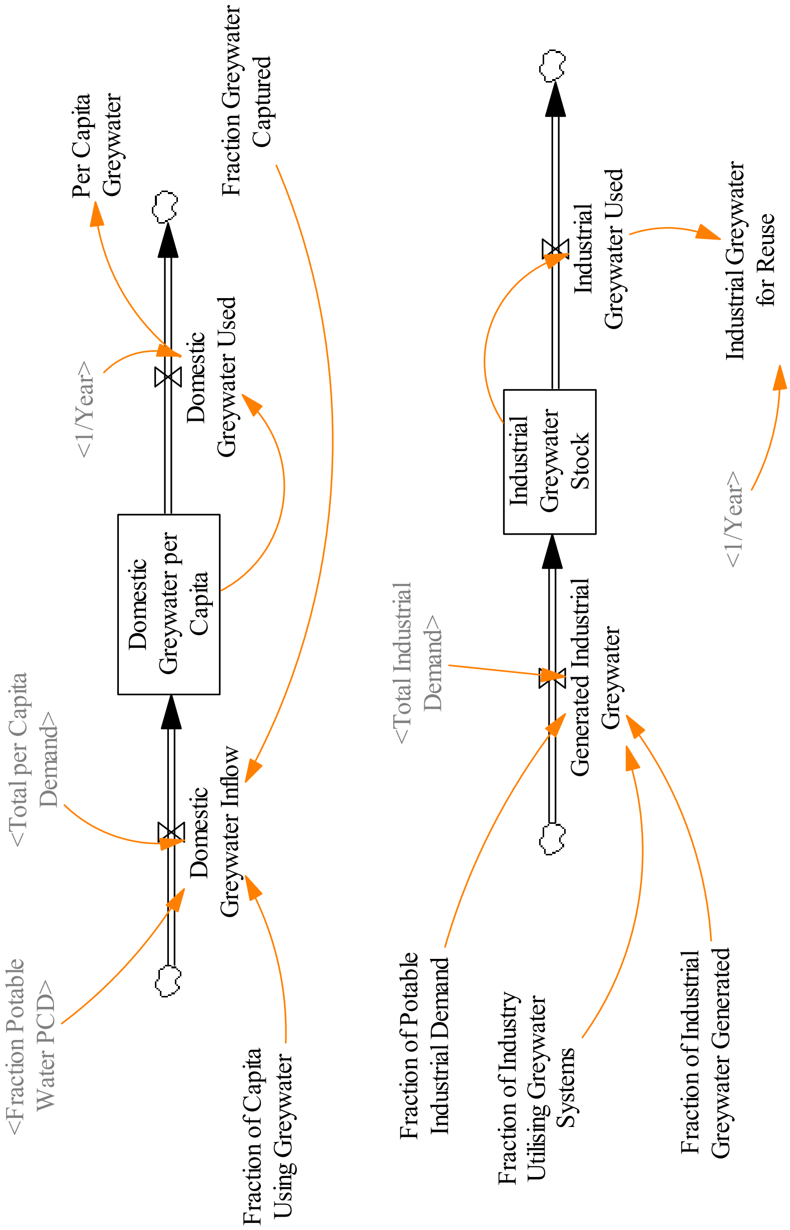


Figure D.11: Reuse Supply Sub-Model: Domestic and Industry Greywater

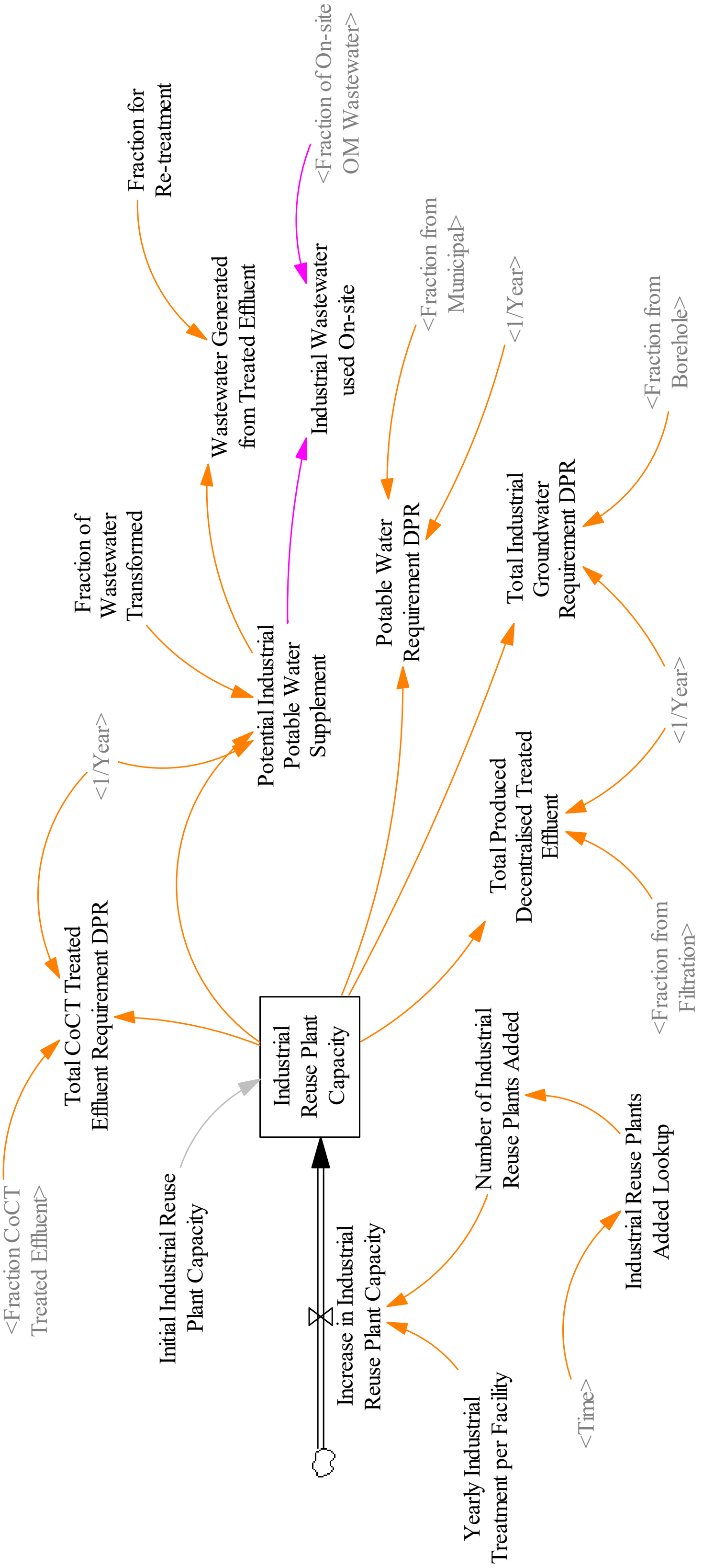


Figure D.12: Reuse Supply Sub-Model: Industrial Wastewater Reuse

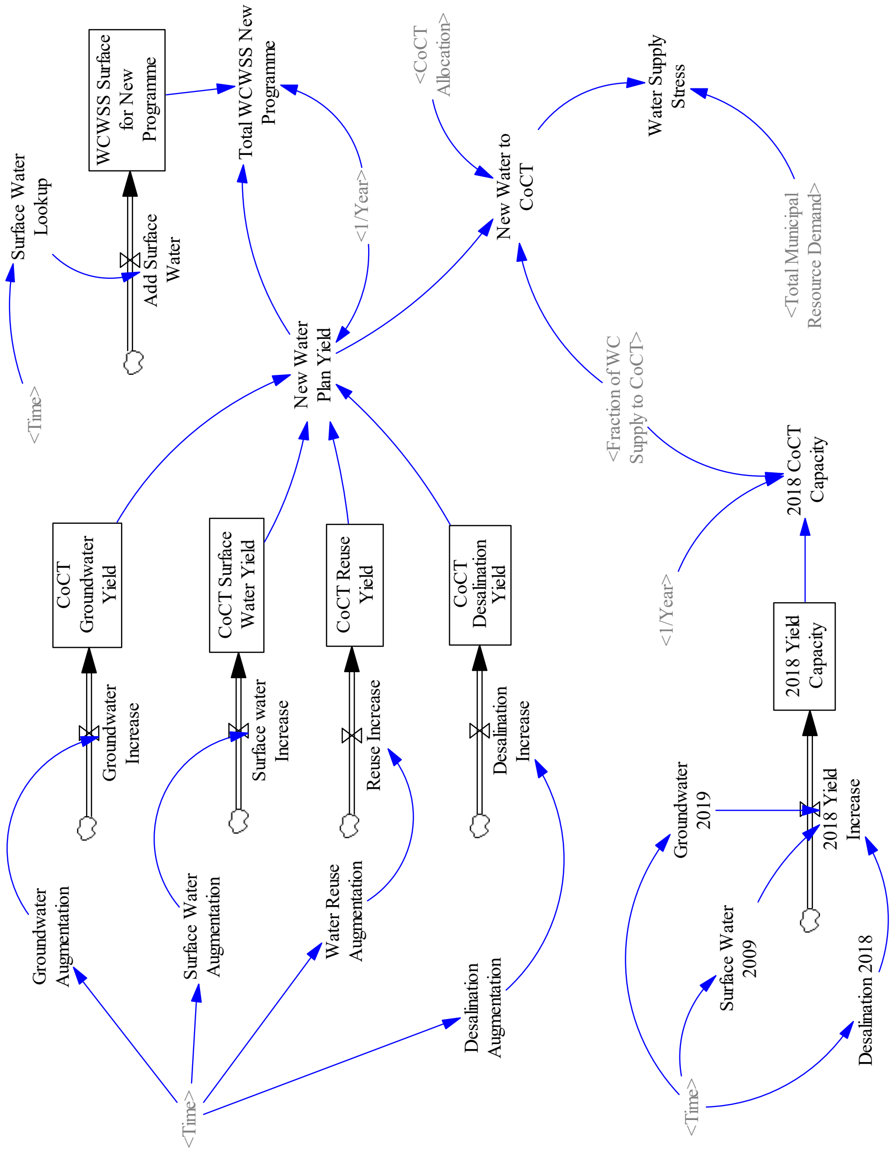


Figure D.13: Water Supply Stress Sub-Model: New Yield vs Demand

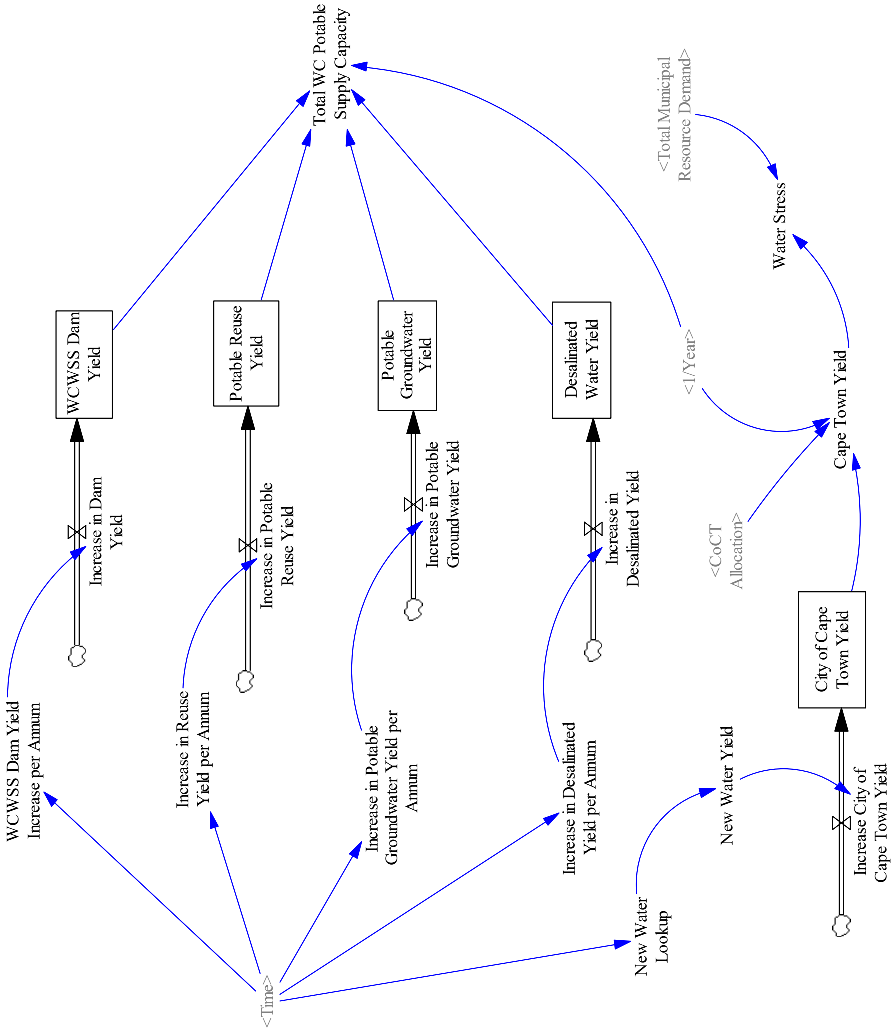


Figure D.14: Water Supply Stress Sub-Model: 2018 WCWSS Yield vs Demand

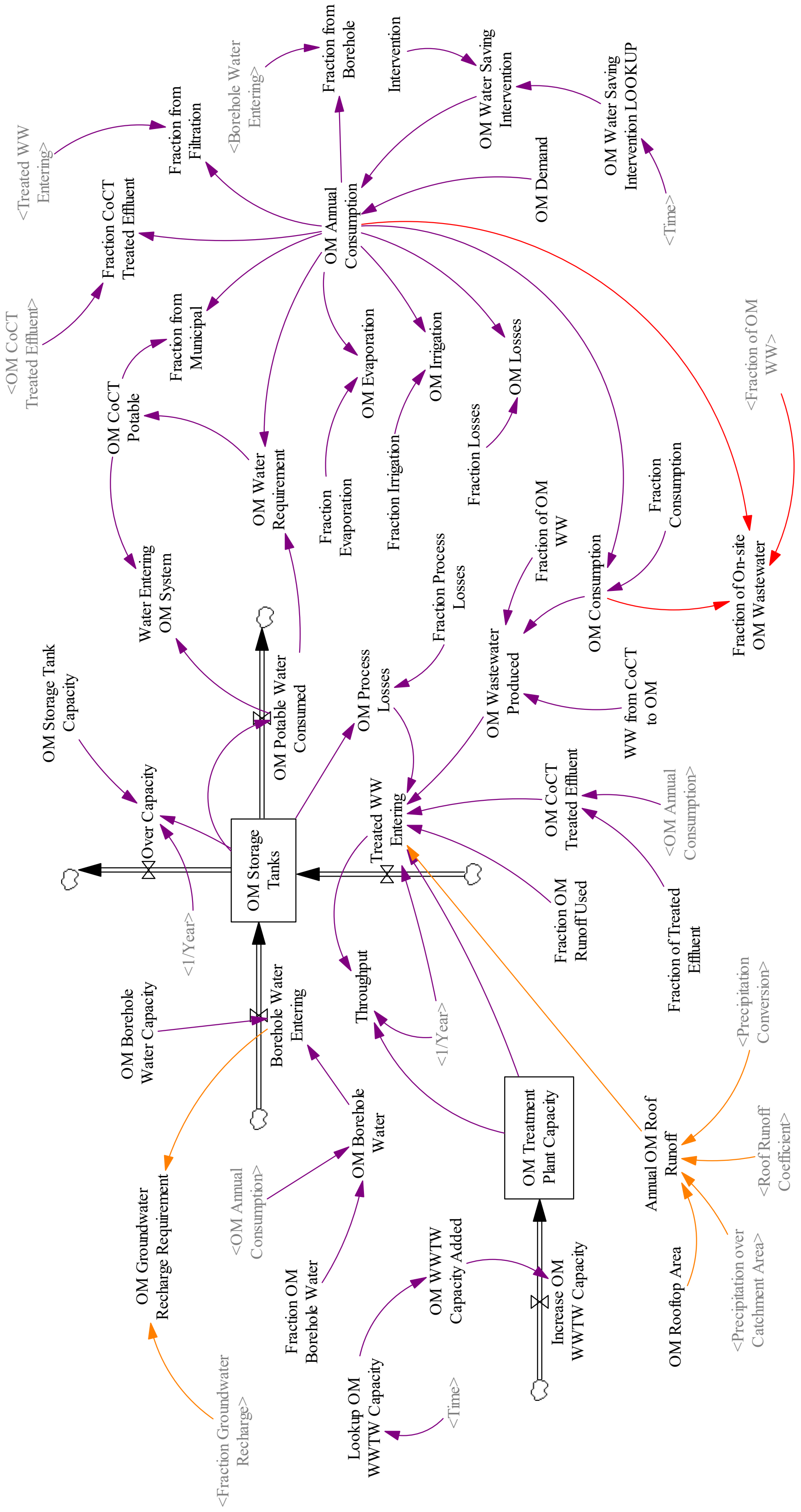


Figure D.15: Old Mutual Blackwater Filtration Plant Sub-Model

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