Water Resource Infrastructure Implications of a Green Economy Transition in the Western Cape Province of South Africa: A System Dynamics Approach

by

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DECLARATION

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ABSTRACT

For the Western Cape Province of South Africa to transition to a green economy, sustainable use of water resources is identified as a critical necessity. The green economy transition is seen as the most efficient way to transform the Western Cape Province to the lowest carbon emitting province in South Africa as well as the leading green economy hub on the continent. This research aimed to conceptualize the factors that influence the transition to a green economy in the Western Cape Province regarding the water resources and provide a dynamic model with a modelling technique that will best suit this industry. Ultimately the objective of the research was to utilize results generated by the model to assist policy makers with important decisions regarding the transition to a green economy.

Many different role-players in the water industry interact on a non-linear basis which makes it difficult to know what consequences different actions will have. Therefore, the water resource industry was found to be a system with complex interconnections and dependencies. A number of modelling techniques namely; econometrics, optimisation and system dynamics were studied to establish which technique would be best suited for the case of water resources in the Western Cape Province. System dynamics was identified as an appropriate approach to this complex system.

Even though this real-life situation is impossible to model to perfection it was concluded that system dynamic modelling will best represent the dynamic complexity that are inherent in green economy transitioning. System Dynamics characteristics, such as its stock and flows and casual loop utilization as well as its ability to model complex real life situations on a relatively low level of complexity proved it to be the appropriate tool.

The results generated by the model, for the water supply and demand, showed that the Western Cape Province could possibly experience extreme water shortages in the near future if the current way of living continued. However, it was established that, with sufficient investment and effective management, the demand of the Western Cape Province could be met. After thorough research and careful consideration various interventions were simulated into the model against a climate change scenario. Since the proposed interventions proved to be sufficient to supply water until 2040, the scenario implementing the interventions was identified as a possible strategy for the Western Cape Province.

This research ensured a better understanding of the complexities and implications involved in the transition to a green economy for the water resources of the Western Cape Province. Therefore, the research lays the platform for future studies in this field and can hopefully inform the Western Cape Province in its discussions in becoming the lowest carbon emitting province in South Africa and the leading green economy hub on the African continent.

UITTREKSEL

Vir die Wes-Kaapse Provinsie van Suid-Afrika om te transformeer na 'n groen ekonomie, word die volhoubare gebruik van water geïdentifiseer as 'n noodsaaklikheid. So 'n groen oorgangsproses word beskou as een van die belangrikste maniere waarop Suid-Afrika 'n samelewing sal kan kweek wat gestel is op omgewingsvolhoubaarheid, doeltreffende hulpbron gebruik, lae-koolstof ekonomiese aktiwiteite sowel as 'n regverdigheid. Hierdie studie het beoog om die faktore wat die oorgangsproses na 'n groen ekonomie beïnvloed, binne die water sektor van die Wes-Kaap, te konseptualiseer. Verder het die studie beoog om 'n dinamiese model te simuleer om uiteindelik die resultate van die model te kan gebruik om beleidmakers tydens die oorgangsproses te help.

Verskeie rolspelers in die industrie reageer op 'n nie-lineêre basis, wat dit moeilik maak om te weet watter gevolge verskillende aksies sal hê. Die water sektor is daarom geïdentifiseer as 'n sisteem met komplekse interaksies en afhanklikhede. 'n Ondersoek van akademiese literatuur rakende so 'n oorgangsproses en die bestuurspraktyke wat daarmee gepaard gaan, het gelei tot die begrip van die gekompliseerde stelsels in die oorgang tot 'n groen ekonomie. Daarna was verskeie modellerings tegnieke ondersoek om uiteindelik vas te stel dat stelsels dinamika die beste gepas is vir die spesifieke probleem.

Selfs al is dit onmoontlik om die werklike situasie met perfeksie te moduleer het stelsels dinamika die ingewikkelde verwantskappe tussen die rolspelers in die water sektor die beste voorgestel. Die resultate wat gegenereer is deur die model, vir die water voorsiening en aanvraag, het daarop gedui dat die Wes-Kaap moontlik ekstreme water tekorte kan ervaar as die huidige praktyke voortgesit word. Nietemin, dit was vasgestel dat die aanvraag van die Provinsie bereikbaar is met genoeg befondsing en behoorlike bestuur. Na deeglike navorsing en versigtige oorweging was verskeie water-besparings tegnieke in die model gesimuleer saam met 'n klimaat veranderings scenario. Die water-besparings tegnieke was genoeg om water te voorsien vir die Wes-Kaap, daarom is dit voorgestel as moontlike strategie om die voorspelde water tekort te beveg.

Die studie het gelei tot 'n beter begrip van die kompleksiteite en implikasies wat gepaard gaan met die oorgangsproses na 'n groen ekonomie, spesifiek vir die water sektor van die Wes-Kaap. Daarom skep die studie 'n platform vir toekomstige studies in hierdie veld. Hopelik kan die studie ook 'n bydrae lewer aan die Wes-Kaap tydens die proses om die laagste-koolstof-vrystellende provinsie in die land te word asook die beste groen ekonomie op die Afrika kontinent.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

BAU	Business As Usual
BGCMA	Breede Gouritz Catchment Management Agency
BOCMA	Breede Overberg Catchment Management Agency
CAS	Complex Adaptive System
CCT	City of Cape Town
CLD	Causal Loop Diagram
CMA	Catchment Management Agency
CMF	Catchment Management Forum
DEA	Department of Environmental Affairs
DEA&DP	Department of Environmental Affairs and Development Planning
DLG	Department of Local Government
DM	District Municipality
DOA	Department of Agriculture
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
F(t)	Value of stock over the entire time horizon
f(t)	In and outflows
FSL	Full Supply Level
GDP	Gross Domestic Product
GEI	Green Economy Initiative
kg	kilogram
l	Litre
m^3	Cubic meter
MAR	Mean Annual Runoff
MLP	Multi-Level Perspective
NDP	National Development Plan
NSSD1	National Strategy for Sustainable Development 2011-2014
NWRS1	National Water Resource Strategy First Edition
NWRS2	National Water Resource Strategy Second Edition
RWU	Regional Water Utility
SCOT	Social Construction Of Technology
SDM	System Dynamics Modelling
SFD	Stock and Flow Diagram
SRY	Storage Reliability Yield
t_0	Start of time horizon = 2001
t_n	End of time horizon = 2040
TCTA	Trans-Caledon Tunnel Authority
UAW	Unaccounted for water
UN	United Nations
UNEP	United Nations Environment Program
URV	Unit Reference Value
WC	Water Conservation
WCED	World Commissions on Environment and Development
WCWRM	Western Cape Water Resource Model
WCWSS	Western Cape Water Supply System
WDM	Water Demand Management
WeCaGEM	Western Cape Green Economy Model
WeCaWaRM	Western Cape Water Resource Model
WHO	World Health Organisation

WMA	Water Management Area
WRC	Water Research Commission
WSA	Water Service Authorities
WSP	Water Service Providers
WWTW	Waste Water Treatment Works

Note on the Department of Water and Sanitation (DWS)
The Department of Water and Sanitation (DWS) has undergone two name changes in the recent years. Until 2009 it was known as the Department of Water Affairs and Forestry (DWAF). After the election of April 2009 the Forestry Branch of the Department was incorporated into the Department of Agriculture to form the Department of Agriculture, Forestry and Fisheries (DAFF). Further restructuring took place in May 2014, which established the Department of Water and Sanitation (DWS).
Throughout this document the abbreviations, DWAF and DWA is used when the text refers to actions or documents under the jurisdiction of the then Department of Water Affairs and Forestry or the Department of Water Affairs respectively, while the abbreviation DWS is used for all references to the current departmental structure.

CHAPTER 1: INTRODUCTION

This chapter introduces the problem that the research addresses. Background and context is provided on the origin and development of sustainability and subsequently the green economy. A brief discussion on the complexities involved in the transition to a green economy in the South African context, and more specifically the Western Cape Province, is provided. Ultimately, the importance and role of water resources within the green economy transition in South Africa and the Western Cape Province is pointed out.

Furthermore, the necessity and objective of the research as well as the research strategy is stated in this chapter. The research strategy aims to guide the reader through the research which will consequently ensure a better understanding thereof.

1.1 Background

Internationally urbanisation and industrial development are destroying the environment. Natural resources are continually diminishing as the economic welfare of the human race is growing. The awareness that natural resources is the cornerstone of life necessitated the need to regulate and alleviate the depletion thereof, and subsequently led to the concept of sustainable development.

Sustainable development was defined with the publication of Our Common Future in 1987 by the World Commissions on Environment and Development (WCED). It stipulated the importance of close interaction between economic, social and environmental development to meet the needs of the present without compromising the ability of future generations to do the same (Brundtland et al, 1987). In 1992 Agenda 21 was established at the United Nations (UN) conference on environment and development. Agenda 21 initiated the implementation of policies and strategies to control development through integrating the three pillars of sustainability, which is known from Our Common Future as economic, social and environmental.

Today many concepts have been developed to drive sustainable development and one of the more recent concepts is the transition to a green economy. The United Nations Environment Program (UNEP) defines a green economy as: *"an economy that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities"* (UNEP, 2011). The UNEP has a Green Economy Initiative (GEI) that attempts to leverage significant green economy expertise within its global network of partners to build a global green economy. According to UNEP's definition, building a green economy involves analysing challenges and opportunities in specific sectors. Sectors that require investigation include agriculture, fisheries, forests, green buildings, industry, renewable energy, transport, waste management and water (UN, 2011). Swilling, Musango and Wakeford (Forthcoming), however, calls for a shift from a sector focus that tends to be narrow, to a "*broad understanding of greening as a transitioning process of becoming more economically, socially and environmentally sustainable across the entire economy"*. The green economy principles are especially applicable to third world countries, which rely mainly on natural resources to drive the economy and sustain the populations' livelihood.

The South African economy is heavily dependent on its vast natural resources. Economic growth, wealth creation and the livelihood of millions depend on the fruitful soils, forests, fisheries and other natural resources. As the young population of South Africa keeps growing, the demand for fresh water, food and health also grows and therefore the natural capital faces great pressure. In the light of this knowledge, South Africa has adopted numerous programmes and initiatives to support the transition to a green economy. One of these is the National Development Plan (NDP), which the South African government established in 2012 (National Planning Commission, 2012). The NDP plans to eliminate poverty and reduce inequality by 2030. Furthermore, the NDP states that the existing policies should be transformed into action and that each province in South Africa will require tailor made policies to suit its own complex needs.

In the Western Cape Province the transition to a green economy has its own complex requirements. The Western Cape Province is South Africa's major agricultural export area and also the country's most important international tourist attraction (Western Cape Government, 2013). Climate Change is expected to affect the Western Cape Province the most of all the provinces, with drought conditions that will increase in this already water-stressed region. The Western Cape Government has made an effort in the right direction by releasing a document called *Green is Smart* in 2013 (Western Cape Government, 2013). Accordingly, the Western Cape Province strives to become the lowest carbon province and the leading green economic hub of the African continent (Western Cape Government, 2013). They plan to do this by implementing smart-living and working, -mobility, -ecosystems, -agri-production and smart-enterprise (Western Cape Government, 2013). An integral part of *Green is Smart* is to promote and improve the sustainable use of water resources.

Internationally, it is crucial to recognise the centrality of water for sustainable development and in the transition to a green economy, particularly in water-scares areas such as the Western Cape Province. In a green economy, the role of water in maintaining ecosystem services and water supply would be acknowledged, appreciated and paid for (UNEP, 2011). The green economy will recognise the direct benefits that the society as a whole will gain by conserving water-critical ecosystems, investing in water supply and sanitation and including investment in wastewater treatment. The cross-sectoral transition to a green economy requires new approaches among society. These new approaches include; embracing green technologies, planning for adaption for uncertain futures, improving the efficiency of water provision and developing alternative water resources as well as forms of management (UNEP, 2011). Another enabling factor for the green economy is to charge full cost for service provision, however this has proven to be impractical since it can be difficult to implement in developing countries like South Africa.

Managing water sustainably supports the overall objectives of a green economy or a green growth pathway, and also satisfies critical social imperatives of poverty alleviation, food and energy security, and health and dignity, through the provision of water and sanitation services. A green economy advances long-term human well-being within ecological limits. A green economy is advanced when water resources are invested in, protected and managed sustainably. Management and allocation of water resources impacts the whole of the society and economy. Therefore, sufficient governance of water should be prioritised. Embedding water management as the central pillar of sustainable development requires institutions that facilitate discussion and decisions on society's targets and the allocation of water resources to optimize generation and equitable distribution of its many benefits. Consequently, it is water management's role to initiate and implement the process of transitioning to a green economy (WWAP, 2012).

When transitioning the Western Cape Province to a green economy the water resources involve a number of non-linear and sophisticated interactions among various role players. Noting that the interactions between the role players are complex it becomes evident that it is essential to investigate the analytical modelling tools that can appropriately account for these complexities. Transition theory also requires an investigation to fully comprehend the potential and extent of transforming the Western Cape Province to a green economy.

Consequently, this research involves a discussion of the water resources in the Western Cape, an overview of complex systems, transition theory and possible modelling tools. With this information an informed decision will be made regarding the modelling tool that will be utilised. Subsequently, the complex water resources system in the Western Cape Province is modelled by the chosen tool, which provides insight into how the water resources could be managed to ensure available fresh water for future generations.

1.2 Problem statement

Water is recognized as an important resource and will be essential in the Western Cape as this Province aspires to transition to a green economy. While water demand in this province is increasing as a result of population and economic growth, water resources are predicted to be under even greater strain as temperature is expected to rise due to climate change. Therefore, the need exists to act decisively and to prioritise the management of water resources in the Western Cape Province.

Even though many studies have identified water conservation (WC) and water demand management (WDM) initiatives as well as supply side intervention, which aims to augment the water supply in the Western Cape Province, none have utilized a modelling tool to assist in the decision making process. Furthermore, it has been identified that there is a lack of previous investment into the water resources of the Western Cape Province. Now an uncertainty exists with regards to future investments.

Therefore, this research aims to investigate different reconciliation strategies and investment scenarios, with the aid of a modelling tool. The intention is to build a supply-demand water model of the Western Cape Province that will enable stakeholders and interested parties to see when the need for the implementation WC/WDM initiatives and supply-side interventions will become critical. Scenarios that are studied in the model also inform stakeholders of the required financial aid, which goes hand in hand with the water augmentation initiatives. Ultimately the research aims to ensure informed management of the water resources in the Western Cape Province.

1.3 Research objectives

Ultimately, the research aims to inform policy makers during the process of transitioning the Western Cape Province to a green economy by providing a better understanding of the implications of investment into the water sector, using a dynamic model. Various sub-objectives to reach the ultimate objective are to:

i. Understand the implications for water resources in the Western Cape Province when transforming to a green economy.
ii. Model the water supply and demand situation with a carefully selected modelling tool.
iii. Evaluate the results generated by the model against certain scenarios.
iv. Provide recommendations based on the results which can be used by policy makers and stakeholders.

1.4 Research strategy

The research strategy for the remainder of the research is illustrated in Figure 1.1. As seen in the figure the next chapter contains the literature review. Complex systems, systems thinking, transition theory, as well as possible modelling tools, are discussed throughout the chapter. The possible modelling tools are evaluated against certain criteria that could be chosen as a result of the knowledge gained throughout the literature review. Subsequently the most appropriate modelling tool is selected.

The literature review of the concepts mentioned ensures that a comprehensive understanding of the problem and all the intricacies involved are gained and that the case study can be done with the required skill. The case study involves the step-by-step modelling of the water resources in the Western Cape Province with the aid of the chosen modelling tool. A comprehensive discussion of the water resources in the Province and all the required concepts are provided.

The results found through the modelling process is presented and discussed in the section following the case study. From the results a conclusion is drawn. The conclusion stipulates the implication of water resources on the transition to a green economy. Furthermore, a proposed investment scenario with regards to water resources is formulated which might be helpful to stakeholders in the near future.

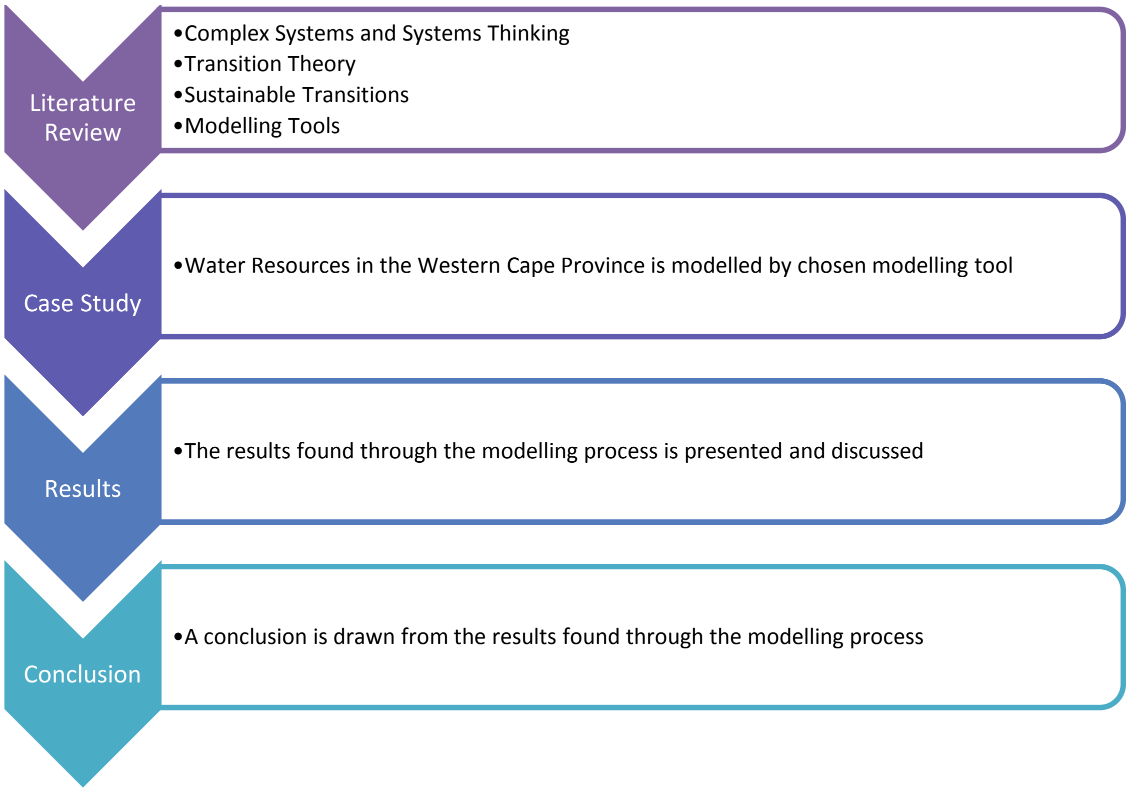

Figure 1.1: Research Strategy

1.5 Introductory Conclusion

This chapter introduced the research problem addressed in the research. The history of sustainable development was discussed to show where the green economy initiative originated. Furthermore, some intricacies involved in water resources in South Africa as well as the Western Cape Province were emphasized as well as the importance of water when transitioning to a Green Economy. Furthermore, the problem of the research was formulated in this chapter and the objective was stated.

Lastly, the research strategy was discussed to facilitate the structure of the document. From the research strategy it is evident that the following chapter is the literature review. Various aspects are studied to gain a better understanding of the complexity that is involved in the transition to a green economy. Ultimately an appropriate modelling tool is chosen to model the water resource situation in the Western Cape Province.

CHAPTER 2: LITERATURE REVIEW

This chapter contains the literature review. As discussed in the introduction water resources play a significant role in the transition to a green economy in the Western Cape Province. Consequently, in order to reach the objectives of the research, which is to comprehend the implications that water resources might have on the transition, a broad understanding of different aspects need to be attained. In the section that follows the methodology and the various concepts discussed in the review can be found.

2.1 Literature Review Methodology

To fully comprehend and cover all the necessary fields for this research a traditional literature analysis method was used. Cronin, Ryan and Coughlan (2008) state in their article that a traditional literature review critiques and summarises a body of literature and draws conclusions about the topic under considerations. The primary purpose of this analysis method is to provide a wide-ranging background for understanding current knowledge and highlighting the importance of new research. The five steps listed below are typically followed in the literature review process according to Cronin et al. (2008). These steps are described below in the context of this research:

i. Selecting a review topic
ii. Searching the literature
iii. Gathering, reading and analysing the literature
iv. Writing the review
v. References

The review topic selected was; to understand the implications for water resources in the transition to a green economy, as discussed in the first chapter. This topic is considered to be refined enough to ensure that the amount of data that it generates is manageable and sufficient. Furthermore this topic is currently of high interest in various domains such as in academics, politics and business.

The internet and the databases of Stellenbosch University were utilised to conduct this search. Figure 2.1 illustrates the approach followed while searching for literature. As seen in the figure the ultimate intention is to determine what modelling tool is the most appropriate to model the transition to a green economy. Knowing that the transition to a green economy is complex and involves many intricacies consequently calls for a comprehensive review of complex systems, systems thinking and the transition theory. Subsequently, the search vocabulary included; water, South Africa, Western Cape Province, green economy, sustainability, transition theory, complex systems, systems thinking and modelling approaches/tools. Combinations and variations of these terms were also used to find relevant information. To help with the combinations Boolean operators such as 'AND', 'OR' and 'NOT' were used.

The idea is that a better insight into the functioning of this societal problem, known as the transition to a green economy, provides more insight into the possibilities for directing this system. The study of complex systems is used to gain understanding of the dynamics of societal systems and to be able to work from a basic set of guidelines when considering water resources in the Western Cape Province of South Africa. Understandably, societal systems, because of their intricacies, cannot be directed and commanded by a set of guidelines. However, it is assumed that it is possible to use the understanding of transition dynamics to influence the direction and the pace of a transition of a societal system into a more sustainable direction. The explicit normative orientation of sustainability is important to ensure that the transition leads to a more sustainable society. Lastly a study of possible modelling tools is done to determine which tool is the most appropriate tool to utilize for the specific problem. An appropriate modelling tool and the understanding of transition dynamics is bound to deliver results that can aid in the Western Cape Province in the transition to a green economy.

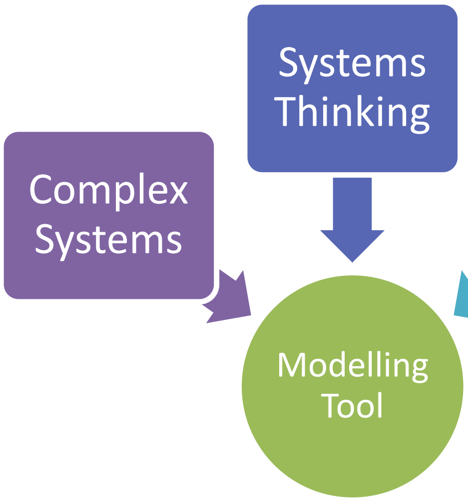

Figure 2.1: Illustration of Literature Review Methodology

Literature that was gathered of the related terms mostly included books, journals and government documents. Existing literature reviews were also considered to be important sources of data as they offer a good overview of the research that has been done as well as references to sources that can be accessed. Special care was taken to ensure that all sources used were recent (ranging from 2000-2015) and reliable.

This search yielded a large amount of information and therefore it was clear that decisions had to be made about which papers to include and which to exclude. According to Cooper (1984) the relevance of information to a literature search depends on the reviewer's open-mindedness and expertise in the area, the manner in which the research is documented and the amount of time the reviewer has for making relevant decisions. To determine whether or not a source should be used the type of source was identified. Three main types of sources are outlined in Table 2.1.

Table 2.1: Different types of Literature Sources (Cronin, Ryan & Coughlan, 2008)

Source type	Definition
Primary source	Report by original researchers
Secondary source	Description by someone other than the original researcher
Conceptual source	Papers concerned with description or analysis of theories associated with the topic

For this research primary sources were focused on as far as possible and the secondary sources were also considered. Conceptual sources were not used as this research does not include theories. The literature that was gathered and considered appropriate was stored on the computer in folders. The folders were labelled in accordance with the search vocabulary. All literature was stored even though it seemed irrelevant at the time in case it should become required at a later stage. This systematic review kept the reviewer focused and facilitated easy retrieval of material as a large amount of literature was used.

Weaknesses that are associated with traditional literature reviews include, among others, the large amount of literature yielded by the search. This makes it difficult to draw viable conclusions. Another weakness is the fact that the process is subject to the reviewer's open-mindedness and expertise in the area. Furthermore, bias that supports the reviewer's own work could lead to fruitless research and results.

2.2 Complex Systems and Systems Thinking

According to Glouberman and Zimmerman (2002) a system can be understood as being simple, complicated and complex. Simple problems involve basic steps and terminology which can ensure a very high rate of success if the same steps are followed. Complicated problems are different, as its nature is not only related to the scale of the problem (simple system) but also to the issue of coordination and specialized expertise. Complicated problems are still similar and therefore once a success has been achieved a relatively high rate of success can be expected. In contrast, complex systems are based on relationships, their properties of self-organisation, interconnectedness and evolution (Allen, 2013).

A complex system is any system that involves a number of subsystems which in turn consist of interacting adaptive agents (Glouberman & Zimmerman, 2002). Therefore formulae have limited application on complex problems and experience or expertise may contribute but cannot assure success. Complex systems cannot be understood solely by simple or complicated approaches; therefore complex systems theory should be utilized to represent real life more closely as it includes the study of the interactions of many parts of a system. The following characteristics of complex systems should be kept in mind; non-linearity, order/chaos dynamic, emergent properties, self-organization.

Sustainability and the transformation to a green economy were found to encompass the same characteristics of complex systems. Transforming the Western Cape into a green economy has been identified to involve many interrelated components that require analysis. Sustainable development is an open system that constantly evolves and unfolds. The interrelated components interact on a non-linear basis meaning that a small incitement may have a large or a small effect and on the contrary a big incitement may have a large or a small incitement. Furthermore, sustainability contains feedback loops. According to Rotmans and Loorbach (2009) these are all characteristics of a complex system.

Rammel, Stagl and Wilfing (2007) agree with Rotmans and Loorbach (2009) by stating that the management of natural resources should be able to deal with different spatial and social scales, complex uncertainty, multidimensional interactions, nested hierarchies and developing properties. To map the interactions between the different networks he drew his ideas from the Complex Adaptive System (CAS) theory, evolutionary theory and evolutionary economics. A CAS is a special case of complex system and is known to be “adaptive in the sense that they have the capacity to change and learn from experience” (Rotmans & Loorbach, 2009). This is a characteristic of the transformation to a green economy as people are the drivers behind the initiative and consist of the ability respond to change and adjust themselves in their environment.

Having established that sustainable development and the transition to a green economy is a CAS, the way in which it operates needs to be understood for the purpose of this research. The CAS theory aims at improving the understanding of co-evolving, social-ecological systems and natural resource systems specifically. Co-evolution in this context refers to the interaction between different systems that influences the dynamics of the individual systems, leading to irreversible patterns of change within each of the systems (Kemp & Martens, 2007:5). In such a co-evolutionary process, both competition and cooperation have a role to play (Rotmans & Loorbach, 2009). For natural resource management a CAS approach emphasises that these systems are known for the change in behaviour, rules and structure over time. This happens as the system adapts to their external environment like climate change or urbanisation (Rammel, Stagl & Wilfing, 2007).

Static and predictive approaches will not be helpful in the case of a CAS. Therefore an approach should be identified that can combine all the different components of this specific CAS known as the transition to a green economy. A possible method to deal with complexity in a holistic manner is a systems thinking approach. Maani and Cavana (2007a:3) define systems thinking as a field of knowledge for understanding change and complexity through the study of dynamic cause and effect. The principles that are embodied by systems thinking is listed below (Maani & Cavana, 2007a:3):

i. Viewing the situation holistically or in other words the “big picture”
ii. Balancing short term and long term perspectives
iii. Recognising dynamic, complex, and interdependent nature of systems
iv. Taking measurable and non-measurable factors into account
v. Noting the presence of feedback loops
vi. Distinguishing between cause and symptom
vii. Using Either-Or thinking

Furthermore, systems thinking has three distinct but related dimensions: paradigm, language and methodology. The paradigm of systems thinking is the way the world and relationships are thought of. The "big picture" view, referred to in the principles above, as well as dynamic-, operational- and closed-loop thinking explains what this paradigm refers to. The Language dimension of systems thinking refers to the tool used to understand the complexity and dynamic cause and effect. The language is visual and therefore translates the perceptions into pictures with the guidance of a set of rules. In systems thinking a methodology is used to enable a better understanding of the structure of a system. The methodology considers all possible influencing factors and establishes their interconnectedness and effects largely by means of modelling and learning technologies. These tools of systems thinking include causal loop maps, stock and flow models, computer simulations as well as group work and learning laboratories (Maani & Cavana, 2007a:3).

The main contribution of a green economy transition has been identified as being the integration of several sectorial interventions and systems in a comprehensible way. Therefore complex adaptive systems theory and systems thinking provides a practical set of guidelines which can be used to approach this transition. However, it is noted that such a green economy transition cannot be directed by only a set of guidelines. Therefore it is assumed that an understanding of the transition theory will be helpful to direct and drive the transition of this societal problem.

2.3 Transition theory

Complex systems and systems thinking were discussed in the previous section and provided a set of guidelines which can be used in the approach to the transition to a green economy. Clearly this societal problem cannot be solved by a mere set of guidelines. However, hypothetically, an improved understanding of the transition theory will ensure a better and faster transition.

Transition to a green economy can be considered as a CAS that is characterized by uncertainty, vague boundaries and multidimensional interactions, and is deeply rooted in our societal structures and institutions (Loorbach, 2010), as discussed in section 2.2. The only way to resolve and uproot these problematic characteristics of the transition to a green economy is by the revision of both development processes and the institutions that have been built to handle them. A transition is necessary to resolve persistent complex societal problems. Loorbach (2010) describes transitioning as:

> "A long term process of change during which a society or sub-system of society fundamentally changes."

To bring about a lasting successful transition, system innovation is required according to Loorbach and Rotmans (2009). The fundamental structure of the system and the relation among the participants will have to change. Innovation at the individual levels, in terms of product, process and project, will change within the system innovation. Guidance and governance also play an important role according to Loorbach (2010).

Markard, Raven and Truffer (2012) identified four different conceptual approaches that have been leading the way over the past years in transition studies. Here follow the four different approaches and a short description of each (Markard, Raven & Truffer, 2012):

i. Socio-technical regime: Combines ideas and concepts from evolutionary economics and highlights that scientific knowledge, engineering practices and process technologies are socially embedded.

ii. Strategic Niche Management (SNM): Create and support niches to trigger off shifts.

iii. Transition Management: Combines work from technological transitions with insights from complex systems theory.

iv. Technological innovation systems (TIS): Concerned with the emergence of new technologies

According to Markard et al. (2012) water supply can be classified as a socio-technical system and therefore involves “far reaching changes along different dimensions”. Such systems consist of many elements such as technology, regulations, user practices, infrastructure, maintenance networks and supply networks. The different elements of the system interact, and together they provide services for the society. The systems concept highlights the fact that a broad variety of elements are tightly interrelated and dependent on each other.

Geels (2010:495) agree that socio-technical transitions to sustainability do not come about easily. This author argues that existing energy, transport, housing, water supply and agri-food systems are stabilized by lock-in mechanisms that relate to behavioural patterns, assigned interests, infrastructure, favourable subsidies and regulations. Geels (2010:495) suggests a multi-level perspective (MLP) framework for understanding transitions in socio-technical systems that provide an overview of the multi-dimensional complexity of changes.

Genus and Coles (2007) agree with Geels (2010:495) and states that MLP framework is a good approach to socio-technical systems. However they suggest a few possibilities which would complement the MLP framework. One possibility is the constructionist approach known as social construction of technology (SCOT). In this approach technologies are considered to be social constructions to which various groups of people have given shape. Social constructivism means that all technologies are to be regarded as human made objects, which reflect the choices of humankind (Mulder, 2006:219). The SCOT theory has two important concepts that are necessary to understand the development of technology (Mulder, 2006: 219):

i. Artefact: a consciously human made, artificial object; and
ii. Relevant Social group: people who are involved in a certain technical development and who hold the same view regarding that artefact.

Around each artefact a number of relevant social groups can be distinguished. People involved with an artefact all hold a certain image of it. What people regard as problematic about an artefact is of high importance as that will facilitate the next “new and improved model” or solution. Figure 2.2 is a figurative way to explain this. The SCOT theory argues that those who seek to understand the reasons for acceptance or rejection of a technology should look to the social world. Furthermore, this approach emphasizes the open ended character of technology development so as to analyse the potentially many paths or trajectories negotiated between the relevant social groups and artefacts. It addresses the specifics of development for any case and exposes the political processes involved in constructing the notion of best fit between technology and society.

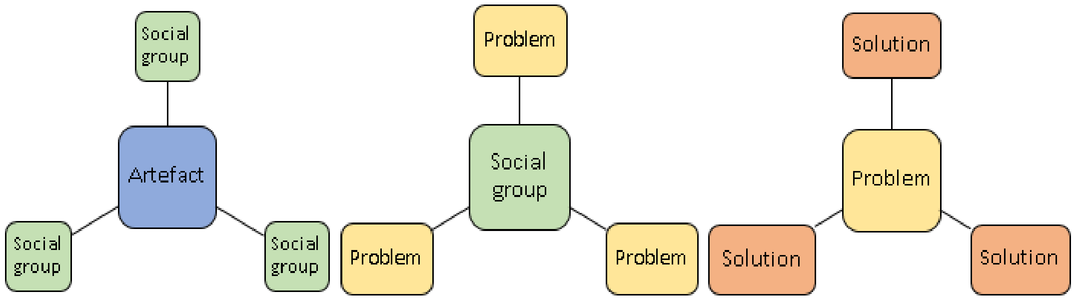

Figure 2.2: SCOT Approach (Mulder, 2006:219)

While MLP framework and SCOT may be an applicable approach to the transition of socio-technical systems, the Nexus approach is thought to include all the necessary fields of study which is required for this transition. This approach gained prominence only recently in the lead-up to the Bonn2011 conference on the "Water, Energy and Food Security Nexus". Since then, the nexus approach has been used widely to explore the driving forces behind the challenge of water security and its relationship with climate change, food and energy production. It is argued that such an approach integrates "management and governance across all sectors and scales", reducing trade-offs and building synergies, ultimately promoting sustainability and the transition to a green economy (Hoff, 2011). KPMG (2012) also suggests a nexus approach to bring about a lasting transition in socio-technical systems. In Figure 2.3 they illustrate how three nexuses together represent the challenges of sustainable growth.

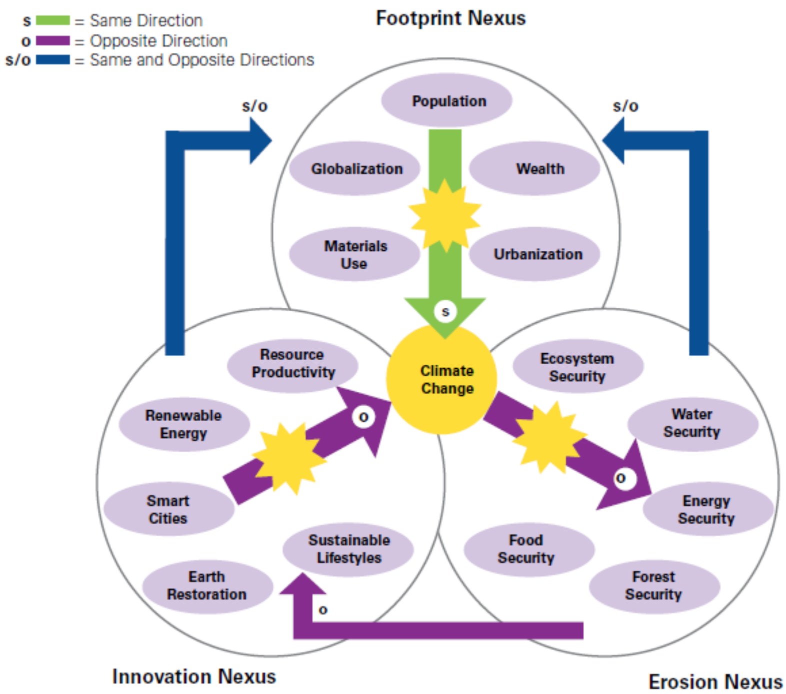

Figure 2.3: Nexus Approach (KPMG, 2012)

The following guiding principles are central to the nexus approach (Hoff, 2011); Investing to sustain ecosystem services, Creating more with less, Accelerating access, and Integrating the poorest. Investment into ecosystems are of high importance as ecosystems and the hydrological cycle are closely interlinked and ecosystems serve as a natural water infrastructure often providing services like improved water quality, much more efficient than man-made infrastructure. Investments in man-made infrastructure often leads to negative externalities, such as reduced ecosystem diversity and services as well as reduced bio-diversity. The second principle aims to emphasize that technologies for higher productivity of water do not always have to be newly developed, for example rainwater harvesting and supplementary irrigation. Also, reduced wastage along the supply chain generally reduces pressure on resources and mitigates other looming scarcities. The last guiding principle of the nexus approach realizes that if the living conditions of the poor are improved positive feedbacks can be generated. For example, while access to clean water is a strong determinant of human health, healthy people at the same time can be more productive and contribute to economic growth.

Throughout the literature analysis of transition management it was found that a water supply system can be classified as a socio-technical system. Such systems have been studied widely by many scholars and most found that because of the complexity and many role players involved, the best approach to aid the transition of such a system would be one that accounts for all the possible interactions and relationships within the system. Ultimately, the transition to a green economy is a sustainable transition in that it requires a transition in social, environmental and economic spheres (van Weele & Maree et al, 2013). Therefore, sustainable transitions and its core elements will be discussed now.

2.4 Sustainable Transition

The sustainability philosophy ultimately stipulates the importance of close interaction between economic, social and environmental development to meet the needs of the present without compromising the ability of future generations to do the same (Brundtland et al, 1987). Figure 2.4 conceptualizes the concept of sustainability as a nested model, with the natural environment, social context and economic activities as overlapping spheres, based on a governance system. This conceptualization recognizes the nexus approach that is required to achieve a lasting transition, as mentioned and illustrated in the discussion on the Transition Theory.

It is important that the three components of sustainability should not be seen as being in conflict over the same resources and spaces. The interdependencies between the components ensures that trade-offs between the spheres is not possible. Trade-offs will result in compromised functionality of all spheres as a result of feedback loops between all spheres.

As seen in the review on the transition theory, innovations are required to be initiated from a preconceived goal of sustainable development to bring about a lasting transition. The innovations will need to encompass all spheres of sustainability conceptualized in Figure 2.4. Guidance and governance was also mentioned as an important role player in the transformation of systems, this is illustrated properly in the nested sustainability model found below.

Figure 2.4: Sustainability as a nested model (van Weele & Maree et al, 2013)

Water resources in the Western Cape will be investigated in the next section to determine its intricacies and role in the transformation to a green economy. This knowledge will ensure that an appropriate modelling tool can be chosen for the problem.

2.5 Modelling tools

The literature study thus far has established what the transition to a green economy entails and the specific complexities of the water resource system in the Western Cape. With this knowledge a further literature analysis was undertaken to determine which modelling tools are most appropriate to better understand and analyse the water resource implications with regards to the green economy transition.

With regards to water resources and the hydrological process, modelling tools such as E-SWAT, WaterGAP and the water balance model (WBM) have been developed (IEEP et al., 2009). While these methods all use empirical statistics as analytical technique the input and output data of the models differ (IEEP et al., 2009). A brief overview of the literature showed that the available hydrological models will not be sufficient for the case of this research. Even though a hydrological cycle will be at the core of the model many other sectors will need to be integrated into the model (as required by a green economy transition) which is not possible with the hydrological models.

The green economy intervention is driven by investments. According to Bassi (2014) these investments are leveraged by public expenditure, policy reforms and regulation changes. Consequently modelling tools are required that can support the policymaking process. Furthermore, the study of the transition theory revealed that the nexus approach would be best suited for this transition with specific reference to the integration of the tree pillars of sustainability. Therefore, modelling tools that can be used to generate and analyse simulations of social, economic and environmental pathways and scenarios were identified and are discussed briefly.

The modelling tools that were identified also had to have a “dynamic” nature, meaning that they allow generation of future projections (Bassi, 2014:88). The chosen methodologies include;

Econometrics, Optimisation, and Simulation. Simulation consists of three major approaches known as; discrete event simulation, agent based modelling and system dynamics (Serova, 2013). The discussion of these modelling tools aim to provide information on the tools to contribute to a better understanding of how useful and adequate the tools can be in supporting green economy policy formulation. A brief introduction of each methodology and an analysis of their strengths and weaknesses are given with the green economy transition in the Western Cape in mind.

2.5.1 Econometrics

The term econometrics was first mentioned in 1933 by Ragnar Frisch, the primary editor of the Econometrica journal. Frisch (1933:1) explains the term "econometrics" in an editorial note, which states that it aims to advance economic theory in its relation to statistics and mathematics. In other words, econometrics ties into economic theory by providing statistical and mathematical tools necessary to quantify the qualitative statements that are made using theory. Frisch (1933:1) emphasizes that econometrics should not be seen as economic statistics, economic theory or the application of mathematics to economics; it should rather be seen as a unified study of these three view-points. That is what makes econometrics powerful, Frisch (1933:1) claims.

The definition stated by Frisch (1933:1) is still valid today, as it is supported by a more recent study by Bassi (2014:88), which states that econometrics runs a statistical analysis of historical economic data to find the relation between selected variables. Many economic branches including finance, labour economics, macro-economics, micro-economics and economic policy make use of econometrics. Economic policy decisions are rarely made without econometric analysis to assess their impact (Ouliarism, 2011).

Econometrics generally involves three stages namely specification, estimation and forecasting, and applies statistical methods and mathematics to economic theory, throughout these stages. Econometrics consists of various tools. The most commonly used tool is known as regression. Regression allows the estimation of an approximate conditional mean of the dependent variable given another set of variables. Econometrics can provide quantitative estimates, predictions and forecasts.

A limitation of econometrics relates to the data that is used to quantify the economic models (Ouliarism, 2011). Econometricians estimate economic relationships using data generated by a complex system of related equations, in which all variables may change at the same time. Therefore it is uncertain if the data used is feasible and this leads to the rising of concerns with the validation of the projections. Another limitation lies in the general assumptions that characterize the most economic theories. These assumptions include; rational human behaviour, availability of perfect data and market equilibrium (Bassi, 2014:88). The projections are not able to back track historical data, which causes further concern.

2.5.2 Optimisation

Optimisation is similar to mathematical programming, which was first coined in the 1940s. It included the study of the mathematical structures of optimisation problems, the invention of methods for solving these problems, the study of the mathematical properties of these methods and the implementation of these methods on computers. Optimisation is a tool that leads to models that provide information on how to make the best of a situation.

Three main inputs are required to optimise a situation. They are the objective function, areas of intervention and the restrictions (Bassi, 2014:88).The objective function will be maximised or minimised depending on the expected return of the current problem. Areas of intervention refer to the identification of variables which quantities can be manipulated in order to optimise the objective. Restriction refers to a set of constraints on the values that the identified variables can take.

Important classes of optimisation are linear and non-linear programming. Figure 2.5 shows typical solutions that can be found with these classes of optimisation. Other important classes of optimization include stochastic programming, network optimization and combinatorial optimisation.

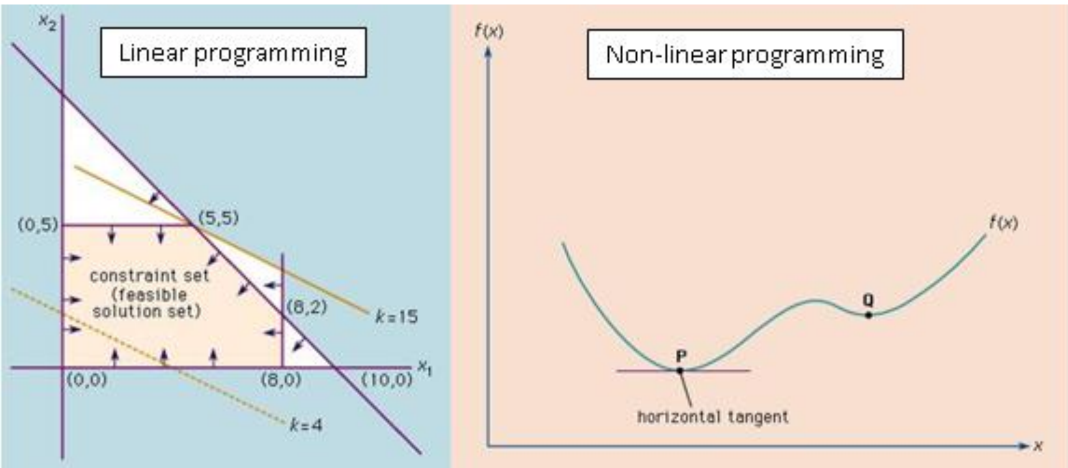

Figure 2.5: Linear and Non-Linear Programming (Wright, 2015)

The challenges related to optimization include the correct definition of the objective function, the extensive use of linearity and the limited representation of feedback dynamics (Bassi, 2014:88). These models generally do not provide forecast, however some have the ability to provide snapshots of specific time intervals.

2.5.3 Simulation

The first example of a simulation experiment was conducted by a French naturalist Buffon in 1777 (Goldsman, Nance & Wilson, 2010). Buffon's famous needle tossing experiment is the earliest example of using independent replications of a simulation to approximate an important physical constant. Since then, the development of computers has ensured the vast growth of the field into a powerful modelling tool.

Today, simulation refers to the creation of quantitative scenarios or projections of possible future patterns emerging from systems. Mathematical simulation models are used to create simulations and answer "what if" questions of given situations. Simulation enables studies of more complex systems because it creates predictions by looking into the future instead of only relying on historical data. It is also a way of doing experiments of possible future scenarios. While assumptions may be simple, the consequences may not be predictable.

Axelrod (2005:21) identifies seven purposes to which simulation can be put, namely; prediction, performance, training, entertainment, education, proof and discovery. Simulation has three major approaches, namely discrete event modelling, agent based simulation and system dynamics (Bassi, 2014:88). According to Dooley (2002:829), the conditions for use in each of the simulation approaches are as follows:

i. Discrete event simulation: A system described by variables and events that trigger change in those variables.

ii. Agent based modelling: A system described by agents that react to one another and the environment.

iii. System Dynamics: A system described by variables that cause change in each other over time.

These three approaches are normally used separately; however some complex scenarios require a combination of two or all three of the approaches. The approaches will now be discussed in more detail.

Discrete event simulation

This approach is most effective when the system studied is characterized by variables and events that change in a rule-oriented manner. Discrete event simulation has the ability to simulate random or ordered event-driven systems, where the entities have to take part in the process.

A limit of this approach is that it has a rigid sequencing of events and a stochastic nature, which produces varying solutions. Furthermore, it becomes time consuming to run the various simulations.

Agent Based Modelling

Agent based modelling works on agent level and is therefore able to capture emergent phenomena. Agent based models are generally labelled as bottom-up models as individual agents and their patterns of interactions are described without necessarily knowing what might emerge as patterns of behaviour in the larger , more aggregate system (Dooley, 2002:829). However, it has a limited capability to integrate agents from different sectors on the same platform.

System Dynamics

System Dynamics is one of the methods that recognise the interactions among disparate but interconnected subsystems driving the system's dynamic behaviour. When dealing with the issues of green economy and broadly, sustainable development, it becomes essential to "describe variables that cause change in each other over time", which is the condition for use of system dynamics (Dooley, 2002:829). System Dynamics, in contrast to the other two approaches is a top-down approach and therefore requires extensive knowledge about how the variables of the system interact.

System Dynamics offers a model that resembles reality structurally, so one can review it for usefulness and consistency. It offers a way to see the consequences of that simplification through simulation, so one can test mental model assumptions and dynamic hypotheses

(Williams and Harris, 2005). Further, system dynamics accounts for feedback loops and it is particularly well suited to modelling social problems that are related to sustainability challenges (Sterman, 2001:8). Variables are arranged into feedback loops to form the important structure of the system. Since the way that structure behaves over time is easily simulated, system dynamics can give powerful insights (Sterman, 2001:8).

System dynamics tend to treat systems rather mechanistically therefore a limitation of simulation potentially include the correct definition and understanding of a system. Correct model boundaries and realistic identification of the causal relationships characterizing the system are often hard to determine.

2.5.4 Modelling tools conclusion

To choose the most viable and appropriate modelling tool, some key criteria were identified by which the tools were analysed. The key criteria were identified by considering the objective of the research which ultimately is to support the Western Cape to transform to a green economy. As previously mentioned, the green economy is driven by investments that are leveraged by improved regulations and policies. Therefore a methodology is required that supports the policymaking process (Bassi, 2014:88).

This process involves quantitative projections and evaluation of trends, identification of possible entry points for interventions, assessing potential impacts across sectors and effective problem solving abilities of selected interventions. The process also involves the evaluation of the impact of the interventions chosen against a baseline scenario. The methods are not only evaluated for their ability to support the policymaking process but also its capability to involve various stakeholders and whether it can be used simultaneously with different models.

More specifically the modelling tools are evaluated on their ability to represent social, economic and environmental dimensions of the problems and opportunities that comes with water resources in the Western Cape Province. The modelling tool should be able to address climate change, by forecasting impacts as well as analysing mitigation and adaption option, seeing that it is big challenge regarding water resources. Since South Africa in a developing country, data, time and financial resources are scarce and therefore trade-offs will need to be addressed. Therefore, the modelling tools are also evaluated with the following factors in mind; applicability to the Western Cape Province, transparency and flexibility, implementation time and audience that the outcomes will be presented to. A summary of the evaluation of the modelling tools and the criteria used can be found in Table 2.2.

Table 2.2: Evaluation of modelling tools

Modelling tool	Endogenous variable representation	Flexible	Proper representation of dynamic complexity	Indication of behaviour over time	Accurate outcomes
Econometrics				X	
Optimisation			X		X
Discrete Event Simulation	X			X	
Agent based modelling	X	X		X	
System Dynamics	X	X	X	X	X

As seen in Table 2.2 these five criteria are best taken into account by system dynamics when compared to the other modelling tools. Furthermore, econometrics was dismissed as the data that is used for this modelling tool is generated by a complex system of which the variables are unpredictable. Therefore the data used is incomplete and imperfect and consequently the projections are hard to validate. It is important to be able to validate the projections made to convince and encourage people to adopt a "green" way of living. Econometrics also does not account for the feedback effect which is of high importance in a socio-technical regime such as water supply. The most important limit of optimisation is that it does not identify the drivers contributing toward reaching the goal and it also supports linearity rather than the feedback effect. Based on the evaluation and the main weaknesses identified, optimisation was also dismissed.

System Dynamics has been used by a few water resource scholars (Musango, Brent & Bassi, 2014:257; Qi & Chang, 2011:1628; Susnik, Vamvakeridou-Lyroudia, Savic & Kapelan, 2012:290; Xi & Leng Poh, 2013:157; Zarghami & Akbariyeh, 2012:99), which is further confirmation that System Dynamics is an appropriate modelling tool. There is no perfect method for forecasting a given real-life situation, especially the transition to a green economy as it involves a complex system. However, system dynamics is chosen as the most appropriate modelling approach for the purpose of this research.

2.6 Literature Review Summary

The literature study done in this chapter discussed Complex Systems, Systems Thinking and the Transition Theory. The study of Complex Systems revealed that the transition to a green economy encompasses the same characteristics of a Complex Adaptive System which cannot be approached with linear and predictive formula. This transition involves many interdependencies among several sectors and therefore requires Systems Thinking, which will allow a holistic view.

Transition theory states that the only way a lasting transition can take place is by means of a long-term process where society and sub-systems of the society fundamentally changes. Further research on the transition theory established that the water supply system can be classified as a socio-technical system which requires a nexus approach to bring about lasting change. This nexus approach should focus on the three pillars of sustainability known as social, economic and environmental. Emphasis is put on the fact that governance plays an important role.

The importance of water resources with regards to the green economy transition in the Western Cape Province was also discussed in the introduction to show the necessity of the study and to ensure that an informed decision could be made regarding the most appropriate modelling tool. Five different modelling tools were identified and studied in more depth, which showed that System Dynamics is the most effective modelling tool for the specific problem.

Chapter 3 is the case study. A comprehensive discussion of the intricacies and dynamics of the water resources in the Western Cape Province and of the System Dynamics method can be found. The process involved to develop the model for the water resources in the Western Cape Province is presented in detail.

CHAPTER 3: WESTERN CAPE PROVINCE WATER RESOURCE MANAGEMENT MODEL

In chapter 2, complex systems, systems thinking and transition theory were discussed broadly. The study of the above mentioned aspects revealed the characteristics of the transition to a green economy. Subsequently, it was established that the nexus approach is the most applicable to this case. With that knowledge, five different modelling tools were studied. Key criteria were identified with the objectives of the research in mind, which subsequently led to the conclusion that System Dynamics is the most appropriate modelling tool.

This chapter contains all the steps involved in developing a System Dynamics model for the water resources in the Western Cape Province. Firstly, the method followed to build the System Dynamics model is presented. The method primarily comprises of two modelling types, namely: qualitative and quantitative modelling. The first phase of the qualitative modelling is problem formulation. Problem formulation involves a discussion on the water resource sector in the Western Cape Province. This ensures that all the dynamics and intricacies involved are understood before conceptualisation of the model is undertaken.

The second phase of qualitative modelling involves the conceptualisation of the model. The key variables are identified and a causal loop model is developed, which enables the modeller to proceed to quantitative modelling. Quantitative modelling involves three phases, namely: dynamic modelling, model validation and implementation. A detailed step-by-step discussion regarding each phase is presented in the sub sections of the chapter. It should be noted that although the modelling process is divided into phases it is an iterative process which requires the modeller to revise previous phases. The formal system dynamics modelling (SDM) process is documented throughout the chapter.

3.1 System dynamics modelling method

System Dynamics is a method to define, model, simulate and analyse 'real-world' issues dynamically (Pruyt, 2013). It provides an outline for qualitative description, investigation and analyses of systemic problems in terms of processes, rules, information and boundaries (Mirchi, Madani, Watkins & Ahmad, 2012:2421). It enables quantitative computer simulation modelling and analyses to assist in understanding the underlying reasons for observed behaviours (Sterman, 2001:8).

System Dynamics is particularly good at capturing the dynamics of a feedback system. Feedback systems have a closed loop structure that brings results from past actions of the system back to control and affect future behaviour. Therefore feedback systems are influenced by their own past behaviour (Mirchi, Madani, Watkins & Ahmad, 2012:2421).

Generally, SDM involves five major phases, namely: problem identification, conceptualisation, dynamic model building, model testing and policy analysis (Sterman, 2001; Maani & Cavana, 2007). These phases are iterative and involve qualitative and quantitative modelling. Qualitative modelling entails problem identification and conceptualisation, and the topic investigated is mapped out using either causal loop diagrams (CLD) or influence diagrams. The quantitative modelling in system dynamics entails the three other phases of modelling process. Quantitative modelling provides insight into the actual behaviour of the system over time, and it makes use of stock and flow diagrams. A stock and flow diagram is generally constructed from a CLD and is usually more detailed than the CLD.

Table 3.1 illustrates the five phases and the steps involved in each phase that is followed throughout the model building process. While it is similar to the phases Maani and Cavana (2007) identified, the quantitative modelling phases differ slightly. Phase four has been changed from Scenario Planning to Model Validation. In this model building process Scenario Planning, which is Maani and Cavana's (2001) fourth step, is done as part of the conceptualization phase and Model Validation is seen as a critical part of the process before the model can be implemented and used to address the "real-world" issue.

Table 3.1: System Dynamics Modelling Process (Maani and Cavana, 2007)

Modelling type	Phases	Steps
Qualitative	1. Problem formulation	• Hydrological cycle • Water Resources in the Western Cape • Identify model boundaries • Collect preliminary information and data
	2. Conceptualization[1]	• Identify main variables • Develop CLD's
Quantitative	3. Dynamic model building	• Construct stock-flow diagrams • Collect detailed information
	4. Model Validation	• Test model to confirm if it is fit for its purpose
	5. Implementation	• Scenario development and implementation • Results evaluation and documentation • Communicate results to stakeholders

Although the modelling process is divided into the phases in Table 3.1, it should be noted that SDM is an exceptionally iterative in nature. Every phase in the process may reveal the need to revise the model structure. Furthermore, modelling is an explorative process of knowledge generation, which feeds back and forth between each of these phases (Pruyt, 2013). The phases and steps found in Table 3.1 are discussed in more detail throughout this chapter.

3.2 Problem formulation

The purpose of modelling for this research was to examine the implication of green economy interventions on water resources in the Western Cape Province of South Africa. In order to formulate and develop an effective System Dynamics model for this analysis, it is important to understand how the water cycle works. It is equally important to understand the context of the water resources in the Western Cape Province. This section therefore sets out some important facts about the water cycle as well as the specific water situation and challenges in respect thereof, in the Western Cape Province.

[1] The conceptualisation and dynamic modelling phases are done in VENSIM software.

3.2.1 Understanding water resources: The hydrological cycle

The first step of formulating the problem includes a study of the hydrological cycle. It is important to generally understand how the water cycle works in order to build an effective System Dynamics model. Figure 3.1 provides an illustration of the cycle.

The universal hydrological cycle is applicable in the Western Cape Province. The cycle operates in a closed loop system. In essence, heat results in water evaporation from land and water sources. As the water vapour rises, it cools and condenses to form clouds. When conditions are right, the water in the clouds is released as precipitation (rain). Precipitation is virtually the source of all freshwater in the hydrological cycle. In the Western Cape Province it falls everywhere but its distribution is highly inconsistent and variable. As precipitation reaches the surface of the earth some water is stored as surface water whilst some water immediately percolates and is stored as groundwater. Water that is not stored as surface or groundwater is returned to the atmosphere or consumed by plants through evaporation, transpiration or evapotranspiration (DWA, 2013b).

Surface water features include rivers, dams, oceans, ice, and snow, among others. Groundwater is water that is stored below the surface of the earth either in aquifers or as soil water. Groundwater either discharges into some surface water features or is released back into the atmosphere through plant transpiration. Traditionally management of water resources has focused on surface water and groundwater as separate entities. As development of land and water resources increased, it became apparent that the development of either of these affects the quantity and quality of the other.

Water infrastructure, such as dams, enables the provision of reliable supply of water, and to increase the amount of water available for use, by storing water that would otherwise run into the sea. Storage of water in dams enables a reliable supply of water even during a drought. Other technologies and possibilities are also available to increase water availability.

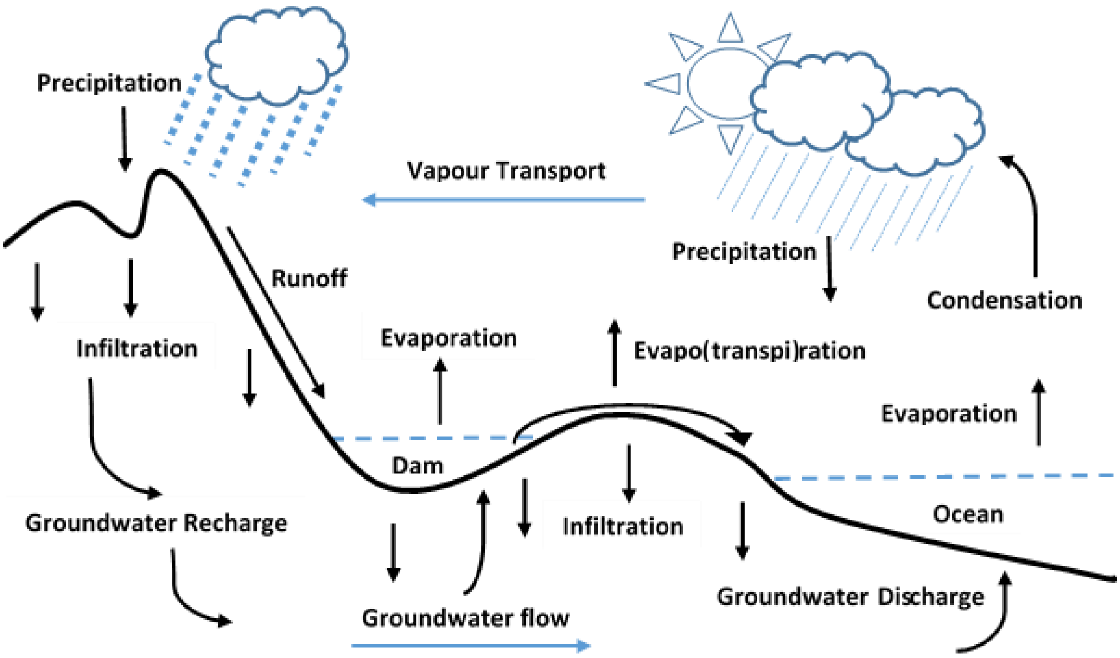

Figure 3.1: Hydrological Cycle (Adapted from (DWA, 2013b))

3.2.2 Water Resource in Western Cape Province Context

This section contains a discussion on the unique and complex water situation in the Western Cape Province, as well as the management institutions and their role in the sector. Subsequent to that, some characteristics of the sector are discussed as well as the supply and demand dynamics. More detail with regards to the values used in the model is presented in the Dynamic Modelling section (Section 3.4).

Water Governance and Management Entities

In South Africa water resources are governed by two acts namely the National Water Act (NWA, Act 36 of 1998 and the Water Service Act (WSA, Act 108 of 1997) (GreenCape, 2015). Various institutions that report to the Minister through government arrangements enforce these Acts. In Figure 3.2 the institutional structure as originally outlined by the DWA (2013b) in the National Water Resource Strategy (NWRS2) document is presented. In 2010, the Department of Water and Sanitation (DWS) (at the time, Department of Water Affairs (DWA)) initiated institutional restructuring and realignment of the water sector in the country (DWA, 2013b), which is still in progress. In the NWRS2 as well as in a recent document known as the Market Intelligent Report, compiled by Green Cape (2015), the envisioned key players and the role they will fulfil in the water sector are discussed.

Firstly, it is pointed out that the twelve existing water boards will be consolidated into nine viable regional water utilities (RWUs). The aim of the consolidation is to strengthen the development, financing, management, operation and maintenance of regional bulk water and wastewater infrastructure. Water service authorities (WSAs) and water service providers (WSPs) will receive bulk water and support from the RWUs. Furthermore, RWUs will manage bulk sanitation infrastructure for waste water treatment, operate existing regional water resource infrastructure and develop new regional water resource infrastructure (DWA, 2013b).

Catchment Management Agencies (CMAs) are established to be in line with the Water Management Areas (WMA). Until recently South Africa comprised of nineteen WMAs, however, this has been restructured into nine (see Figure 3.4). To date, the only CMA established in the Western Cape Province, the Breede-Overberg CMA (BOCMA), is in the process of being realigned into Breede-Gourits CMA (BGCMA, 2014:1). This process is 98% complete (DWA, 2014). The establishment of CMAs for the other areas of the country are still in progress. The CMAs are responsible for all water resource management functions within the defined WMAs and will subsequently serve as the first port of call for all water resource management issues (DWA, 2013b).

Catchment management forums (CMFs) will be established to act as non-statutory bodies to support CMAs and to enable participation by all in water resource management. In the envisioned water sector, water users associations (WUAs) would be another important role player. It will operate at restricted localised level and in effect be co-operative associations of individual water users. WSAs and WSPs are municipalities that have the constitutional responsibility for planning, ensuring access to and regulating provision of water services within the area of jurisdiction (DWA, 2013b).

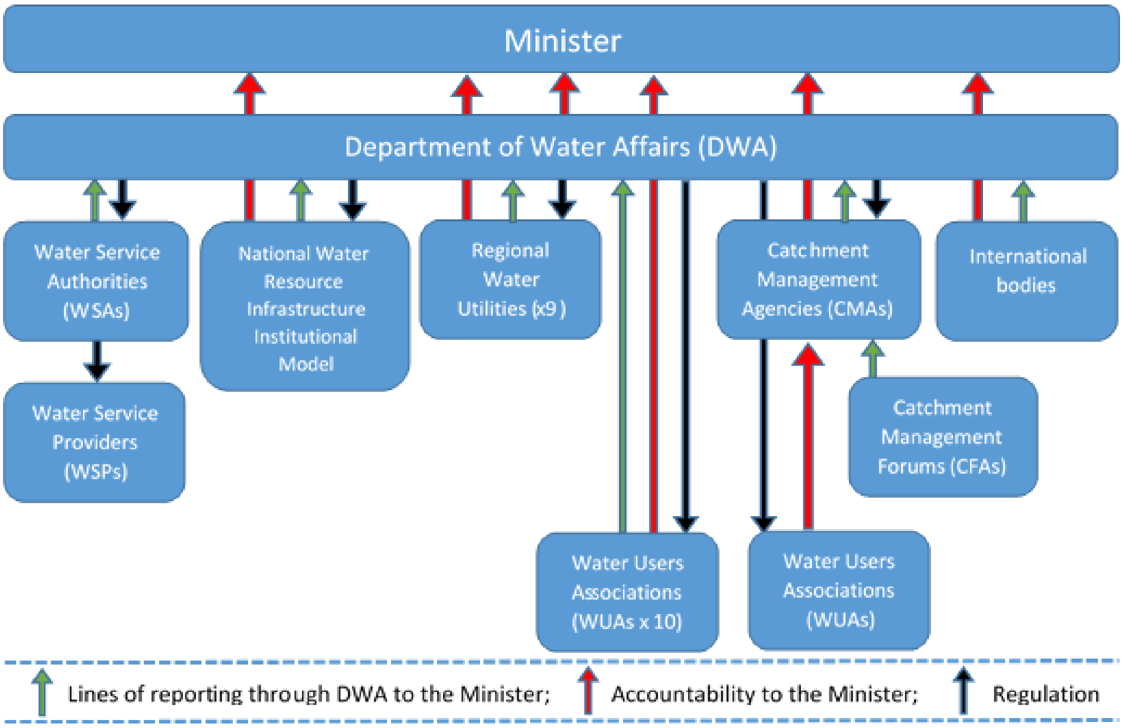

Figure 3.2: Institutional Vision (DWA, 2013b)

As the water sector is highly complex, supplying water effectively involves contributions from various stakeholders and institutions at different points in the value chain. The water value chain, as shown in the NWRS2, comprise of seven broadly defined stages, namely: basin/catchment management, abstraction, storage, treatment, distribution, use, wastewater treatment and discharge (DWA, 2013b). Figure 3.3 illustrates the value chain.

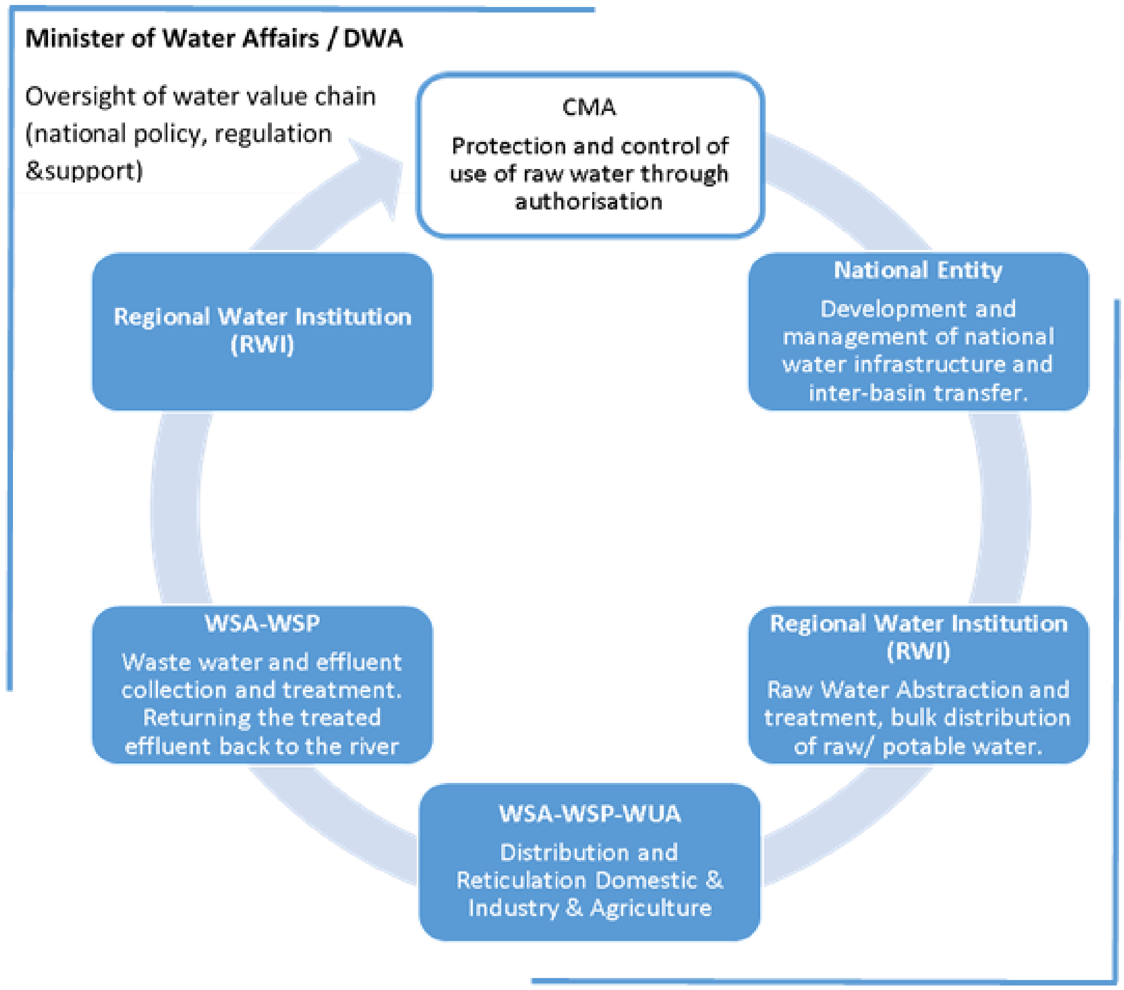

Figure 3.3: Water value chain (DWA, 2013b)

Literature supporting the Green Economy and Water Conservation

Wasteful and irresponsible use of water is not a fully reversible process at timescales relevant to policy-making. However, there is a high degree of policy alignment in several documents, recently published at national and provincial level, that support the green economy and address the issues associated with water resources.

The National Development Plan (NDP), published in 2011, is one example of a document endorsed by the National Government of South Africa which supports the green economy transition and aims to eliminate poverty and reduce inequality by 2030. The discussion in the NDP is largely oriented around the promotion of renewable energy and energy efficiencies. The NDP also states that long term strategies are required to achieve an equal and low-carbon economy. The National Strategy for Sustainable Development 2011-2014 (NSSD1), published in 2011, is another example of such a document. The NSSD1 identifies "*Towards a green economy*" as one of five key priorities. All documents endorsed by the National Government share the following vision; "*South Africa's short, medium and long-term national vision includes planning for environmentally sustainable, climate resilience and a transition to a low carbon economy and just economy*". The documents also share the opinion that water resources are a key priority in the transition.

The most recent document, which is entirely based on the water resources, and which was developed to inform the implementation of the NWA, is the National Water Resource Strategy (NWRS2). The Act specifies that the strategy should be updated every five years (GreenCape, 2015). The first strategy document was released in 2004 and the second version was delayed until 2013, which is the NWRS2. This document is an important reference throughout this research.

The Western Cape Government took initiative and also endorsed several documents that focus specifically on the Province. Some of the most recent documents which support the green economy transition and which has specific reference to the water resources in the Province are listed in Table 3.2. The data found in these documents are primarily used in this research.

Two documents that should be highlighted is the State of the Environment Outlook Report: Inland Water Chapter by the DWS; and the Green Cape's Market Intelligent Report on the water sector. Both documents provide an overview of the water sector, specific to the Western Cape Province. They are the most recent documents that contain actual figures that can be utilised and compared, which is done in the following sections.

All the documents listed in Table 3.2 recognize that a nexus approach is required with regards to the three pillars of sustainability (see Figure 2.4) to ensure a lasting sustainable transition to the green economy in the Western Cape Province. Furthermore, it is clear that water resources are essential in the sustainable transition envisioned for the Western Cape Province.

Table 3.2: Western Cape Government documents on the Water Sector

Document heading	Author	Year	Focus and aim
Development of Reconciliation Strategies for all towns in the Southern Planning region: Provincial Summary Report, Western Cape	Department of Water Affairs	2011	Water situation of all towns in the province is studied with the aim of identifying towns with a high need of reconciliation strategies
Western Cape Integrated Water Resource Management (IWRM) Action Plan	Department of Water Affairs	2011	"The overall aim of the IWRM Action Plan is to guide water resource related activities towards meeting the growth and development needs of the region"
OneCape 2040 agenda	Western Cape Government and City of Cape Town	2012	"Deliberate attempt to stimulate a transition towards a more inclusive and resilient economic future for the Western Cape region."
State of the Environment Outlook Report for the Western Cape Province: Inland Water Chapter	Written by Tasneem Collins & Earl Herdien for Western Cape Department of Environmental Affairs	2013	Describes the water situation of the province as a whole while highlighting possible future threats.
Western Cape Infrastructure Framework	Ian Palmer and Nick Graham, Western Cape Government	2013	Aims to align all existing provincial planning processes to be able to make strategic decisions on trade-offs that need to be made.
Green is Smart	Western Cape Government	2013	"Aims to position the Western Cape as the lowest carbon province in South Africa and the leading green economic hub of the African continent"
WCWSS[2] Reconciliation Strategy Status Report	Department of Water Affairs	2013	Report on the progress of current water reconciliation strategies for the CCT
Western Cape Government Green Economy Report 2014	Western Cape Government	2014	Identifies Green Economy issues and reports on topics that were prioritized in the Green is Smart.
Market Intelligent Report: Water	Green Cape: Chris Millson and Annelie Roux	2015	An overview of the water sector of the Province is provided, including the key players, legislation and regulation, opportunities and challenges and key developments and achievements.

[2] Western Cape Water Supply System (WCWSS)

Even though many changes are being made and regulations are becoming stricter with regards to the water resources in the Province, the consequences of these actions are unpredictable. These unpredictable outcomes are a result of the amount of complex interactions and role players involved, specific to the Western Cape Province, which cannot be understood in a linear fashion. To gain a better understanding of the complex dynamics in the Province, a discussion of the characteristics thereof follows.

Characteristics

The Western Cape Province of South Africa is located in the south most point of the country. It stretches from Strandfontein on the West Coast around the Cape Peninsula and Cape Point, to Nature's Valley along the Garden Route on the South Coast (van Weele & Maree, 2013). The Province is different from the rest of the country as it is characterised by a Mediterranean climate, which implies dry summers and wet winters (DWA, DEA&DP, DLG & DOA, 2011). Average rainfall in the region ranges from 1000 mm per annum in the mountainous areas in the south and eastern regions, to less than 150 mm per annum over parts of the Karoo and the north-west regions (DOA, 2015). Mountain ranges stretching north-south along the west coast and east-west in the south act as orographic barriers, implying that they force moist air to rise. This causes a dry interior and coastal region as well as augmentation of rainfall in the mountainous areas. The regional climate is influenced further by the coastal low pressure system, resulting in hot and dry mountain winds, blowing from the interior consequently causing above normal conditions during spring and late winter. Furthermore, extreme rainfall events can occur during spring and autumn as a result of the frontal systems (DWA, DEA&DP, DLG & DOA, 2011).

The Western Cape Province is divided into two (previously four) Water Management Areas (WMA's) as shown in Figure 3.4, namely; Berg-Olifants and Breede-Gouritz WMA. The two WMA's differ in terms of surface area, groundwater resource availability, population size, landscape ecology, sensitivity for exploitation, rainfall patterns and temperature, just to name a few. Accordingly, each WMA require a unique management approach. Water transfers between the WMA's are also becoming more important.

However, for the purpose of this research the model is built for the Western Cape Province as a whole. This was decided because this model is built to ultimately form part of a bigger model named Western Cape Green Economy Model (WeCaGEM)[3], which aims to include all sectors contributing to the green economy transition. Therefor for this model to be able to contribute and form part of WeCaGEM it has to be built for the Province as a whole.

[3] WeCaGEM was presented at the 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts(Musango et al, 2015)

Figure 3.4: Water Management Areas in South Africa (DWA, 2013b)

Investigation suggests that the rapid development of the Western Cape Province, as well as general water, energy, pollution, waste, transport and other inefficient uses of resources are leading to extensive environmental degradation (Collins & Herdien, 2013). Growing demand and non-sustainable management have increased the ecological footprint and caused degradation of natural resources. The bad conditions of land and soil have decreased the water productivity and storage as well as the biodiversity and wide range of ecosystem services of the Western Cape Province (DWA, 2013b). Whilst water is a renewable resource, pollution and overuse have long lasting impacts, such as degraded and depleted aquifers and loss of aquatic ecosystems and wetlands (DWA, 2013b).

Wasteful and inefficient use of water, together with the fact that water is known as a key driver of economic and social development, clearly indicates that management and planning for water resources in the future becomes progressively more important in the Province (Collins & Herdien, 2013). As the population and the economy grow, water will subsequently be in higher demand.

The water shortage is also likely to be aggravated by the expected rising temperatures and consequently higher and more variable rates of evaporation and decreasing run-off (Carter & Gulati et al, 2014). CSIR scientists predict that South Africa and the Western Cape Province is to become generally drier (CSIR, 2011; GreenCape, 2015). This argument is supported by Dr Celeste Barnardo-Viljoen (2013) who claims that rainfall in the Western Cape will decrease in the future. This will reduce surface runoff and slow down the recharge rate of groundwater aquifers. Ultimately, this implies a reduced water yield from both surface and groundwater sources. Changes to coastal rainfall patterns could also lead to increased salt water intrusion into estuaries and coastal aquifers or raised groundwater tables near the coast (Statistics South Africa, 2010).

Not only will the water availability become a matter of concern in the Western Cape Province but the water quality as well. This is why the trade-off between different the water consumers is complex; both energy and agriculture are among the sectors that are responsible for the pollution of the water. In the agricultural sector, which consumes 60% of South Africa's water, inappropriate water management and irrigation technology are being used (Von Bormann & Gulati et al, 2014). The excessive use of fertilisers and pesticides are responsible for the contamination of groundwater sources.

Supply

Throughout the literature review of the water resources in the Western Cape Province it became evident that data with regards to water supply and demand in the Western Cape Province is limited. The DWS provides some data on their website which can be downloaded as excel spreadsheets. However, the data is not applicable for the purpose of this research. Consequently, the two documents that were highlighted previously, namely, the State of the Environment Outlook Report: Inland Water Chapter by Collins and Herdien (2013) for the DWS, and GreenCape's Market Intelligent Report (2015) on the water sector were primarily used throughout this research. Figure 3.5 shows water supply in the Western Cape Province according to the two documents.

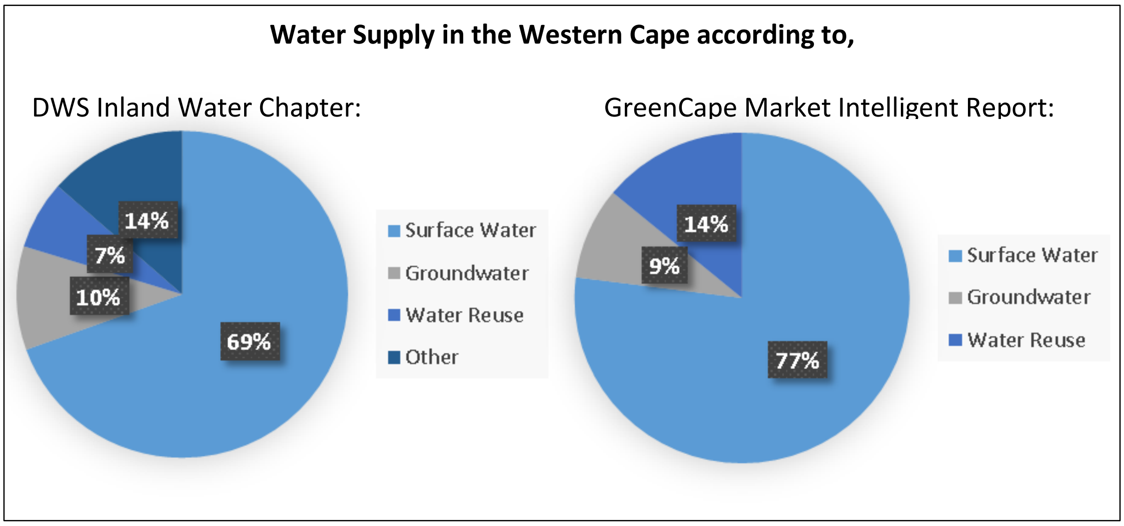

Figure 3.5: Water Supply in the Western Cape (Collins & Herdien, 2013; GreenCape, 2015)

Even though it is evident that uncertainty exists with regards to the contribution of the supply sources in the Province some similarities can be identified. Undoubtedly, surface water is the Western Cape Province's primary source of water, supplying approximately 70% of the water. Water reuse and groundwater are the two other base supplies of the Western Cape Province, supplying approximately 15% and 10%, respectively.

The Western Cape Water Supply System (WCWSS) serves to manage surface water resources for a large proportion of the Province. The WCWSS's different components are currently managed and owned mainly by the regional DWS, City of Cape Town (CCT) Municipality and Eskom. The WCWSS is a network of dams and conveyance pipelines that supply fresh water for urban use and agriculture. The system supplies raw water to the CCT, the West Coast District Municipality (DM) for domestic supply to Swartland Local Municipality (LM), Saldanha LM and

Bergrivier LM, the Stellenbosch LM to augment supply to Stellenbosch, and to agricultural users downstream of the Berg River Dam, Voëlvlei Dam and Theewaterskloof Dam (DWA, 2013a). The major raw water supply dams of the WCWSS are Riviersonderend-, Voëlvlei- and Berg River Dam, owned and operated by the DWS, as well as Wemmershoek-, Steenbras Upper- and Steenbras Lower Dam, owned and operated by CCT. The main dams and their storage capacities are shown in Table 3.3.

Table 3.3: Major raw water storage dams (GreenCape, 2015)

Major Dam (99.6% of total WCWSS system capacity)	Storage Capacity (million m^3)	Dam owner (Desalination thesis)	Dam operator
Wemmershoek	58.644	CCT	CCT
Steenbras Lower	33.517	CCT	CCT
Steenbras Upper	31.767	CCT	CCT
Voëlvlei	164.122	DWA	DWA
Theewaterskloof	480.25	DWA	DWA
Berg River	130.00	TCTA	DWA

The WCWSS also consist of Waste Water Treatment Works (WWTW). These treat waste water to produce recycled water, which contributes approximately 10% of the total water supply in the Province (DWA, 2011). Waste water is water that has been adversely affected in quality by anthropogenic influence. Waste water can originate from a combination of domestic, industrial, commercial or agricultural activities, surface runoff or storm water, and from sewer inflow or infiltration. Reuse of waste water is becoming more essential in the province.

Currently the City of Cape Town recycles approximately 5% of the water used. This water is not used for drinking water in the province but only for irrigation and industrial use. Potable water is more expensive than the treated water to encourage the industries to rather use the treated water. Table 3.4 shows the capacity and the sources of the WWTW in the WCWSS.

Table 3.4: WWTW of WCWSS (Blersch, 2014)

Waste Water Treatment Works	Treatment Capacity	Sources
Faure WTW	500	Riviersonderend-Berg River Government Water Scheme and Upper Steenbras Dam
Blackheath WTW	400	Riviersonderend-Berg River Government Water Scheme
Wemmershoek WTW	270	Wemmershoek Dam and Theewaterskloof Tunnel
Voëlvlei WTW	270	Voëlvlei Dam
Steenbras WTW	150	Lower Steenbras Dam
Withoogte WTW	72	Misverstand Weir
Swartland WTW	30	Voelvlei Dam
Paradyskloof WTW	10	Riviersonderend-Berg Rivier Government Water Scheme.

Groundwater resources contribute approximately 10% of water to the supply sources of the Western Cape Province. It is estimated that the Western Cape has an Utilisable Groundwater Exploitable Potential (UGEP) of 1049.3 m^3/ annum (DWA, 2010). According to the DWA (2010) there is potential to substantially increase the groundwater supplies although it is difficult to determine the properties of the aquifers. Groundwater could be a very important supply source if climate change continues at the current rate (DWA, 2010).

The “other sources” of supply found in Figure 3.5 refers to water supply gained from potential afforestation removal and alien plant removal. It could also refer to water transfers between WMAs, desalinated water or rain water harvesting.

Demand

According to the recent document by GreenCape (2015), water demand in the Western Cape Province is divided into five main sectors, namely: cropland, livestock, commercial, water supply services (domestic use) and urban-industrial, as seen in Figure 3.6. The DWS does not fully agree in their document named Inland Water Chapter, as seen in the figure. However, from the figure it is clear that irrigated agriculture demands the most water. Another recent report written by the Western Cape Government (2013) agrees that agriculture is a key economic sector and requires the most water in relation to other sectors in the Province. It is also predicted that water will be the biggest constraint the agricultural sector will face (Western Cape Government, 2013).

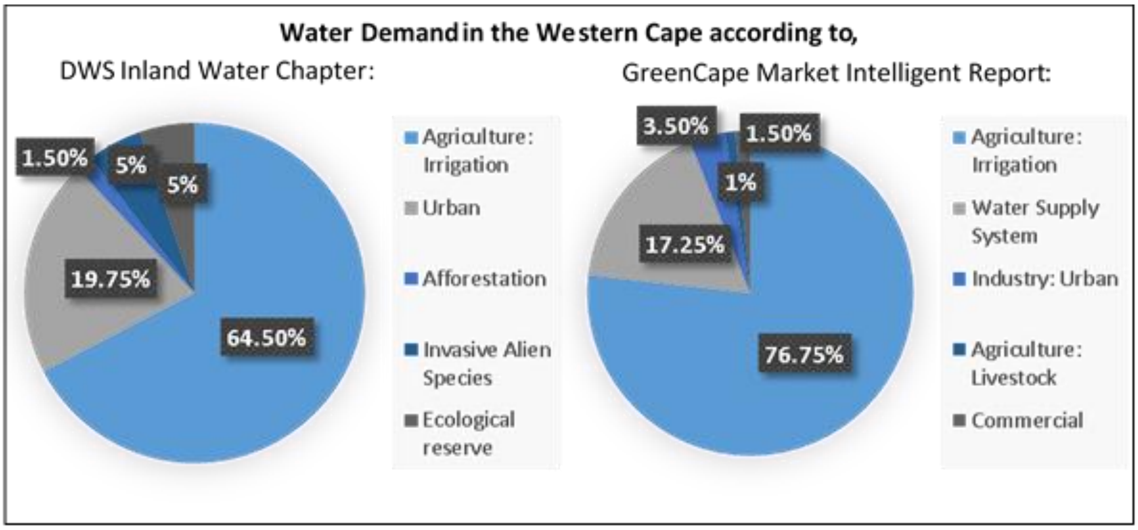

Figure 3.6: Western Cape Water Demand (Collins & Herdien, 2013; GreenCape, 2015)

The water demands of each of these sectors grow according to a specific driver of that sector. In a broad sense, domestic demand grows mainly due to population growth. Factors such as education can possibly reduce the domestic demand. Non-domestic demand, which includes irrigation, afforestation and mining and bulk industries, grows with the economy. Therefore, GDP growth could be a valuable guideline. This is discussed in more detail in the dynamic modelling section (Section 3.4). Even though it is clear that uncertainty exists around this complex system, valid estimations are made where necessary to ensure an effective model is developed.

3.2.3 Model boundaries and key variables

As mentioned previously, this model forms part of a larger Western Cape Green Economy Model (WeCaGEM)[4]. The aim of this model is to assist the Western Cape Province in the transition to a green economy. Various sub-models such as population, education, provincial GDP and the land model is built for the Province as a whole and will contribute to the results generated by this model. Furthermore, the water model aims to determine the Water Stress Index for the Province, which in turn will affect other sectors such as agriculture, biofuel production, transport, electricity generation and consequently also GDP and population.

The water model is based on a water supply-demand framework. On the demand side, population growth and economic growth are the drivers behind the growth in demand. On the supply side the Province has built a diversified water supply system which includes catchment water in dams, recycle water and groundwater. The hydrological cycle, which involves these supply and demand sources, is modelled in an attempt to include all the feedback loops and intricacies involved.

The key variables are considered essential with regards to the development of future investment scenarios for the green economy transition. These variables and their main influences are listed in Table 3.5. It must be emphasized that the variables are calculated endogenously and that the

[4] WeCaGEM was presented at the 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts (Musango et al, 2015)

influences listed in Table 3.5 are only the direct influences. Various factors exist which influences these variables indirectly.

Table 3.5: Key Variables and their influences

Key Variable	Primary Influence	Secondary Influence
Water Supply	Surface water Ground water Recycled water Desalination water supply	Capacity of supply system Depreciation of system Western Cape Runoff Mean Annual Precipitation Evaporation rate Percolation rate
Water Demand	Domestic (Urban and Rural) Irrigated Agriculture Afforestation Mining and bulk industries	Growth rate of demand Population growth rate GDP growth rate
Water Stress Index	Water Supply Water Demand	All supply and demand sources
Supply demand deficit	Water Supply Water Demand	All supply and demand sources
Green Economy Water infrastructure investment	Capital cost of scenario Maintenance cost of scenario	Change in capacity of supply system

Water supply, water demand, Water Stress Index and supply-demand deficit are key variables as each variable gives information on the water resource situation in the Province. Water supply and water demand determines the amount of water received and required. The supply-demand deficit variable determines the difference between the water supply and demand. Evidently, this indicates when the demand is greater than the available supply and therefor when further water conservation and demand management schemes will be required. The WSI is a ratio which represents the demand against the available supply. It is a universally recognized ratio which is used to indicate water deprivation.

The green economy water infrastructure investment variable is used to determine the financial aid required to implement certain water conservation and demand management schemes that are specified in the scenarios section (section 3.6) in this chapter. As indicated in Table 3.5 this variable is influenced by the capital cost as well as the maintenance cost involved.

3.2.4 Time horizon

The model is developed to evaluate the impact of green economy investments into water conservation and demand management schemes on medium- to long-term. Based on the available data the model is simulated over a period of 40 years, starting in the year 2001 up until 2040. The historical trends from 2001 to 2014 were used to ensure that the modelling replicates the characteristics of the behaviour of certain issues investigated.

In VENSIM's model setting it specifies that the unit for time is in years and that Euler integration type is used (see Appendix B). Furthermore it states a time step of 0.0625 is used and that the results are saved per year. Subsequently, the Western Cape Province is the geographical boundary and the time frame is from 2001 until 2040.

3.3 Causal loop modelling

This section forms part of the conceptualisation process of SDM. In the previous section the problem was formulated. The hydrological cycle was discussed with the aim of gaining an understanding of the general water cycle. An understanding of the dynamics of the water resources, specific to the Western Cape Province, was also gained. Furthermore, the key variables and time horizon were established.

In this section a causal loop diagram (CLD) was developed for the problem that was formulated in the previous section. This was done using the systems thinking approach. The aim was to illustrate all the role players and feedback loops of the specific problem by using variables and links.

3.3.1 Basic causal loop modelling concepts

CLD's illustrate the relevant parts of a system using variables, the links between the variables are arrows pointing in the direction of influence (Maani & Cavana, 2007b:14). The signs "+" or "–" are used to indicate whether the influence is positive or negative while the signs "R" and "B" are used to denote whether a feedback loop is reinforcing or balancing respectively. Any mechanism that experiences a growing or decreasing/slowing action can be described by a CLD. Figure 3.7 is the illustrative CLD and explains the most basic components of CLD with a simple population system.

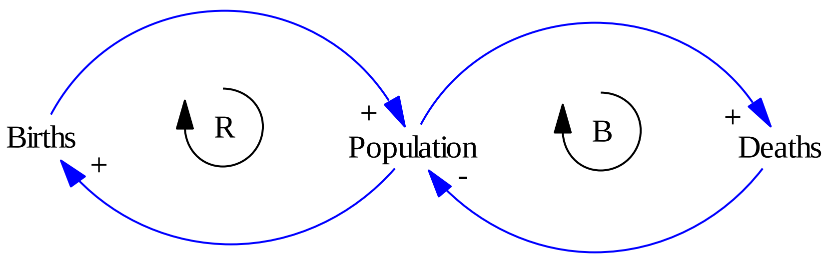

Figure 3.7: Illustrative CLD

A reinforcing loop is a positive feedback system. It can represent growing or declining actions (Maani & Cavana, 2007b:14). The reinforcing loop shown in Figure 3.7 is an example of a growing action where the more the births the more the population will be. Also, the more the population the more births will there be. A balancing loop is a negative or counteracting feedback loop and seeks stability (Maani & Cavana, 2007b:14). The balancing loop in Figure 3.7 indicates that the more the population the more the deaths would be, however the more the deaths the less the population.

Delays are a characteristic in most systems. Different types of systems experience different types of delays (Mirchi, Madani, Watkins & Ahmad, 2012:2421). For example, in system dynamics delays refer to the time lapse between a cause and its effects (Mirchi, Madani, Watkins & Ahmad, 2012:2421). These delays can either be information delays or material delay. In a CLD, the notation "||" on the arrow is used to represent a delay.

Figure 3.8 thus demonstrates a material delay in a water demand system and reads as follows; The more the domestic water use, the less the available potable water, which in turn implies the need for more water treatment. The more the water is treated, the more the potable water supply. However, there is a time delay in treating the water to become potable. The more the potable water that is available, the more is the available water for the domestic use.

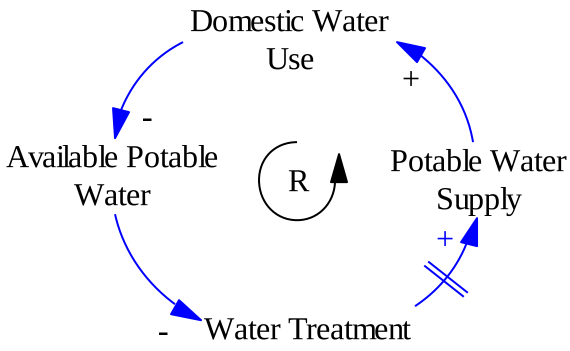

Figure 3.8: Reinforcing CLD with a Delay

The CLD for the water resource sector in the Western Cape Province was developed by using VENSIM software. The main feedback loops are discussed in separate CLD's (see section 3.3.2-3.3.4) which are ultimately linked together to show the overall Water Resource CLD (see section 3.3.5).

3.3.2 Water resource investment CLD

Figure 3.9 shows the water investment CLD, which consist of one balancing loop, B1, and one reinforcing loop, R1. B1 indicates that if the available water stock is not sufficient to provide all the sectors and Western Cape population with water, there will be more urgency to save water and the green economy water budget would need to be increased. An increase in the budget results in an increase in water management investment. An increase in water management investment would ensure that more water saving initiatives are invested in and subsequently increasing the total water supply. Ultimately the available water stock would increase.

It is important to note that the total water supply in this model, for the business as usual (BAU) case, is the sum of four different sources of water, which are not shown in this CLD but can be seen in the overall CLD (Figure 3.14). These sources include surface water (water in dams specifically), ground water, recycled water and desalinated water. For the green economy scenario, water that is gained from the water conservation and demand management (WC/WDM) is taken into account. Surface water, groundwater and recycled water consist of their own CLDs. Consequently, the water savings initiatives seen in this CLD (Figure 3.9) refers to WC/WDM. WC/WDM initiatives are discussed in more detail in section 3.6.

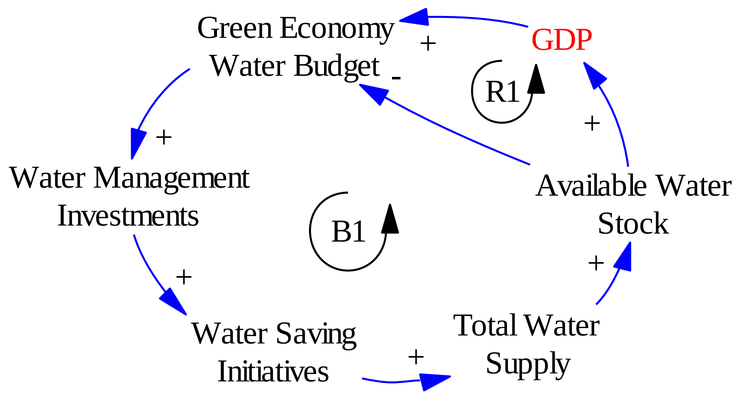

Figure 3.9: Water resource investment CLD

On the other hand, the reinforcing feedback loop, R1, shares most variables with B1 but has an additional variable namely, GDP. With R1, the more the available water stock to support the economic activities such as agriculture, industry and services, the more the GDP would be. The more GDP an economy has implies a potential to allocate more of the budget to green economy activities in water or as stated by Eyraud et al (2011) *"green investment is boosted by economic growth"*. The more the budget allocated, the more the water management investment, which will then result in an increase in water savings initiatives, therefore the total water supply will increase and ultimately an increase in available water stock.

3.3.3 Water Supply CLDs

The CLD's of the three main sources of supply in the Western Cape Province are presented and discussed in this sub section. These sources are recycled water, surface water and groundwater. Various variables are repeated in the three CLDs discussed since all eventually linked to total supply and subsequently available water stock. However, it was still required to mention the variables to ensure a sufficient understanding of the feedback loops in the water system.

In the Western Cape Province the contribution of desalination of sea water is currently limited. The existing plants are operated intermittently, either during the summer seasons when the water demand at the coastal towns increase or during drought periods. However, the small contribution that is made by desalination in simulated in the model. The CLD for desalination is not discussed separately in this section. It is however included in the combined water resource CLD (Figure 3.14).

Water Recycling CLD

Figure 3.10 shows the water recycling supply CLD which consists of one balancing loop, B2, and one reinforcing loop, R2. R2 indicates that the more the available water stock, the more water will be used. The water that is used is equal to the minimum between the total water demand and the available water stock. The total water demand is dependent on various sectors (see Figure 3.14) which is discussed in more detail in the dynamic modelling section.

The more water that is used the more waste water from indoor and outdoor use will be produced. Waste water goes through a treatment process before it becomes recycled water, hence a time delay between indoor and outdoor waste water and recycled water. The more water that is recycled, the more the total water supply will be. The more the total water supply ultimately ensures more available water stock.

B2 indicates that recycled water has the potential to be increased by an increase in the water savings investment. This is true, since an increase in water savings investment could increase the available WWTW capacity. Evidently the amount of usable recycled water is dependent on the capacity of the WWTW. Furthermore, it is argued that the green economy water budget will increase if the available water stock is not sufficient to meet the demand and subsequently urgency arises among investors, and vice versa.

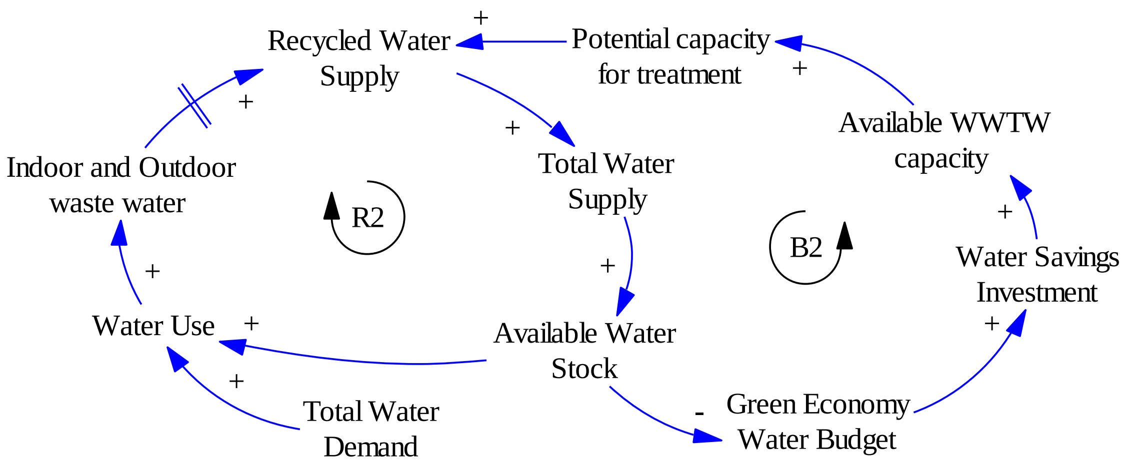

Figure 3.10: Water Recycling CLD

Surface Water CLD

Figure 3.11 represents the surface water CLD, which consists of two balancing loops, B3 and B4. B3 is balanced due to the connection between available water stock and the green economy water budget, as discussed in the previous CLDs. The more the available water stock the smaller the green economy water budget will be. The more funds that are available in the green economy water budget the more investment could be made into the augmentation of surface water sources. The more the augmentation and construction that takes place, the more the available dam capacity and ultimately the more surface water supply. It is evident through this CLD that surface water supply is limited by the available dam capacity.

B4 shows the causal relationship between surface water and evaporation. The more surface water the more the evaporation and the more evaporation the less surface water. Evaporation could be reduced if new dams are built deeper rather than wider, however this could result in a “fixes that fail” system since water quality is reduced if the dams are built too deep. Therefore this is not taken into account in this model.

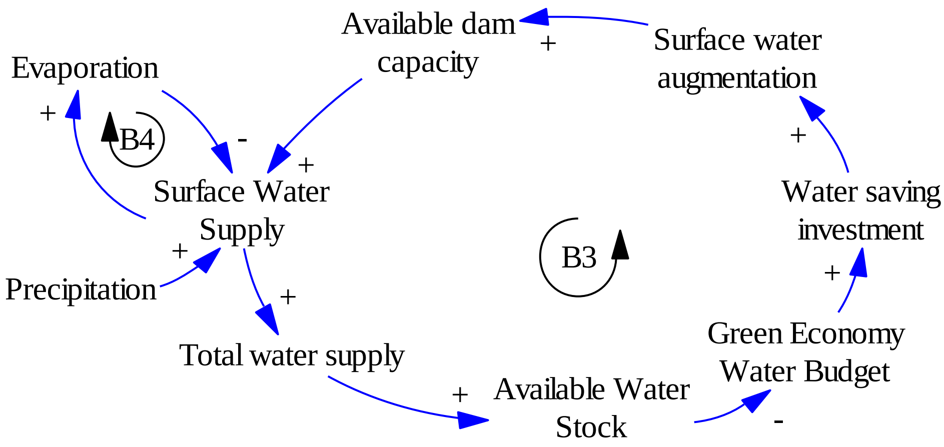

Figure 3.11: Surface water CLD

Groundwater CLD

Figure 3.12 represents the groundwater CLD, which consists of one balancing loop, B5. Again the same relationship exists between the available water stock and green economy water budget as mentioned in the previous CLD discussions. The water saving investment in the case of groundwater will increase the development thereof and ensure that more groundwater is extracted more efficiently. However, groundwater development is limited to the utilisable groundwater exploitable potential (UGEP). The UGEP represents a management restriction on the volumes of water that may be abstracted based on a defined allowable water level drawdown. Evaporation decreases groundwater supply while precipitation increases it through percolation.

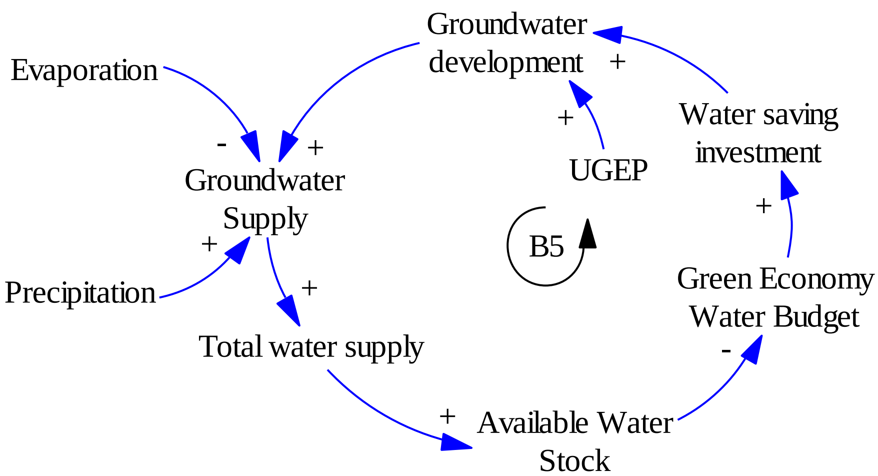

Figure 3.12: Groundwater CLD

3.3.4 Water demand CLD

It should be noted that the water demand/requirement is modelled in the dynamic model and not the water use/consumption. Water use is however accounted for in the CLD to illustrate the difference between water demand and water use. Water demand drives water use, but the water use cannot exceed the water supply whereas water demand can.

Figure 3.13 describes the water demand CLD which consists of three balancing loops, B6, B7 and B8, and one reinforcing loops, R3. It is assumed that water demand in the various sectors are increased by three factors namely, population, GDP, and climate change as seen in the Figure 3.13. The basic population CLD forms part of Figure 3.13 and consists of one reinforcing loop, R3, and one balancing loop, B7. The more the population, the more the total water demand will be. The second driver of water demand is GDP. It is generally accepted that GDP is required to sustain economic growth, therefore the bigger the GDP the more water demand will be. Lastly, climate change is predicted to increase temperature in the Western Cape Province as well as reduce precipitation. Subsequently, irrigated agriculture and afforestation will demand more water.

The increase in total water demand in turn influences the amount of available water stock in that, the more this demand, the more total water demand, the more the total water demand, the more water can be used and less the available water stock. This creates a reinforcing loop (R3).

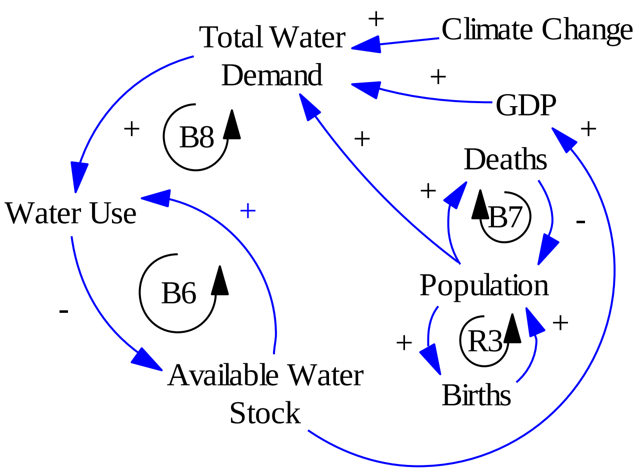

Figure 3.13: Water demand CLD

3.3.5 Combined water resource CLD

The CLD's described throughout the section were combined to show overall Water Resource CLD in Figure 3.14. This figure illustrates that there are two sides to the conceptualization of the model, namely the water supply side and the water demand side. As discussed in section 3.3.2 the water supply in this model, for the BAU case, is increased by three main water sources namely, surface water (water in dams), groundwater and recycled water. Desalination also makes a small contribution to the water supply of the Western Cape Province. Water gained from WC/WDM and other interventions were only considered as an extension of the model.

The water demand in this model is driven by population growth, GDP growth and climate change. Population growth drives demand for the obvious reason that people require water to survive form day to day. Also, the more people there are the more agriculture, industry etc. is required and therefore more water is required. GDP increases by the demand of the various sectors (discussed in section 3.3.3) seeing that the sectors will require more water as it expands. It is predicted that the Western Cape Province will become hotter as a result of climate change, this will increase the demand since it will cause people and agriculture to require more water as it will be warmer. Furthermore, an additional connection not mentioned in the previous CLDs is between evaporation, precipitation and climate change. Climate change is assumed to increase evaporation and decrease precipitation.

Water supply and water demand has an influence on the available water stock and the Water Stress Index. The available water stock refers to the amount of water that is available for use. In this CLD demand is seen as conceptual and the water use is seen as the actual amount of water used. The Water Stress Index is an auxiliary variable that is influenced by the total water supply and the total water demand. Generally a Water Stress Index is an indicator used to show areas of water stress. In this model it is also used as an indicator to show the water stress that the Western Cape Province experiences. It is calculated by dividing the total demand by the total supply, therefore, the more the demand the higher the Water Stress Index.

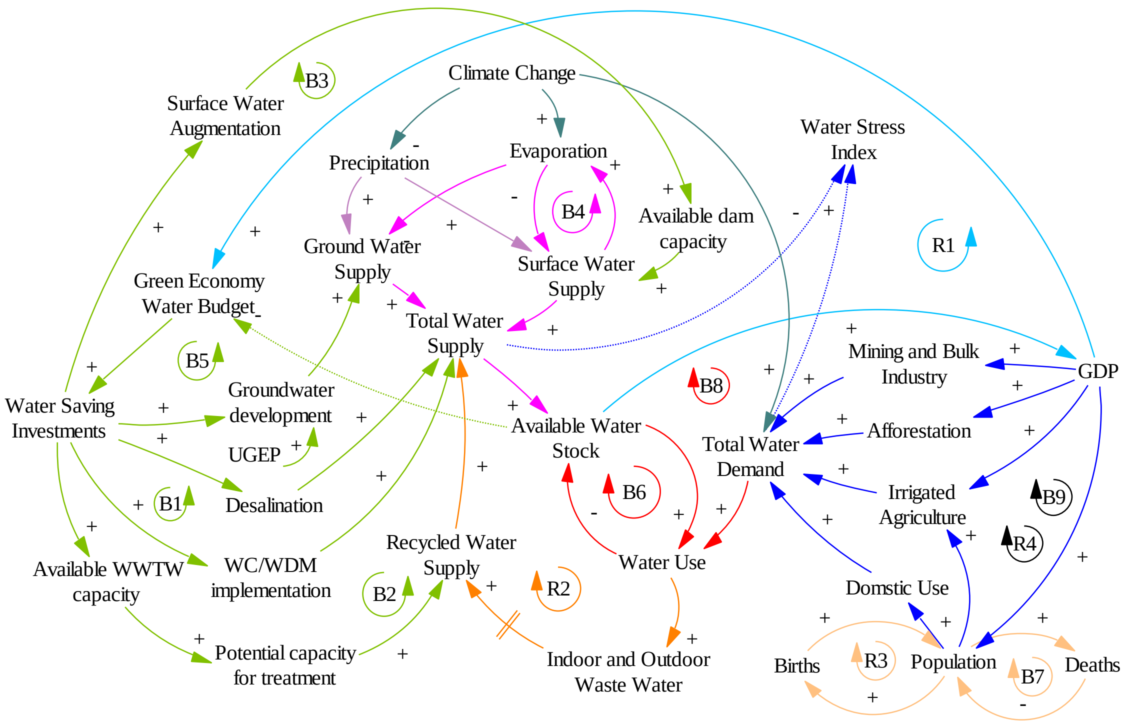

Figure 3.14: Water Resource CLD

Additional feedback loops that should be noted are B9 and R4. These loops emerged as a result of the link between GDP and population. The link shows that the population will increase as the GDP increases. This is a result of more available funds to sustain life. The two loops follow the same path until they reach the variable named water use. B9 originates as a result of the connection between water use and available water stock. The more water used results into less available water stock. R4, increases available water stock since the more water used increases the amount of recycled water and also total water supply and ultimately increases available water stock. In the dynamic model however, the link between GDP and population is not simulated. The reason for this is that even though there is a connection between the variables it is not certain what the exact mathematical equation would be to represent this connection. Hence, the link is merely to show that the connection was considered.

3.4 Dynamic Modelling

The causal loop modelling done in Section 3.3 gives insight on the intricacies involved in the water system. However, a number of advantages are gained from the development of a dynamic computer simulation model. Such a model enables a deeper investigation of the dynamic issues that are of concern to management as it contains more information than a conceptual model (Maani & Cavana, 2007c:59). Therefore, this section discussed the system dynamics simulation model that was developed.

As mentioned previously, the VENSIM software was used to develop the model. The key variables that were considered as essential in catalysing the green economy transition, with water resources as the primary focus, were calculated endogenously in the model. The model consists of eight sub-models (four of which are entirely based on the water resources of the Western Cape Province) and together they formed the Western Cape Water Resource Model (WeCaWaRM). Firstly, a brief introduction to the concept of dynamic modelling is discussed and subsequently a description of the WeCaWaRM sub-models is detailed in sections 3.4.1-3.4.6. The sketches of the sub-models are found in Appendix A.

3.4.1 Basic dynamic modelling concept

In SDM the dynamic behaviour is believed to arise due to the Principle of Accumulation. This principle states that all dynamic behaviour in the world occurs when flows accumulate in stocks (Maani & Cavana, 2007c:59). The principle of accumulation holds regardless of the number of inflows, outflows and auxiliary variables that work to change the number of entities accumulating in the stock. A stock and flow diagram (SFD) is generally constructed from a CLD, although in some cases it might be easier constructing the SFD directly.

An illustration of this basic stock and flow metaphor can be found in Figure 3.15. In the figure the stock is the water reservoir and the flows are the inflow and outflow assembly that fills or drains the reservoir. Stocks describe the condition of the system and it would continue to exist even if all flows in the system would be stopped. Flows are the changes in the stocks that occur during a period of time. It should be understood that the amount of water in the reservoir will rise when the inflow exceeds the outflow and vice versa.

In Figure 3.15 two additional variables can be seen namely, precipitation and demand. These variables are known as constants, which are used to influence or substitute the flow if desired since they are exogenous variables (Maani & Cavana, 2007c:59). In the case shown in Figure 3.15; the constant labelled precipitation substitutes the inflow and shows that the inflow into a reservoir happens as a result of precipitation. The demand variable illustrates that outflow is aggravated by the intensity of the demand for water.

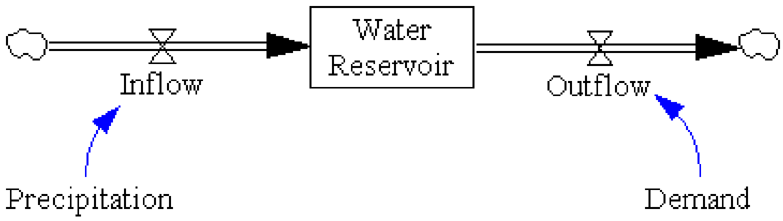

Figure 3.15: Basic Stock and Flow diagram

Auxiliary variables are endogenous variables which are generally used to break down the complex flows into simpler components with the aim of making the model easier to understand. Auxiliary variables are influenced by the constants, also known as exogenous drivers.

For the purpose of illustration the stocks and flows that characterize this model, the mathematical representation are discussed. Stocks are represented as integrals while flows are presented as differential equations. The first fundamental theorem of calculus describes how the stocks and flows of the model are represented. The first fundamental theorem of calculus states that, if f continues on the closed interval [t_0, t_n], then (Loomis and Sternberg, 1968);

$$\int_{t_0}^{t_n} f(t)dt = F(t_2) - F(t_1) \tag{3.1}$$

Consequently, the following is also true:

$$F(t) = F(t_0) + \int_{t_0}^{t_n} f(t)dt \tag{3.2}$$

For this model the closed interval [t_0, t_n] is taken as [2001, 2040] which is the time horizon over which the model is simulated as mentioned previously. The function $F(t_0)$ is the initial value of the stock in the year 2001 and the differential equation $f(t)dt$ represents the in- and outflows under consideration. $F(t)$ is the integral function and represents the value of the stock over the entire time horizon. Furthermore, the unit used to quantify the amount of water throughout the model is kilogram (kg). The simple conversion between kg, litres (l) and cubic meters (m^3) that was used is:

$$1m^3 = 1000l = 1000kg \tag{3.3}$$

3.4.2 Water based sub-models

As mentioned previously the WeCaWaRM consists of eight sub-models. Four of the sub-models are clustered as water based sub-models and are discussed in this section since they are primarily based on the water resources in the Western Cape Province. The remaining five are mainly the sub-models that are key drivers of the water based models. The water based sub-models discussed in this section are:

i. Water Supply and Demand sub-model
ii. Waste Water sub-model
iii. Surface water and Groundwater sub-model
iv. Green Economy Investments sub-model

Together, the four water based sub-models consist of fourteen stocks, whose dynamics are dependent on various flows, auxiliary variables and constants. The stocks and flows are discussed in detail throughout this section, however, a summary of the stocks, flows and first order auxiliary variables (the auxiliary variables that influence the stocks or flows directly) that characterise the four sub-models can be found in Table 3.6. Each stock and the variables that influence it as well as the data used is discussed in detail in this section.

Table 3.6: Stocks, flows and auxiliary variables of water sub-model

	Stock	Flow	Auxiliary variables
Supply	Dam Capacity	Annual dam construction Dam depreciation	Change in dam capacity Life expectancy of WWTW
	Potable water	Potable water inflow UAW in treatment system Outflow for domestic use	Total supply Domestic and municipal water demand Fraction of water lost through the system
	WWTW Capacity	Annual WWTW Construction WWTW Depreciation	Fraction of waste water being recycled WWTW Capacity Fraction of water lost through supply system
Demand	Irrigated Agriculture	Irrigation demand growth	Irrigation growth factor influenced by GDP and Climate Change and Population growth
	Afforestation	Afforestation demand growth	Afforestation growth factor influenced by GDP and climate change
	Mining and bulk industry	Mining and bulk industry demand growth	Mining and bulk industry growth factor and Population growth
	Domestic and Municipal water demand: Determined exogenously as an auxiliary variable, influenced by water demand per capita and total population.		

Water Supply and Demand sub-model

This sub-model represents the supply and demand of the Western Cape Province. Water supply in the model, for the BAU case, is the sum of recycled water, groundwater and surface water, which are all calculated in the sub models. Therefore, the different supply sources are shadow variables in this sub model, which indicates that they are calculated in other sub models.

Historic data of water supply for the Western Cape Province as a whole is scarce and different information is available from different sources. However, after careful consideration and thorough research it was decided to use the data presented by Statistics South Africa (2010). This data has been represented by various other documents, such as the NWRS1 (DWAF, 2004), and can therefore be used with confidence. The data represents the water supply for the year 2000, however it was assumed to be valid for the year 2001 since the time horizon of the model spans from 2001 to 2040. The data is used as the initial values in 2001 can be found in Table 3.7.

Table 3.7: Western Cape Water Supply in 2000 (DWAF, 2004; Statistics South Africa, 2010)

Source	Supply in 2000 (million kg/ annum)	Percentage of total supply
Surface water (water in dams)	1547000	78
Groundwater	275000	14
Waste water reuse	162000	8

The water demand in this model is based on irrigated agriculture (IA), afforestation (AF), mining and bulk industry (MI) and domestic demand (DD). All, except domestic demand are calculated with a stock and flow diagram. The non-domestic demand sectors are all dependent on the growth factor of the specific sector, which is discussed throughout the section. The stock and flows of the non-domestic demands are given as:

$$IA(t) = IA(t_0) + \int_{t_0}^{t_n} [r_{ia}]dt \qquad (3.4)$$

$$AF(t) = AF(t_0) + \int_{t_0}^{t_n} [r_{af}]dt \qquad (3.5)$$

$$MI(t) = MI(t_0) + \int_{t_0}^{t_n} [r_{mi}]dt \qquad (3.6)$$

Desalination of sea water in the Western Cape Province had its origin at a coastal town named Sedgefield in 2009 (Blersch, 2014). Since 2009, four additional desalination plants have been built throughout the Province. Even though the existing desalination plants are only operated intermittently it was still considered as part of the base supply of the Province, adding a total of 8687 million kg water to the system.

Similar to historic data of water supply, data for water demand for the Western Cape Province as a whole is also scarce and different information is available from different sources. Again the data presented by Statistics South Africa (2010) is used for the water demand case. The data represents the water demand for the year 2000, however it is assumed to be valid for the year 2001. The data is used as the initial values in 2001 can be found in Table 3.8.

Note that power generation is zero, according to Statistics South Africa (2010). Power generation in South Africa requires vast amounts of water since ten out of the eleven existing base load power stations are coal fired. The eleventh base power station is a nuclear power station (Koeberg Power Station), which provides the base power of the Western Cape Province (Wassung, 2010). Koeberg claims to be a strategic water user who uses seawater to cool the condensers (Eskom, 2015). The sea water is not consumed and is returned to the ocean after use. Therefore, the Western Cape Province does not require fresh water to generate power.

Table 3.8: Western Cape Water Demand in 2000 (DWAF, 2004; Statistics South Africa, 2010)

Industry	Demand in 2000 (million kg/ annum)	Percentage of total demand
Agriculture: Irrigation	1488000	72.7
Afforestation	21000	1.03
Mining and bulk industry	9000	0.43
Power generation	0	0
Urban and Rural (Domestic)	529000	25.84

Many factors influence the water demand in South Africa. These factors include climate, the nature of the economy and standards of living among others (DWAF, 2004). In this model the non-domestic water demand growth is thought to be driven by the economy. Literature confirmed this by using GDP as a guideline for the future demand growth pattern (Wang, Xu, Yang & Wang, 2014:1070).

In Table 3.9 the GDP growth according to Trading Economics of the applicable sectors over the time horizon are presented. These GDP growth rates are calculated for South Africa, however it is assumed to be applicable to the Western Cape Province as well. The graphs for the GDP growth of the specific sectors are presented in Appendix B. From this data the annual percent growth rate is calculated and utilized in the model as the water demand growth rate for the specific sector. The annual percent growth rate equation is given as:

$$PR = \frac{\left(\frac{Vpresent - Vpast}{Vpast}\right) \times 100}{n} \tag{3.7}$$

Where;

$PR = Annual\ percent\ growth\ rate$

$Vpresent = Present\ or\ future\ values$

$Vpast = Past\ or\ present\ value$

$n = Amount\ of\ years\ between\ past\ and\ present\ values$

Table 3.9: South African GDP growth

Sector	Year		Growth
	2001	**2015**	
Agriculture and forestry	53986.6575	67151.464	1.6%
Mining and quarrying	235000	229000	-0.17%

Domestic demand is calculated as an auxiliary variable, where the dynamics is determined by population growth and per capita demand. According to Statistics South Africa (2010) the rural and urban demand was 529 billion kg of water in 2000 (assuming this is also true for 2001) and the population was 4524000 people. To determine the per capita demand per year the demand was divided by the population, which is equal to 320kg/person/day.

The minimum domestic water requirement according to the World Health Organisation (WHO) is 25kg/person/day, however, according to the Provincial Summary Report (DWA, 2011), the Western Cape Province has much higher and a particularly variable water requirement throughout the Province. Rural villages in the Province require an average of 60-100kg/person/day whereas permanent residents in coastal towns require an average of 200-250kg/person/day (DWA, 2011). Based on these requirements the DWA has established a theoretical average water requirement for domestic use of approximately 110kg/person/day. Furthermore, the DWA states that the actual consumption is significantly higher due to water losses and irresponsible use (DWA, 2011).

Subsequently it is concluded that the 320kg/person/day, which was established from the Statistics South Africa's rural and urban demand in 2000, was due to major losses and ignorant water use. Also, since 2000, some water demand management initiatives and reconstruction of the supply system has taken place, which reduced the per capita water demand. Hence, in the model the per capita demand is reduced throughout the time horizon from 320l/person/day in 2001 to 200l/person/day in 2040 over regular intervals, for the BAU scenario.

Waste water sub-model

This sub-model represents the waste water system in the Western Cape Province. Waste water is treated in the waste water treatment works (WWTW) to produce recycled water, which is used as a source of the water supply system. Recycled water supply is calculated as an auxiliary variable in the model. It is primarily dependent on the indicated WWTW capacity and the amount of waste water available for treatment which in turn is dependent on the potable water SFD as well as the WWTW SFD. Potable Water (PW) stock's dynamic behaviour is dependent on the potable water inflow (r_{pwi}), UAW in the treatment system (r_{uaw}) and water outflow for domestic use (r_{dom}). The WWTW capacity stock (WC) is dependent on two flows namely Annual WWTW Construction (r_{wc}) and WWTW depreciation (r_{wd}). The two SFD's are given as:

$$PW(t) = PW(t_0) + \int_{t_0}^{t_n} [r_{pwi} - r_{uaw} - r_{dom}]dt \qquad (3.8)$$

$$WC(t) = WC(t_0) + \int_{t_0}^{t_n} [r_{wc} - r_{wd}]dt \qquad (3.9)$$

In the potable water SFD, which is presented in Equation 3.9, the amount of potable water inflow is driven by the total water supply. It is assumed that potable water is given the highest priority with regards to water allocation and therefore the total supply is available should it be required. An outflow from the potable water stock is the unaccounted for water (UAW) in the treatment system. UAW is water that is lost due to infiltration, leaks as a result of poor maintenance, as well as evaporation. According to the DWA (2011) at least 36 million m^3 of water is lost in the Western Cape Province each year between the water resource and the end user. The DWA (2011) presents a table which contains nine towns with high UAW in the Western Cape Province. For the purpose of the model the average percentage of the UAW for the nine towns is calculated and used in the model, which is 53%.

The other outflow, outflow for domestic use, depends on the variables domestic and municipal demand and the amount of potable water available. The model is simulated to return the variable that is the smallest, which subsequently ensures that only the required amount of water flows from the stock.

Equation 3.10 describes the WWTW capacity SFD. In the Western Cape Province waste water services is performed by twenty seven Water Service Authorities via an infrastructure network comprising of hundred and fifty eight WWTW (DWA, 2012a). The Green Drop Progress report by the DWA (2012a) summarised the WWTW and their capacities in Ml/day can be found in Table 3.10.

Table 3.10: WWTW in the Western Cape (DWA, 2012a)

	Micro size <0.5	Small size 0.5-2	Medium size 2-10	Large size 10-25	Macro size >25	Undetermined	Total (Ml/day)
Number of WWTWs	45	49	35	8	11	10	158
Total Design Capacity	7.33	48.68	157.76	118.2	710.6	10	1042.6
Total daily inflows	4.86	33.43	96.53	101.32	589.00	25	825.1

From Table 3.10 it can be seen that only 79.13% of the total design capacity of the WWTWs is utilised by dividing 825.1 Ml/day 1042.6 Ml/day. In the model this is accounted for by the auxiliary variable "ratio of WWTW capacity being used". Furthermore, from the table the yearly capacity of the WWTW in the Western Cape Province is calculated by multiplying the total design capacity, which is given in Ml/day, with the amount of days in a year. This is equal to 380549 Ml/year (or 380549 M kg/year).

The water treated in these WWTWs is generally considered to be polluted water originating from sewage treatment facilities or the waste water discharge from industrial facilities. In the model this water is accounted for by the inflows named, waste water as a result of indoor and outdoor use. According to the CCT (2010) research indicates that the average waste water flow from a residential unit is approximately 70% of the water consumption. Also, 90% of water consumed by industrial consumers falls in the category of "waste water producing" consumption (CCT, 2010).

Surface water and Groundwater sub-model

This sub-model represents the surface water and groundwater of the Western Cape Province. Surface water supply and groundwater supply are modelled as auxiliary variables. The only SFD that indirectly influences these water supplies is the dam capacity SFD. Dam capacity (DC) stock is dynamically influenced by the annual dam construction (r_{dc}) and dam depreciation (r_{dd}). The SFD is presented as:

$$DC(t) = DC(t_0) + \int_{t_0}^{t_n} [r_{dc} - r_{dd}]dt \quad (3.10)$$

Dam capacity limit is set equal to the sum of the capacities of all the dams in the Western Cape Province (DWS, 2015). The total capacity of the dams has changed throughout the time horizon of the model; these changes are also simulated into the model. The Berg River dam was built and completed in 2009, which added 127.1 million m^3 to the total capacity of the Western Cape Province dams (TCTA, 2013). The Clanwilliam dam is currently undergoing construction, which aims to raise the dam wall with 13 meters, subsequently increasing the capacity by approximately 206 million m^3 (DWA, 2012b:61). The construction of the Clanwilliam dam is predicted to be complete in 2016 depending on funding availability (E. Molewa, 2011). The major dams in the Western Cape Province are presented in Table 3.11.

Table 3.11: Capacity of major dams in the Western Cape Province (Blersch, 2014; DWS, 2015)

Major Dams in the Western Cape Province	**Storage Capacity (million m^3)**
Wemmershoek	58.64
Steenbras Lower	33.52
Steenbras Upper	31.80
Voelvlei	158.58
Theewaterskloof	480.25
Berg River	127.1

Surface water supply is dependent on the indicated dam capacity and the potential water to enter the dams. The potential water to enter the dams is calculated by considering the amount of runoff, evaporation and percolation in the Western Cape Province. The runoff is dependent on the mean annual precipitation (MAP), the total provincial land and conversion of rainfall to runoff. The total provincial land is calculated by the Provincial Land sub-model, discussed in section 3.4.6.

The average precipitation of the Western Cape Province was determined by utilising data from the study done in 2005 known as Water Resources of South Africa (WR2005). Various quaternary catchments throughout the Western Cape Province were analysed from which a mean maximum, minimum and average MAP as well as the standard deviation could be calculated (see Table 3.12). These figures were used in the random normal function in VENSIM to generate random numbers over the time horizon. A map presenting the water stations in the Western Cape Province as well as summarized data and calculations for the MAP are presented in Appendix B.

The prevailing patterns of variable and unevenly distributed rainfall in the Western Cape Province, combined with high evaporation rates, result in very low conversion of rainfall to runoff. A study conducted on the river basins of South Africa indicates the conversion ratio ranges from 3.4 % to 14% throughout the country (Ashton, Hardwick & Breen, 2008). From this study it can be concluded that the conversion ratio for the Western Cape Province is equal to 12.1%.

Table 3.12: MAP characteristics for the Western Cape Province (WRC & WR2005, 2005)

Characteristic	**Value**
Mean Maximum	1416.75 mm/year
Mean Minimum	175.026 mm/year
Mean of the Mean	506.83 mm/year
Standard Deviation	280.312

Water losses that occur before water enters the dams are due to evaporation, transpiration, infiltration losses and water flowing directly into the sea. These losses are accounted for by the auxiliary variable "fraction of rain evaporating immediately" as well as "fraction of rain infiltrating and percolating". Water losses that occur after the water has entered the dams are due to spillage if the dam is full and seepage into aquifers. In the model it is assumed that groundwater stock is recharged if the dam spills or seepage/infiltration occurs.

Groundwater and surface water is commonly hydrologically connected as seen in Figure 3.1, but the interactions are difficult to observe and measure. However, the model attempts to include a connection between these water supply sources. In the model groundwater is assumed to be recharged by spillage and seepage of dams/surface water. Groundwater is also recharged by rainfall that percolates into the ground which is accounted for by the auxiliary variable "possible rainfall to become groundwater". It is highly complex to determine the fraction of precipitation percolating for the whole Western Cape Province, as this fraction is dependent on vegetation cover, slope, soil composition, depth of the water table, the presence or absence of confining beds and other factors, which are greatly variable factors for the Western Cape Province. However, based on the amount of precipitation inflow calculated by the model and the Utilisable Groundwater Exploitation Potential (UGEP) of the Province, it is assumed that 2% of the precipitation percolates to become usable groundwater.

The capacity of the groundwater stock is set equal to the UGEP of the Western Cape Province, which is 1049.3 million m^3/annum (DWA, 2010). The UGEP represents a management restriction on the volumes of water that may be abstracted based on a defined maximum allowable water level drawdown. According to the DWA (2010) only approximately 30% of South Africa's groundwater is being used. This is assumed to be true for the Western Cape Province as well and is simulated into the model with the auxiliary variable "fraction of groundwater extracted".

Green economy investments sub-model

The purpose of this sub-model is to inform stakeholders on the amount of investment required on a yearly basis to ensure that the Western Cape Province has sufficient water supply to meet the growing demand until 2040. The sub-model comprises of seven SFD's. The total annual cost is calculated as an auxiliary variable and involves the costs associated with the maintenance and implementation of WWTW, surface water, groundwater, WC/WDM as well as desalination.

The WWTW cost stock (WC) accumulates the annual costs for WWTW (r_{wac}). The surface water cost stock (SC) accumulates the annual costs for surface water (r_{sac}). Similar to WWTW cost and surface water cost, WC/WDM cost stock (WCC) accumulates annual cost for WC/WDM (r_{wcac}). To determine the groundwater costs the change in pump station capacity is required. The change in pump station capacity is determined by a SFD which consists of one stock namely, pump station for groundwater capacity (PC) as well as an in- and outflow namely, pump station capacity increase (r_{pci}) and depreciation of pump station (r_{dp}). The groundwater costs stock (GC) is subsequently calculated by the accumulation of annual costs for groundwater (r_{gac}), which is subject to change in pump station capacity. Desalination cost (DC) is determined in a similar manner to groundwater. These SFDs are given as:

$$WC(t) = WC(t_0) + \int_{t_0}^{t_n} [r_{wac}]dt \tag{3.11}$$

$$SC(t) = SC(t_0) + \int_{t_0}^{t_n} [r_{sac}]dt \tag{3.12}$$

$$WCC(t) = WCC(t_0) + \int_{t_0}^{t_n} [r_{wcac}]dt \tag{3.13}$$

$$PC(t) = PC(t_0) + \int_{t_0}^{t_n} [r_{pci} + r_{dp}]dt \tag{3.14}$$

$$GC(t) = GC(t_0) + \int_{t_0}^{t_n} [r_{gac}]dt \tag{3.15}$$

$$DPC(t) = DC(t_0) + \int_{t_0}^{t_n} [r_{dci} + r_{dd}]dt \tag{3.16}$$

$$DC(t) = DC(t_0) + \int_{t_0}^{t_n} [r_{dac}]dt \tag{3.17}$$

The annual costs calculated in the model are all calculated with a rand per kilogram water value. A detailed discussion on the specific interventions which are implemented in the model as well as the costs involved can be found in the scenarios section (section 3.6), which follows after the validation.

3.4.3 Population model sub-model[5]

This sub-model represents the population of the Western Cape Province. It was categorised according to age group and gender (male or female). The age groups include school age, adult age and childbearing age, among others. The model consists of one stock, population (P), whose dynamics is influenced by births (r_b), deaths (r_d) and net migration (r_{nm}). This is given as:

$$P(t) = P(t_0) + \int_{t_0}^{t_n} [r_b + r_{nm} - r_d]dt \tag{3.18}$$

[5] The population sub-model was presented as part of WeCaGEM, which was presented at the 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts (Musango et al, 2015)

Population growth is an important driver of domestic and municipal water demand. The complexity when projecting population growth and the future distribution of people between urban and rural areas is recognised in this model. The factors that influence populations (fertility rate and birth rate and migration rate) are taken into account. Urbanisation and economic growth are expected to decrease the growth rate of the population (DWAF, 2004), which is taken into account in the model by the auxiliary variables "effects of economic conditions on fertility rate" and "effect of education on proportion using contraceptives".

As an illustration, a growing population results in an increase in the water demand. With an increasing total demand, the Water Stress Index also increases, implying a reduction in the water reserve margin relative to the demand. An increasing Water Stress Index consequently influences the production sectors such as agriculture, industry and services in a negative way, which in turn influences the size of GDP. The GDP and in particular, per capita income, has an influence on the fertility rate and life expectancy, which in turn determines the level of population in the province. The main output of this sub-model was population which was compared to the available historical population data (see Figure C-3, Appendix C).

3.4.4 GDP sub-model[6]

The GDP sub-model shows the accounting relationship in the calculation for the major income-related indicators. The main income related indicators include the real GDP. The per capita income and the production sectors, among others, influence the real GDP. The available historical data for the Western Cape Province GDP was imported into the model to compare with the simulated results. This comparison is illustrated in Figure C-2, Appendix C.

3.4.5 Education sub-model[7]

The sub-model represents the progression of population through the education system. The sub-model is categorised according to the South African education system of seven years in primary school and five years in high school respectively. The government expenditure in education and per capita income is assumed as the main influences of entrance to school. The module consists of three stocks: students (S), who increase by entrance rate (r_{er}) and decrease by completion rate (r_{cr}); young literate population (YLP), who increase due to completion of the education system; adult literate population (ALP), increased by the rate at which the young literate population become adults (r_{ba}).

$$S(t) = S(t_0) + \int_{t_0}^{t_n} [r_{er} - r_{cr}]dt \tag{3.19}$$

$$YLP(t) = YLP(t_0) + \int_{t_0}^{t_n} [r_{cr} - r_{ba}]dt \tag{3.20}$$

$$ALP(t) = ALP(t_0) + \int_{t_0}^{t_n} [r_{ba}]dt \tag{3.21}$$

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[6] The GDP sub-model was presented as part of WeCaGEM, which was presented at the 33rd International Conference of the System Dynamics Society (Musango et al, 2015)

[7] The education sub-model was presented as part of WeCaGEM, which was presented at the 33rd International Conference of the System Dynamics Society (Musango et al, 2015)

Specifically for WeCaWaRM, this sub-model is used to estimate the level of literacy rate which subsequently influences the contraceptive prevalence. Ultimately the contraceptive prevalence has an influence on the total population (see Appendix A, Figure A-4) which is an important factor influencing the water demand.

3.4.6 Provincial land sub-model[8]

This sub-model represents the land use in the Western Cape Province and includes six stocks namely; agricultural land (AL), invasive species land (IL), settlement land (SL), conservation land (CL), livestock land (LL) and other land (OL). These stocks are given as:

$$AL(t) = AL(t_0) + \int_{t_0}^{t_n} [r_{oa} - r_{ao}]dt \qquad (3.22)$$

$$IL(t) = IL(t_0) + \int_{t_0}^{t_n} [r_{sao} - r_{ro}]dt \qquad (3.23)$$

$$SL(t) = SL(t_0) + \int_{t_0}^{t_n} [r_{os}]dt \qquad (3.24)$$

$$CL(t) = CL(t_0) + \int_{t_0}^{t_n} [r_{oc}]dt \qquad (3.25)$$

$$LL(t) = LL(t_0) + \int_{t_0}^{t_n} [r_{ol} - r_{lo}]dt \qquad (3.26)$$

$$OL(t) = OL(t_0) + \int_{t_0}^{t_n} \left[\left(\sum r_{ao}, r_{ro}, r_{lo}\right) + \left(\sum r_{oa}, r_{sao}, r_{os}, r_{oc}, r_{ol}\right)\right] dt \qquad (3.27)$$

Where; r_{oa} represents the rate that other land is transformed into agricultural land, r_{ao} represents the rate that agricultural land is transformed into other land, r_{sao} represents the rate that alien species spreads to other land, r_{ro} represents the rate that alien species is removed and land is restored to other land, r_{os} represents the rate that other land is transformed to settlement land, r_{oc} represents the rate that other land is transformed to conservation land, r_{ol} represents the rate that other land is transformed to livestock land, r_{lo} represents the rate that livestock land is transformed to other land.

3.5 Validation

In Table 3.1, validation is specified as the forth phase of the SDM process. Validation is a critical part of SDM as it is required before the model can be used for future recommendations or any other use. The WeCaWaRM model was built up gradually in a step-by-step way, with the graphical and tabular data being checked regularly to ensure a thorough understanding of the development and behaviour of the model. Some formal validation tests will be presented in this section.

Firstly, literature on validation of System Dynamics model is reviewed and discussed. From the discussion a decision is made regarding the tests that are required to validate the System

[8] The provincial sub-model was presented as part of WeCaGEM, which was presented at the 33rd International Conference of the System Dynamics Society (Musango et al, 2015)

Dynamics model. The chosen tests are subsequently performed and documented. From the tests a decision could be made regarding the validity of the model.

3.5.1 Discussion on System Dynamics validation

The review of the literature on System Dynamics validation revealed that the dominating papers in the field are those written by Forrester and Senge (1980:209), Coyle (1977; 1983:359), Barlas (1996:183) and Sternman (1984:51). Even though some date back more than 30 years, they are still cited in more recent studies by authors such as Maani and Cavana (2007c:59), Xi Xi et al. (2013:157) and Musango et al. (2014:257) just to name a few. The studies mentioned contain a lot of information, which can only briefly be summarised here.

Barlas (1996:183) argues that model validation comprises of formal, semi-formal and subjective aspects. The semi-formal and subjective aspects refer to the "usefulness of the model with respect to its purpose". He states that the semi-formal validation is required seeing that building confidence in the usefulness of the model does not only take place after model construction but continuously throughout the entire process, starting with problem identification throughout the methodology and even after discussion and implementation of results. Barlas continues by revealing the formal aspects of validation, which according to him includes structural validity and behavioural validity. Structural validity is further dissected into direct structure tests and structure oriented behaviour tests. He briefly mentions statistical significance tests, which he argues is mostly not suitable for system dynamics models.

Coyle and Excelby's (2000:27) review of the literature on validation of System Dynamics models concluded that various authors approach the validation process in different ways, referring to the level of detail by which it is addressed. Forrester and Senge (1980:209) as well as Coyle (1983:359) consider validation in detailed manner, discussing each test thoroughly. Even though the vocabulary used differs, they consider validation from a similar logical point of view and summarises validation to be "the process by which we establish sufficient confidence in a model to be prepared to use it for some particular purpose". Forrester and Senge (1980:209), Sternman (1984:51) and Coyle (1983:359) all agree that there is no single test which serves to validate a System Dynamics model but rather that confidence in a System Dynamics model increases gradually as the model passes more tests and as new points of correspondence between the model and observed reality is identified.

Although all tests of a System Dynamics model aim to establish more confidence in the model structure, Forrester and Senge (1980:209) as well as Coyle (1983:359), have outlined three fundamental tests that should be used to validate a System Dynamics model. Maani and Cavana (2007c:59) have summarized the fundamental tests mentioned by Forrester and Senge (1980:209) in Table 3.13.

Table 3.13: Model testing in system dynamics (Maani & Cavana, 2007c:72)

Tests of model structure (Coyle refers to "verification tests")	
Structure verification	Is the model structure comparable with the structure of the real system that the model represents
Parameter verification	Do the model parameters correspond conceptually and numerically to the real system
Extreme conditions	Are the rate (policy) equations plausible if imaginary maximum and minimum values of each stock variable on which they depend are inserted into the model
Boundary adequacy	Is the level of model aggregation appropriate and does the model include all relevant structure
Dimensional consistency	Are the rate equations dimensionally consistent and do they include "scaling" parameters that have little or no real-life meaning
Tests of model behaviour (Coyle refers to "behaviour tests")	
Behaviour reproduction	How well does the model-generated behaviour match observed behaviour of the real system
Behaviour anomaly	Can a model assumption be defended if implausible model behaviour occurs if the assumption is altered
Behaviour sensitivity	Can plausible shifts in the model parameters cause a model to fail model behaviour tests previously passed
Tests of policy implications (Coyle refers to "legitimisation tests")	
Changed behaviour prediction	Does the model correctly predict how the behaviour of the system will change if a governing policy changed
Policy sensitivity	To what extent are policy recommendations altered by plausible changes to parameter values, and what risk is indicated in adopting a model for policy making

Validation of the System Dynamics model in this research was an iterative process that took place continuously throughout the entire SDM process, as Barlas (1996:183) argues is required. Throughout the section that follows a formal attempt is made to validate the model. This is done by combining a range of the formal tests outlined by Barlas (1996:183) as well as the tests mentioned in Table 3.13.

3.5.2 Tests of model structure

Structure verification implies that the CLD must correspond to the real system that the model represents. The CLD provided in Figure 3.14 does correspond to the real water system in the Western Cape Province. Confirmation that the CLD does correspond structurally to the real system is reinforced by the qualitative analysis of the feedback loops in the causal loop modelling section (see section 3.3). The equations implemented in the model also correspond to the CLD. A close inspection revealed that the direction of the relationships in the CLD matched the direction of those in the dynamic computer model. It should however be mentioned that the CLD contains less variables than the dynamic computer model. This is a result of the detailed model equations. Nevertheless, the process did reveal inconsistent linkages between the CLD and the SFDs, which were corrected to confirm structure and parameter soundness. Further confidence is gained with the "Check Model" tool in VENSIM, which indicates that the model is "OK".

The model parameters were inspected closely to verify if it is dimensionally valid. Dimensional validity implies that it should be possible to convert the units of the variable on the left-hand side of the equation to the units on the right-hand side of the equation. VENSIM consists of a convenient tool, namely Units Check, which performs the dimensional validity test automatically and informs the modeller of errors, if necessary. Various dimensional errors were corrected throughout the modelling process which ensured that the Units Check tool could subsequently alert the modeller that the model is dimensionally valid.

The SFDs has been documented adequately in the dynamic modelling section (see section 3.4). This involved explaining the nature of the relationships of all the variables and the assumptions underlying them. The data that has been used is referenced throughout the discussion. During the documentation of the SFDs it was found that the model can be expanded further. However, the level of aggregation is appropriate for its current purpose and all relevant structures are included, which confirms boundary adequacy.

The model was subjected to a number of extreme conditions tests. Only one test will be described here. The test included the per capita demand. It was assumed that the per capita demand followed the BAU path until 2015, after which it was decreased, in equal time steps, to zero from 2015 to 2040, as illustrated in the graph in Figure 3.16. The per capita water demand directly influences the domestic and municipal water demand and subsequently the total water demand. Ultimately, it should influence the supply-demand deficit.

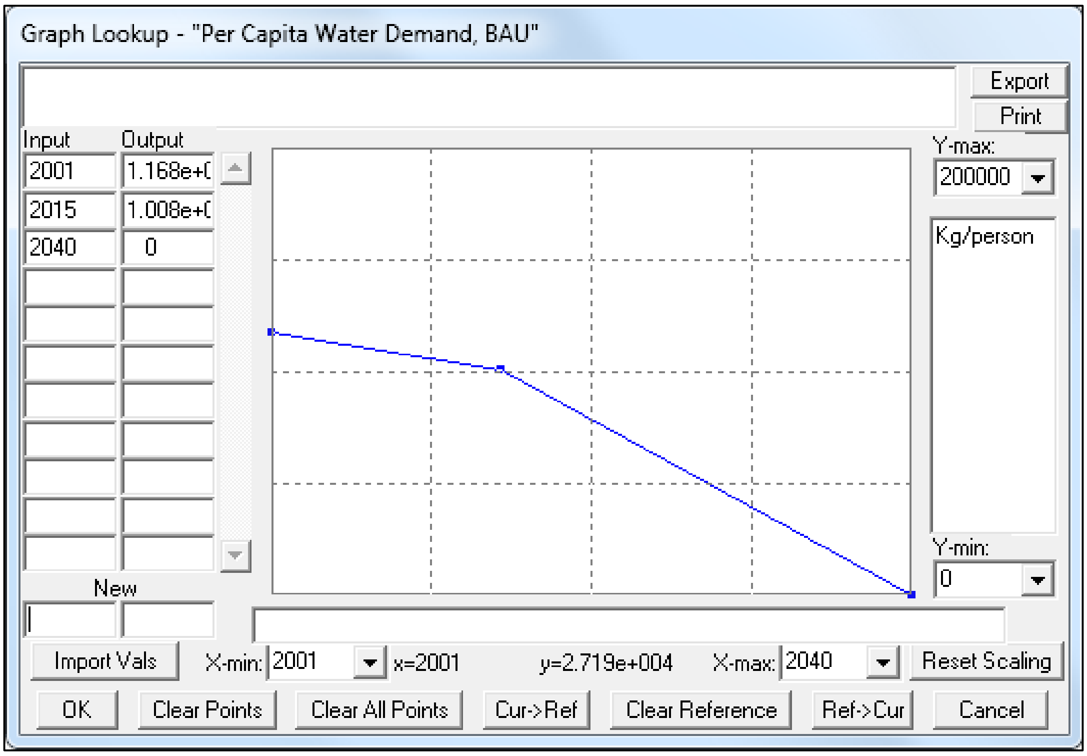

Figure 3.16: Graphical input for extreme condition test

In Figure 3.17 the BAU case of the model as well as the extreme condition test is presented. With inspection of the figure it is evident that the per capita water demand did influence the supply-demand deficit in 2016. This suggests that the model has the ability to return plausible results and responds correctly to the implemented values.

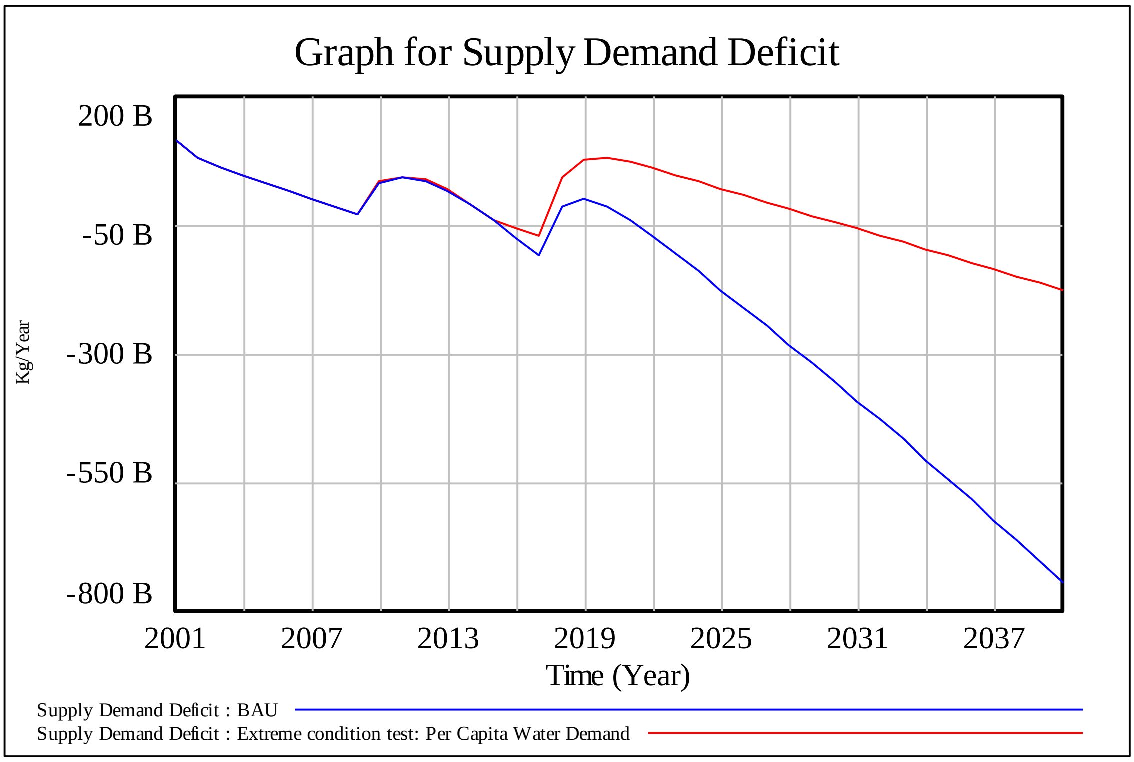

Figure 3.17: Extreme condition test: Graph for supply demand deficit

3.5.3 Tests of model behaviour

Behaviour reproduction tests test the models ability to match observed behaviour of the real system. As previously indicated, historical data regarding the water demand and supply in the Western Cape Province as a whole, is scarce. The only data found represents the water supply and demand in 2000 which was assumed to be true for 2001. The amount of water generated by the model matches that specified in the data in the year 2001. The historical data for the population as well as for the Western Cape GDP has been imported into the model and indicates that the model generated behaviour for these variables do match observed behaviour (see Appendix C, Figure C-1 and Figure C-2).

As part of the behaviour validation a sensitivity analysis was performed. The key variables that were considered most likely to affect the behaviour of the model are specified in Table 3.14. These variables were classified as internal or external. An internal variable implies that the variable is controllable by management where an external variable is uncontrollable (Maani & Cavana, 2007c:249). Since precipitation is classified as an external variable and can therefore not be controlled by management it was not tested as part of the sensitivity analysis. The monitored variables throughout the sensitivity analysis were total water supply, total water demand as well as the Water Stress Index and the change in dam and WWTW capacity. These variables represent key performance measures from both the supply and demand side.

Table 3.14: Key variables for Sensitivity Analysis

Variable	Classification
Precipitation	External
Life expectancy of dams and WWTW	Internal
Demand growth factors	Both
Per capita water demand	Both

Firstly, the sensitivity analysis was facilitated by the tool “SyntheSim” available on VENSIM. This tool produces a “slider” on the exogenous variables which allows the modeller to change the values of the variables while observing the dynamic behaviour, by means of graphical outputs, of the model. This tool is particularly efficient for the sensitivity analysis as it avoids the need to go into each equation to change the variable values. Also, once the sensitivity analysis has been performed, the parameter and graphical values are restored to their base case values.

Another tool that is available on VENSIM to facilitate a sensitivity analysis is called “Monte Carlo”. “Monte Carlo” is useful in that it allows the modeller to specify the maximum and minimum values of the variables and subsequently observe the results in confidence bounds. The “Monte Carlo” sensitivity tests that were done for the key variables identified in Table 3.14 are presented in Appendix C.

The graphical behaviour of the monitored variables observed throughout the sensitivity analysis, facilitated by the “SyntheSim” tool and the “Monte Carlo” tool, indicated that all the key variables identified in Table 3.14 are sensitive to change. Particularly sensitive to change are the variables that influences the total demand of the system. It was noted that the irrigated agriculture growth factor had a greatest impact on the total water demand (see Appendix C,

Figure C-3 to Figure C-6). This is because more than 60% of the water demand is a result of irrigated agriculture. The per capita water demand also influenced the monitored variables extensively. This is confirmed by the extreme condition test documented in the previous sub-section. The variables that influence the total demand are classified as both internal and external which suggest that it can partly be controlled by management. Therefore, these variables should be monitored closely.

Precipitation also proved to be an important variable to the total supply of the system since it is the source of water in dams and groundwater (see Appendix C, Figure C-7). This suggests that climate change could have devastating affects if the Western Cape Province were to become generally hotter as a result thereof. Also, it is of high importance to ensure that the data used is robust. If possible historical data would have been an attribute to increase in the confidence in the model, this was however not available in the sources examined. Precipitation is classified as an external variable. However, the emissions of greenhouse gasses aggravate climate change which subsequently minimises precipitation. Therefore precipitation might be slightly controllable if the emissions from the industries are minimised.

Lastly, life expectancy of dams and WWTW were analysed. It is interesting to note that relatively small changes to these variables did not influence the amount of water supply extensively but rather the “change in capacity” variable which subsequently influences the investment required. This is evident in Figure 3.18. Figure 3.18 illustrates the results generated when life expectancy of dams are increased to 150 years and decreased to 50 years for the maximum and minimum case, respectively. The life expectancy of a dam or WWTW is dependent on the amount of maintenance that it receives. Therefore, the results generated by the model suggests that preventative maintenance should be applied to extend the life expectancy and decrease costs in the long run.

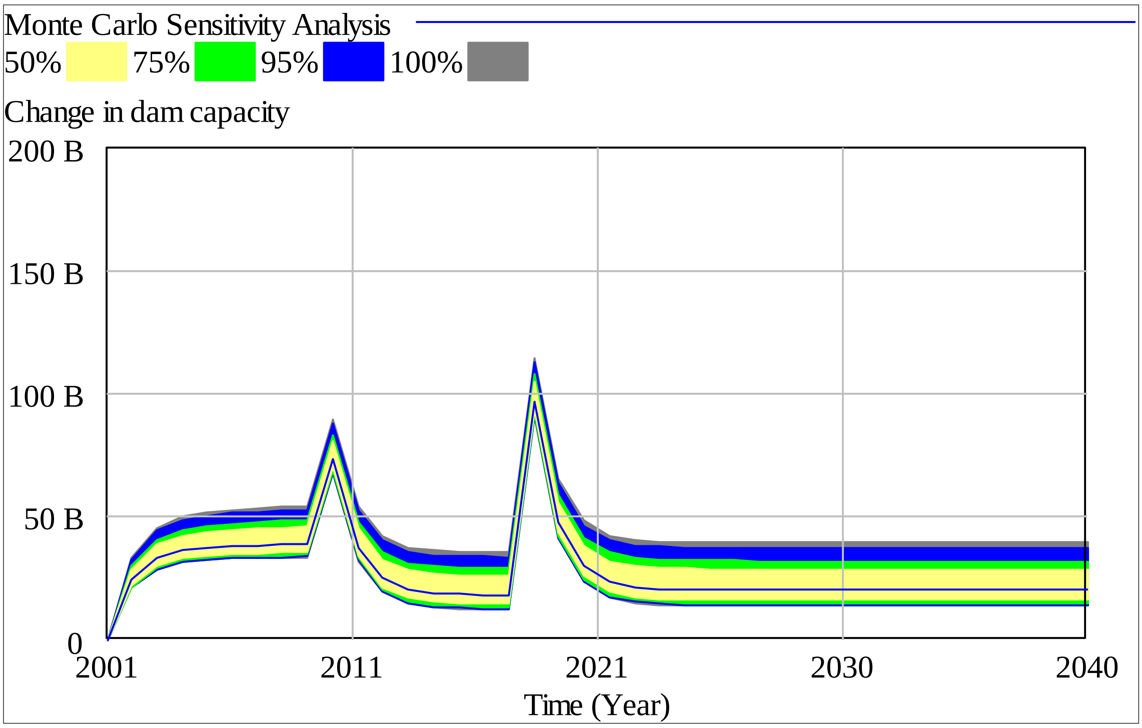

Figure 3.18: Sensitivity analysis results: Change in dam capacity when life expectancy of dams of dams is changed

Ultimately, common sense and previously gained knowledge ensured a thorough evaluation throughout the sensitivity analysis, which provided confirmation that the model generates expected and logical behaviour.

3.5.4 Validation Conclusion

The purpose of the tests performed in the section was to gain confidence in the model so that it can be used for policy analysis and strategy development in order to meet the objective outlined in the introduction of the research. Structural and behavioural validity tests were performed throughout the SDM process of which only a few were documented here. Throughout the process various structural flaws were corrected.

Following the validation process it can be concluded that the model can be accepted as valid for its purpose. However, more substantial historical data for precipitation as well as water supply and demand for the Western Cape Province as a whole is required to gain further confidence in the model. Also of importance to the validation process are the strategy development and testing which is done in the subsequent section. This helps to demonstrate the validity of the model so that it can be used with more confidence to address the objective.

3.6 Scenario Development

In this section the different scenarios implemented in the model are developed and discussed. This is specified as the first step of the fifth phase of SDM in Table 3.1. It is now established that the water resources in the Western Cape Province is depleting at a rapid pace. To be able to transform to a green economy various water conservation and demand initiatives are required. Not only is water resources threatened by the un-sustainable use and poor maintenance and management thereof but also by climate change.

To establish the scenarios that were implemented, a study of the previously suggested reconciliation strategies as well as the possible impacts of climate change that the Western Cape Province water sector might face were studied in this section. A decision rule was subsequently developed which was used to determine and specify various aspects included in the scenarios.

3.6.1 Previously Proposed Reconciliation Strategies

Various studies have been compiled in an attempt to address the possibility of a drier Western Cape Province in the future (see Table 3.2). All the studies emphasize that increased water conservation (WC) and water demand management (WDM) is necessary, as well as alternative supply-side interventions to augment the current available water supply. The restoration of existing infrastructure and initiatives which aim to reduce water demand are generally referred to as water conservation and water demand management (WC/WDM). The term, supply side interventions, is generally used to refer to augmentation schemes. Many projects are currently running to improve existing infrastructure or to determine the feasibility of possible supply side interventions. Possible WC/WDM as well as supply-side interventions has subsequently been developed in these studies.

The WCWSS Reconciliation Strategy (DWA, 2013a) highlights the importance of WC /WDM. The DWA states that the purpose of the WC/WDM Strategy is:

> "to ensure the long term balance between available water resources and water requirement, to postpone the need for expensive capital infrastructure projects for as long as it is economically viable and to minimise water wastage."

The elements within WC/WDM, which the CCT has been focussing on since 2007, include the replacement of non-functional water meters; installing flow limiting devices; introduction of leakage repair projects; water education campaigns; implementing pressure management; and the reuse of treated effluent. Significant savings have been reported through the strategy's implementation for the period 2007-2011. Most of the savings were achieved through pressure management and treated effluent reuse (DWA, 2013a).

The Provincial Summary Report (DWA, 2011) also recommends WC/WDM as an intervention and highlights the following three elements; installation of monitoring devices to measure water consumption; reduction of water loss through leakage repair and pressure management; and reduction of consumption through awareness campaigns and billing systems.

Supply-side interventions identified in the Western Cape Infrastructure Framework are listed below (Palmer & Graham, 2013):

i. Develop available groundwater resources;

ii. Adopt the reuse of wastewater effluent more widely as standard practise;

iii. Adopt large scale desalination; and

iv. Expand and diversify agriculture to increase availability of surface water but reduce the water intensity of the sector, given the limited availability of water for irrigation.

The Western Cape Infrastructure Framework (Palmer & Graham, 2013) further states that little change to infrastructure is envisioned in sanitation infrastructure, potable water (drinkable water) service infrastructure and non-potable distribution infrastructure. However, it highlights that major shifts are required in water resource interventions.

In other recent documents, compiled by GreenCape (2015) and the DWA (2011), similar supply-side interventions have been identified to meet the future demand. It includes; desalination, artificial recharge of aquifers, water re-use, infrastructure maintenance, new infrastructure and a berg river improvement plan. However, the GreenCape and DWA documents are more specific by identifying aquifers, dams and locations for desalination, which could possibly be developed to augment the water supply. It also states that feasibility studies are underway. Evidently, comparable interventions have been identified by the most recent studies on the water sector in the Western Cape Province.

3.6.2 Climate Change

It is globally accepted that the rise in greenhouse gas concentrations, such as carbon dioxide (CO_2) and methane (CH_4), in the atmosphere accelerates climate change (van Weele & Gumbi, 2013). It is argued that the changes brought about by climate change will include more frequent and severe weather events as well as changes in temperatures and precipitation patterns (Petschelt, 2013). The Western Cape Government claims that the Province will certainly face some degree of change in the near future (van Weele and Gumbi, 2013).

Predicted changes in the Western Cape Province include a general decrease in precipitation as well as higher minimum, maximum and mean temperatures (van Weele and Gumbi, 2013). Some studies have predicted up to 2°C temperature increase into the intermediate future (DEA, 2013; Western Cape Government, 2015). The future trends of precipitation are difficult to predict especially in the Western Cape Province with the high variability in landscapes (van Weele and Gumbi, 2013). However, seasonal shifts in precipitation patterns are already being experienced in the Province. Petschelt (2013) aimed to estimate the effect of climate change on water provision in the Cape Town region and found that the average precipitation in the Theewaterskloof sub-catchment will decrease from 630Mm^3/a to 413Mm^3/a, which indicates a decrease of 35%. Another study by the Western Cape Government (Western Cape Government, 2015) predicted an increase of 10% precipitation in a scenario used to determine the sustainable growth of wheat.

The possible changes that are predicted for the Western Cape Province as a result of climate change, will impact the water sector severely. A decrease in precipitation will subsequently decrease runoff, water quality and ultimately decreased water resources. Higher temperatures lead to increased evaporation and severity of droughts (Collins & Herdien, 2013). A sensitivity analysis shows that a 2°C temperature increase is bound to increase evaporation by an average of 3.5% (DEA, 2013). Seeing that the Western Cape Province is known for its wide variety and extensive agricultural sector, decreased water resources and increased evaporation poses immediate threats to the Province's economy. Furthermore, an increased danger of wildfires, floods, hailstorms and cold damage are predicted, which poses a further threat to the agricultural sector (Western Cape Government, 2015).

3.6.3 Scenarios

Scenarios that aim to alleviate the supply-demand deficit in the Western Cape Province are derived and studied in the model. The scenarios involve the implementation, at certain times, of various WC/WDM- and supply-side interventions. A decision rule is used to determine these characteristics of each scenario. The decision rule is based on the cost of the intervention as well as the Water Stress Index calculated in the model. This sub section describes the method in detail.

The WC/WDM elements and supply side interventions that are implemented in the model were chosen based on amount of consideration the intervention received in the literature. If the intervention appeared in all the literature that was reviewed it is assumed that there is a high likelihood that it will be implemented in the future and that it is deemed relatively feasible. The implemented interventions are:

i. WC/WDM (leakage repair, pressure management, user education);
ii. Augmentation (dam construction and groundwater development);
iii. Waste water reuse; and
iv. Large-scale desalination.

These interventions were ranked according to cost, from cheapest to most expensive. In South Africa unit reference values (URV) are commonly used to assess economic efficiency of proposed water projects (van Niekerk & du Plessis, 2013:549). It is calculated by dividing the present value of the costs of the project by the present value of the water supplied by the project. This would be the most effective manner to determine the ranking of the interventions. However, project specific details are required, which is not applicable to this research since specific projects are not considered but rather a general overview of possibilities.

As a substitution for the URV the DWAF (2009) provided an indicative costing of the interventions based on a case study of the marginal cost of water sources in a municipal area. Figure 3.19 provides the cost, in cent per kilogram, of water for each intervention. These costs were adjusted from the costs in the DWAF report according to inflation from 2009 to 2014. It should be noted that the costs found in the graph do not depict the actual cost of the different intervention options as these costs will vary on a project-by-project basis. However, these figures were used in the model to provide an indication of the possible costs involved in the various interventions. Even though the implementation of different interventions depend on various aspects such as the viability, effectivity and practicality, this was not taken into account in this research since these aspects can only be determined with an in-depth feasibility study of specific projects. The ranking of the interventions were purely made on the costs found in Figure 3.19.

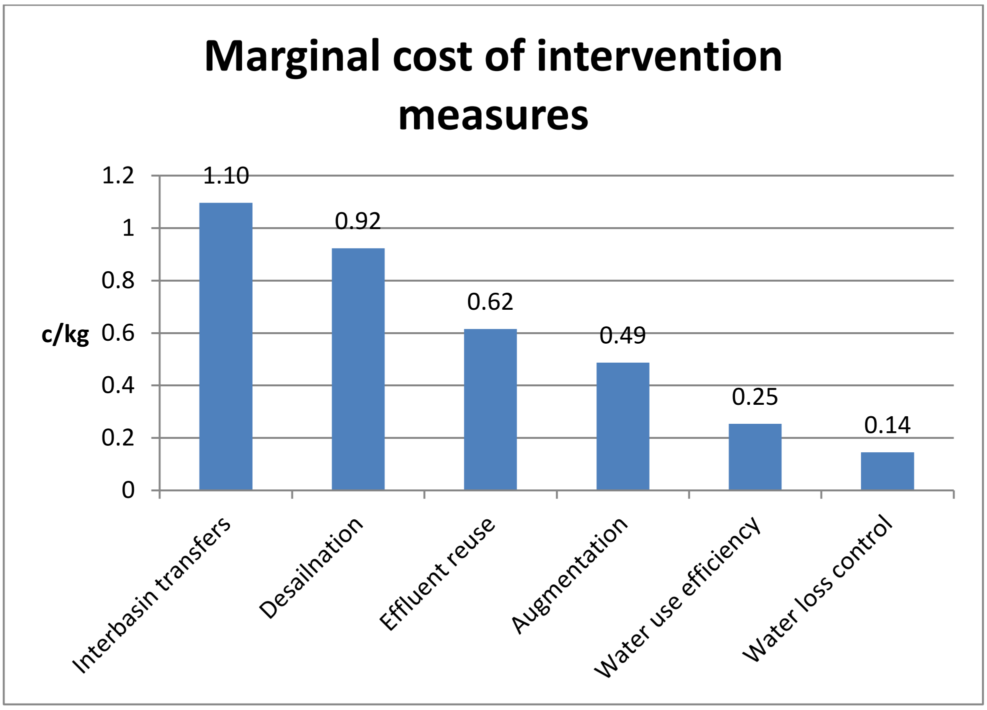

Figure 3.19: Marginal cost of intervention measures (Adapted from DWAF (2009))

WC/WDM interventions include pressure management, leakage repair and user education. It is therefore considered to be categorised as water loss control or water use efficiency interventions. However, the price associated with water use efficiency (see Figure 3.19) was used, with the aim of ensuring a more prudent approach. As previously mentioned augmentation includes dam construction and groundwater development. Evidently, waste water reuse was associated with 0.62 c/kg and desalination was associated with 0.92 c/kg. Inter basin transfers were not taken into account for this research, however it might become necessary in the more distant future.

Subsequent to the ranking of the interventions the Water Stress Index was examined. As mentioned previously the Water Stress Index is a universally recognised ratio which indicates risk. It is calculated by dividing water demand by water supply, therefore once the water demand is more than the available water supply the Water Stress Index will be larger than one which indicates the risk of drought.

By examining the Water Stress Index six scenarios were developed. The first ranked intervention is proposed to be implemented in the year that the Water Stress Index (subsequent to 2015) raised above one. The model was simulated again after the proposed intervention was implemented in the model to establish when the next proposed date for intervention implementation would be. Therefore, each scenario includes the intervention of the previous scenario. This process was continued until a satisfactory (below or equal to one) Water Stress Index was established until 2040. The final results are discussed in Chapter 4.

To provide clarity on the scenarios that are discussed in Chapter 4 a summary of the developed scenarios are presented in Table 3.15. Scenarios 1 to 6 in Table 3.15 are developed and discussed in section 4.1 and, as discussed, each scenario includes the intervention of the previous scenario. Scenario 7 is discussed as part of the results evaluation (section 4.2) with the aim of providing additional information with regards to possible future scenarios without the proposed interventions implemented.

Table 3.15: Scenarios summary

Scenario \ Intervention	BAU	WC/ WDM	Augmen-tation	Waste water	Desalina-tion	Climate change
1	X					
2	X	X				
3	X	X	X			
4	X	X	X	X		
5	X	X	X	X	X	
6	X	X	X	X	X	X
7	X					X

In Table 3.16 a summary of the variables affected with the simulation of the scenarios are presented. The variables affected are categorized into the various interventions. The amount of change is specified as well as in which year the change is brought about. As specified previously, some changes are implemented in the model as a step function where others are assumed to change evenly over the given time periods.

Table 3.15 should be used in conjunction with Table 3.16. For example; it is clear in Table 3.15 that scenario 3 includes BAU, WC/WDM and augmentation. Consequently, in Table 3.16, the variables affected are those specified under WC/WDM and augmentation.

Table 3.16: Summary of input parameters for model scenarios

	Variables affected (Amount and year)				
WC/WDM	Year	2001	2020	2025	
	Fraction of water lost through the system (%)	53	30	10	
	Year	2001	2015	2040	
	Per capita water demand (kg/person/year)	116800	101100	40150	
Augmentation	Year	2015	2017	2021	2030
	Storage capacity of dams (kg)	1.85E+12	2.06E+12	2.09E+12	2.13E+12
	Year	2001	2020	2025	
	Fraction of groundwater extracted (%)	26.21	40	60	
Waste water	Year	2001	2025		
	Ratio of WWTW capacity being used (Dmnl)	0.7913	1		
	Year	2025	2030	2035	
	WWTW Capacity (Kg)	3.92E+11	4.02E+11	4.13E+11	
Desalination					
	Year	2032	2036		
	Desalination (kg/day)	400	400		
Climate Change	Irrigation and afforestation demand growth	Growth increase from 1.6% to 2.5%			
	Mean Annual Precipitation	Average mean is decrease from 506.8 to 300 mm/year. Standard deviation is increased from 280.3 to 300			
	Fraction of rain evaporating immediately	Increases from 93% to 94%			

3.7 Model development conclusion

This chapter discussed the case study. The case study involved a System Dynamics model which aimed to analyse the implications for water resources when transitioning the Western Cape Province to a green economy. For the Western Cape Province to be able to transition to a green economy, sufficient water supply is required. Therefore a supply-demand model of the Province was built to be able to determine the required reconciliation interventions as well as possible costs involved. A detailed discussion of the process involved in developing the System Dynamics model was provided throughout the chapter.

The process is characterised by two modelling types namely, qualitative modelling and quantitative modelling (see Table 3.1). Quantitative modelling involves problem formulation and conceptualisation. An in depth discussion of the water resource sector in the Western Cape Province ensured that the problem could be formulated and that the conceptualisation, which involves the key variable identification and causal loop modelling, could be done with confidence. The overall CLD was divided into five smaller CLDs for illustrative purposes.

Quantitative modelling involves dynamic model building, model validation and implementation. The sub-models and stock and flow diagrams that characterise the dynamic model are presented with a discussion of the relationship between the variables. Model validation was a continual process throughout the entire model development process; however some formal model validation tests were documented. Model validation was considered an important step in the model development as it ensures that the model can be used with confidence for its specific purpose. The implementation of the model refers to the scenario development with the aim of being able to use the results to inform policy makers. The results generated by the model is documented and discussed in the subsequent chapter.

CHAPTER 4: RESULTS

The previous chapter documented the case study that included the development of a System Dynamics model of the water resources in the Western Cape Province, namely WeCaWaRM. The model was developed with the aim of understanding the intricacies of, and implications for, the water resource sector when transitioning the Western Cape Province to a green economy. Finally, scenarios were developed in accordance with the Water Stress Index and the cost associated with the selected interventions. All input parameters for the different scenarios were quantified and illustrated.

The fifth phase of System Dynamics Modelling, Implementation, consists of three steps as specified in Table 3.1. Step one, scenario development, was concluded in the previous chapter. Step two was defined to be the evaluation and documentation of results. Chapter 4 is thus concerned with the results generated by the model for the scenarios, with the discussion being divided into two sections. The first section provides a discussion on the results generated by the six scenarios developed in Chapter 3 with additional findings being discussed in the second section. The third step of Implementation, as per System Dynamics Modelling is the communication of results to all relevant stakeholders.

4.1 Scenario Results

The scenarios were developed with the help of a decision rule that considered the rank of the chosen interventions and the Water Stress Index, as discussed in section 3.6.3. The development of the scenarios as well as the results generated by the model for the Water Stress Index of each scenario is discussed in detail in this section. The graphs illustrating the total water supply and total water demand for each scenario can be found in Appendix D. It should be noted that the variables affected by the scenario development are specified in Table 3.15 and Table 3.16.

Scenario 1: Business As Usual (BAU)

Scenario 1 is a representation of the BAU Scenario. Figure 4.1 depicts the Water Stress Index modelled for the BAU Scenario of the model. In the graph the Water Stress Index exceeded one from 2001 to 2009. In 2009 the Water Stress Index was minimised due to construction and implementation of the Berg River Dam and various smaller dams. In Figure 4.1 the growth in water demand soon outweighed the increase in water supply, which lead to an increase in the Water Stress Index. In addition, the graph shows a further decline in 2017 as a result of the planned implementation of the Clan William dam.

However, the implementation of the Clan William dam fails to fully redeem the water security of the Western Cape Province. Therefore, an additional intervention to the raising of the Clan William dam is required in 2016 to reduce the Water Stress Index.

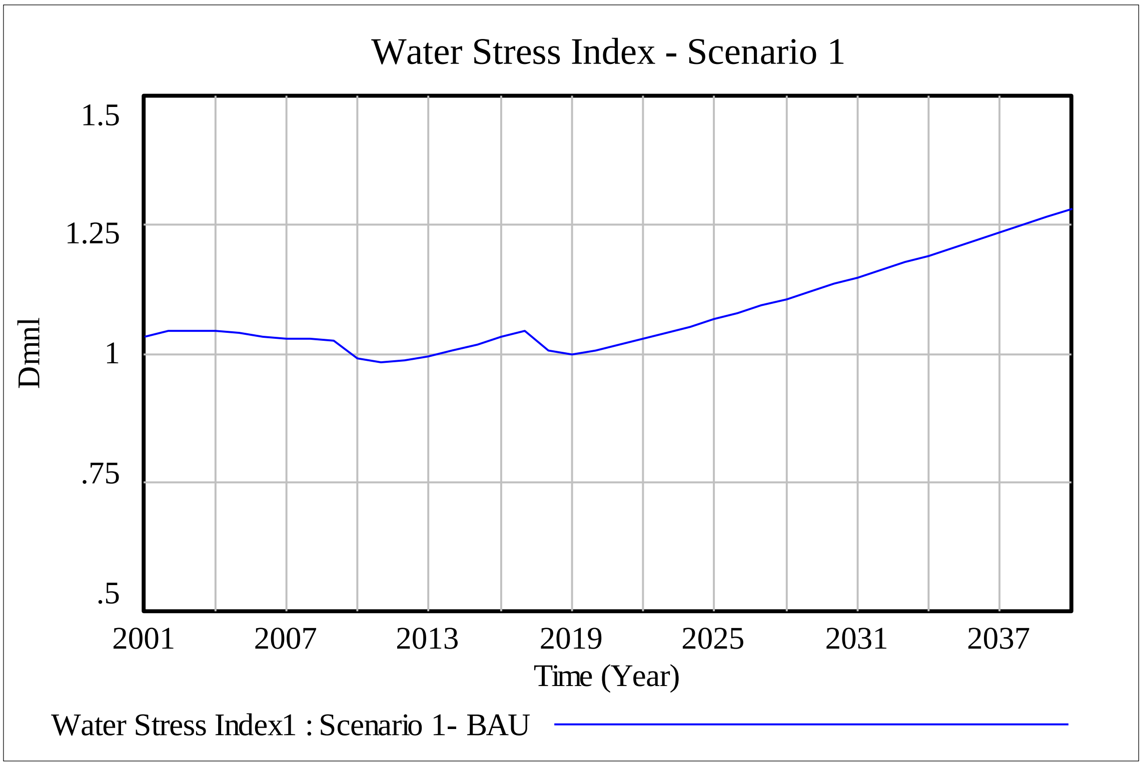

Figure 4.1: Water Stress Index - Scenario 1

Scenario 2: Water Conservation and Water Demand Management (WC/WDM)

Scenario 2 involves the implementation of the first ranked intervention, namely WC/WDM. This includes user education, pressure management and leakage repair, which are assumed to reduce the per capita demand as well as the unaccounted for water (UAW) in the supply system. It should be noted that there is an upper limit to the reduction in the Water Stress Index brought about by these measures and that they can only be effected gradually over time. For example, while the per capita demand can decrease over time, it cannot decrease beyond the point needed to sustain life. To ensure that realistic changes were brought about at the right times in WeCaWaRM, the changes were implemented by means of a lookup table, which was defined in Table 3.16.

In WeCaWaRM the WC/WDM interventions are brought into effect by varying the parameters of the variables termed, “per capita water demand” and “fraction of water lost through supply system”. The per capita water demand affects the domestic and municipal water demand directly and consequently aims to incorporate all interventions that aim to reduce water consumption namely, user education, awareness campaigns, increased water prices, and possible water shedding. As discussed in the dynamic modelling section (see section 3.4.2) the variable “Fraction of water lost through supply system” affects the “UAW in supply system”. The specification of the reduction from 53% water loss to 30% water loss in 2020, and subsequently to 10% by 2025, are assumptions made based on the documents published by the DWA termed Provincial Summary Report (DWA, 2011) and Water Reconciliation Strategy for the Western Cape Water Supply System (DWA, 2013a).

Once the changes for the first intervention were implemented in the model it was simulated again. Figure 4.2 presents the Water Stress Index for the BAU Scenario as well as the Water

Stress Index after the first intervention was implemented. In the figure it is clear that WC/WDM was successful in decreasing the risk of water deprivation in the Western Cape Province. However it is only sufficient to eliminate this risk until 2020. It is therefore suggested that the second intervention, Augmentation, should be implemented in 2020.

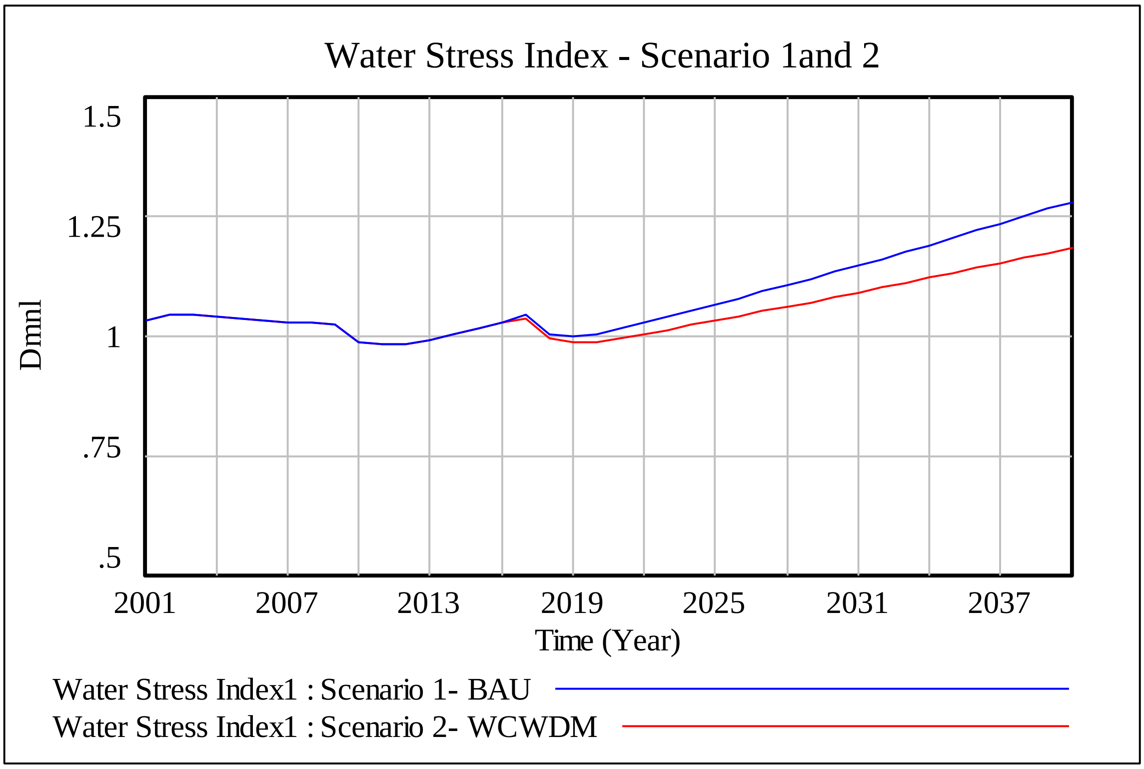

Figure 4.2: Water Stress Index - Scenario 1 and 2

Scenario 3: Augmentation

The second ranked intervention is augmentation of the water supply system. Augmentation includes the development of surface water and groundwater supply. Surface water development refers to the construction of dams throughout the Western Cape Province. The BAU Scenario includes the Berg River dam construction, which was completed in 2009, as well as the augmentation of the Clan William dam, as it is currently in progress and predicted to be completed in 2017.

In WeCaWaRM, a relatively small increase in dam capacity is simulated in 2021 and 2030 based on the document termed "Pre-feasibility and feasibility studies for augmentation of the WCWSS by means of further surface water developments" by the DWA (2012). The document specifies that the augmentation of the dams will only be complete and ready for implementation in 2021 based on the assumption that construction will commence in 2016. The model results indicate that the completion of the dams by 2021 will subsequently ensure that the supply of water exceeds the demand of water in the Western Cape Province for an additional four years.

Groundwater development is a promising alternative source of water supply for the Western Cape Province since it is assumed by experts in the field that only 30% of the UGEP is currently used (DWA, 2010). The BAU scenario assumes that this percentage remains unchanged, while Scenario 3 assumes an increase in the percentage to 40% from 2020 onwards as well as a further increase of 20% in 2025, so that 60% of the UGEP utilised from 2027 to 2040. These assumptions are based on the Groundwater Strategy compiled by the DWA (2010). Should it be required in the future, groundwater could be developed further as an alternative source of water supply in the Western Cape Province. However, since the size and functionality of the aquifers remain uncertain, extensive exploitation might have unforeseen consequences with regards to the groundwater resource availability.

Figure 4.3 presents the Water Stress Index for the first three scenarios. Augmentation is seen to have a significant impact on the Water Stress Index of the Western Cape Province, with groundwater development making the biggest contribution in 2020 and 2025. In 2025 the Water Stress Index is projected to be close to 1, which indicates that water demand is close to the available water supply. To ensure a prudent approach waste water reuse is suggested that to be implemented in 2025.

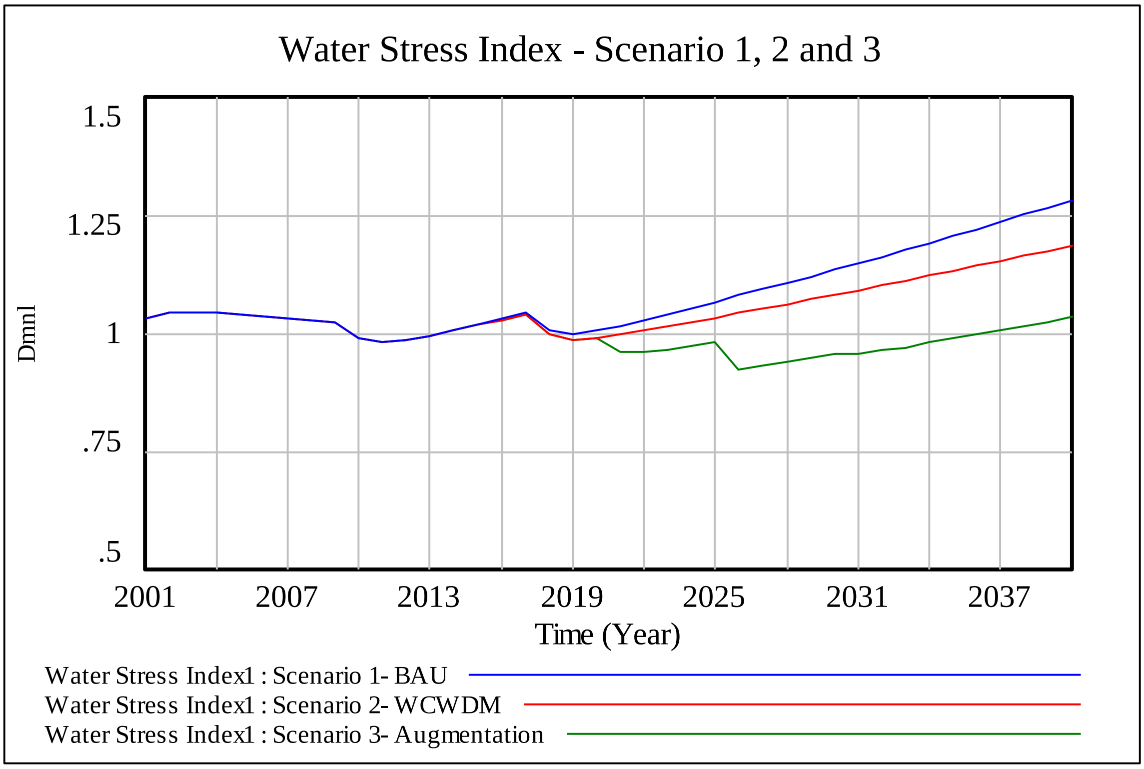

Figure 4.3: Water Stress Index - Scenario 1, 2 and 3

Scenario 4: Waste Water Reuse

Scenario 4 assumed the implementation of augmentation of waste water reuse. Since Figure 4.3 indicates that the Water Stress Index is close to one in 2025, the first expansion of the waste water treatment works (WWTW) is required to be implemented then. The capacity increase of the WWTW is based on the 2012 Green Drop Progress Report compiled by the DWA (2012a).

Currently only 79.13% of the total capacity of the WWTW in the Western Cape Province is utilised, as discussed previously. For the BAU Scenario this was assumed to remain unchanged. For Scenario 4 the utilised capacity is simulated as full capacity usage from 2025 onwards. Furthermore, Scenario 4 assumes the construction and implementation of three macro sized

WWTW in the years 2025, 2030 and 2035. As specified in Table 4.1, a macro sized WWTW has the capacity of 30 million kg/day or 10.95 billion kg/year.

Table 4.1: Scenario 2 WWTW Capacity increase

Year	Capacity increase	Total capacity of WWTW
2025	1 Macro size WWTW	391.499 billion kg/year
2030	1 Macro size WWTW	402.449 billion kg/year
2035	1 Macro size WWTW	413.449 billion kg/year

Figure 4.4 presents the results of the Water Stress Index allowing for waste water reuse. Waste water reuse successfully decreases the risk of water scarcity in the Western Cape Province until 2040. Desalination is considered as the last possible intervention beyond 2040.

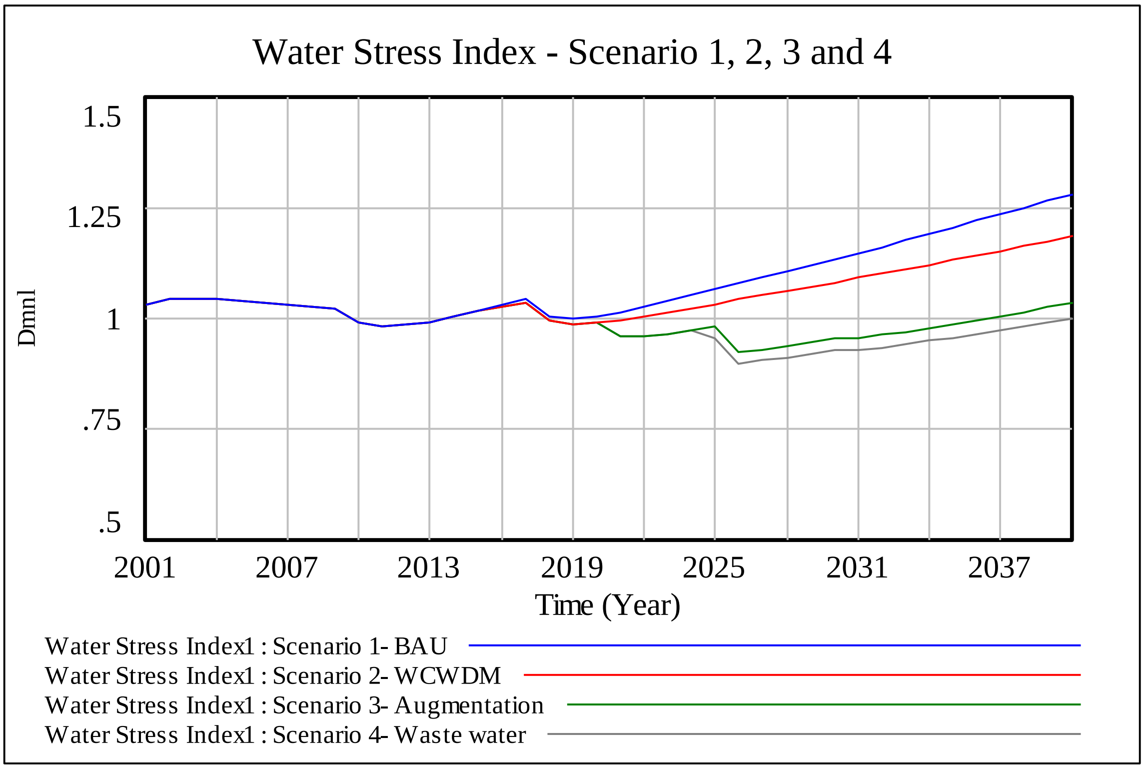

Figure 4.4: Water Stress Index - Scenario 1, 2, 3 and 4

Scenario 5: Desalination

Desalination, being the most expensive intervention (in terms of rand per kilogram of water) considered in this research, was considered last. The interventions implemented prior to desalination (Scenario 2, 3 and 4) proved to be sufficient to ensure the Water Stress Index remains below one until 2040. However, the Scenario 6 (climate change scenario) showed that a supply-demand deficit originates in 2032 (see Figure 4.6) despite the implemented interventions. Therefore desalination was considered as a means to eliminate the predicted water deficit in 2032.

Desalination in South Africa has historically not been considered a viable water resource due to the availability of less costly surface and groundwater sources (Blersch, 2014). Currently there are six relatively small existing sea water desalination plants in the country, five of which are situated in the Western Cape Province. The biggest desalination plant is in Mossel Bay with a capacity of 15 Ml/day. Blerch (2014) concluded in her study that large-scale desalination plants of up to 400Ml/day are required to provide the WCWSS of water. Blerch (2014) further suggests that, if the plants are implemented, it should be operated as base supply and not only in times of drought, since it is economically ineffective to maintain the plants that are not used. Blerch (2014) therefore suggests that desalination plants should not be ranked as the last possible reconciliation intervention but should rather be implemented as soon as possible.

Even though Blerch's recommendation was deemed as a valid possibility in terms of water supply, desalination remains an energy intensive operation. As South Africa is already subject to load shedding[9] it is proposed that desalination is currently not a sustainable solution. Therefore, it was decided to keep desalination as the last ranked intervention.

According to the results generated by the model the supply-demand deficit will approximately be 800 million kg/day by 2040. Blerch (2014) found that a 300 million kg/day plant will satisfy the water demand for approximately 6 years against a certain demand growth. In this model the desalination capacity is assumed to increase by 400 kg/day in 2032 and by another 400 kg/day in 2036. Figure 4.5 illustrates the results of the model based on the inclusion of the proposed desalination plants. Evidently, if climate change is not considered, the Western Cape Province will be sufficiently supplied with water beyond 2040 with the aid of the proposed interventions.

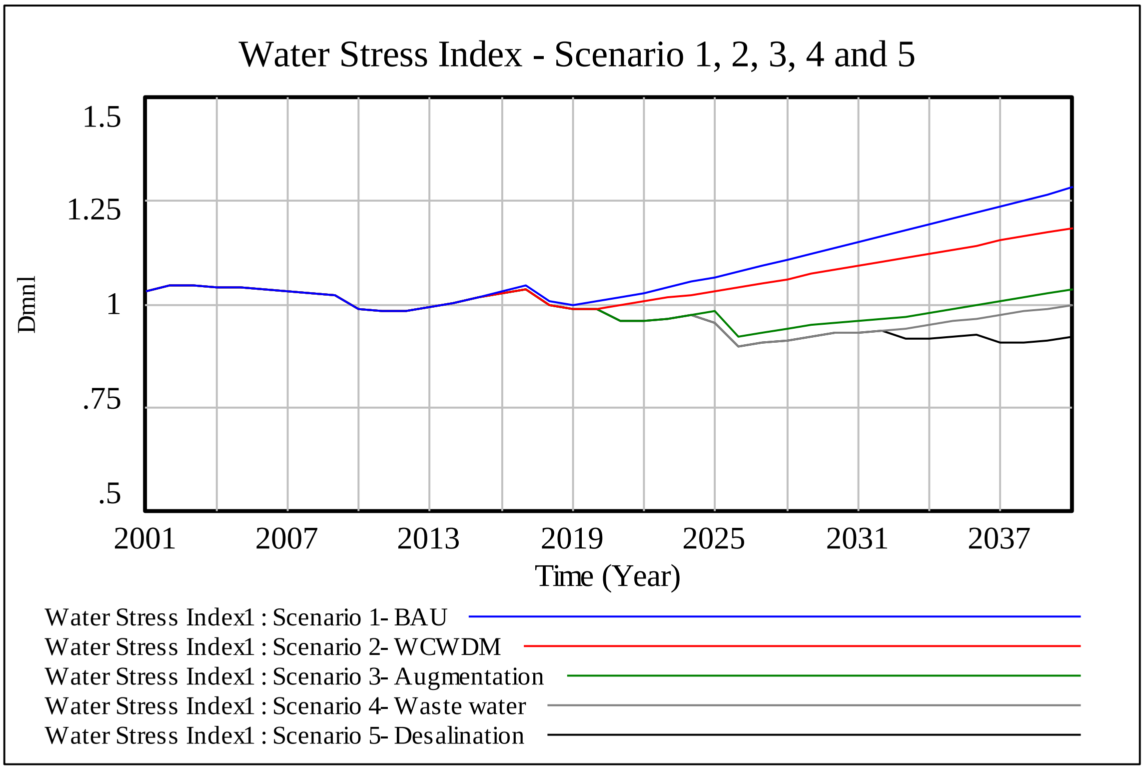

Figure 4.5: Water Stress Index - Scenario 1, 2, 3, 4 and 5

[9] A phenomena where electricity supply is switched off to reduce the load on the generating plant.

Scenario 6: Climate Change

Since climate change is already being experienced in the Western Cape Province by more variable and decreased precipitation during the winter months as well as an increase in temperatures during the summer months, a scenario including climate change is simulated in the model.

The implemented climate change impacts include a 40% reduction of precipitation, a higher variability in precipitation as well as in increase in temperature. The reduction and variability in precipitation is implemented in the model by decreasing the mean precipitation and increasing the standard deviation in the random number generator function. The temperature increase subsequently increases the evaporation rate and causes a higher demand in the irrigated agricultural sector as well as in the afforestation sector. These assumptions are based on the literature discussed in sub section 3.6.2.

Figure 3.25 represents the Water Stress Index for Scenario 5 and 6. As discussed, Scenario 6 includes all the interventions that was included in Scenario 5 with the added effects of climate change. From the Figure 3.25 it is evident that climate change will have a definite effect on the water resources in the Western Cape Province. The spikes occurring in 2019, 2021 and 2032 can be attributed to extreme weather conditions (droughts) occurring as a result of climate change. As seen in the Figure 3.25 the implemented interventions will not fully alleviate the droughts but will serve to reduce its effects.

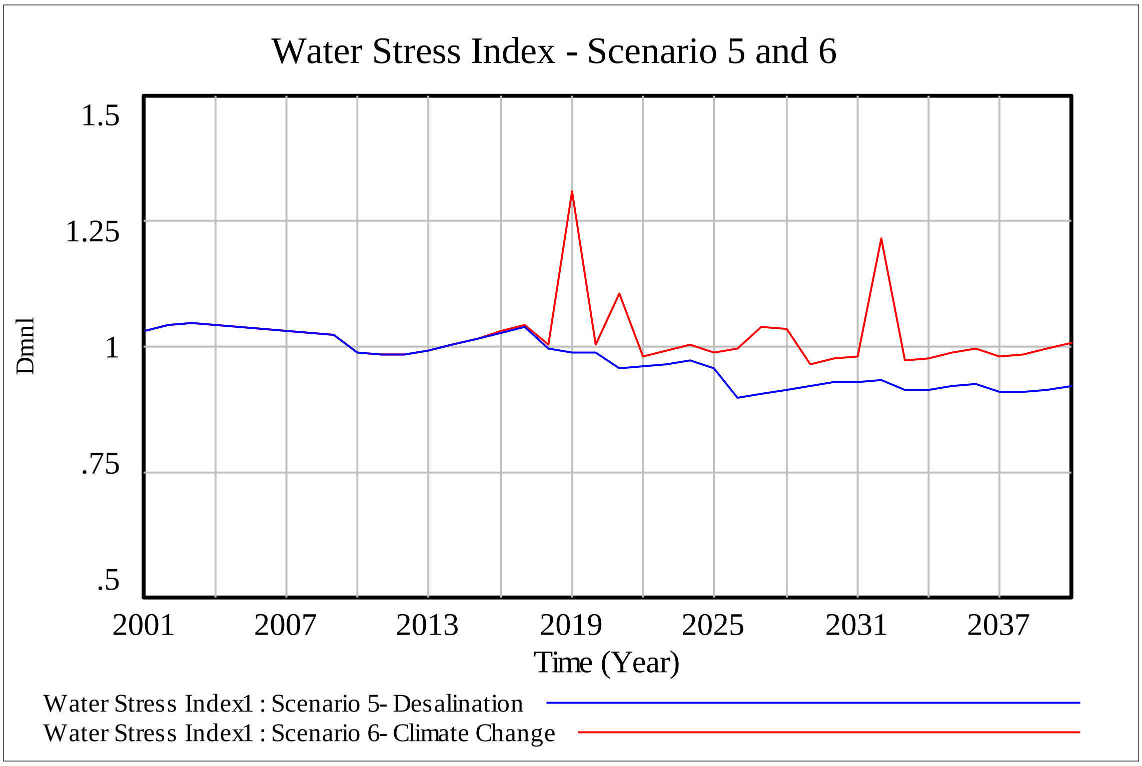

Figure 4.6: Water Stress Index - Scenario 5 and 6

4.1.1 Scenario Results conclusion

Section 4.1 involved a discussion of the development and the results generated by the six scenarios that were simulated in the model with the aim of reducing the supply-demand deficit that is predicted for the near future in the Western Cape Province. Scenario six can be viewed as a possible strategy for the Western Cape Province to transition to a green economy. Scenario six includes all predicted affects by climate change and the selected reconciliation interventions. The interventions prove to be sufficient to ensure that the Western Cape Province has water supply until 2040. However, the implementation of the intervention involves implications for policy makers. The implications are discussed in Chapter 5.

4.2 Scenario Evaluation

In this section the discussion is divided into three sub-sections, which are in line with selected scenarios. The selected scenarios were chosen based on the importance to stakeholders and policy-makers. To gain a better understanding on the scenarios that are discussed in this sub-section refer back to Table 3.15. Scenarios 1 to 6 in Table 3.15 were developed in section 3.6.3 and the results were discussed in section 4.1 and, as discussed, each scenario includes the intervention of the previous scenario. This is also evident in Table 3.15. Scenario 7 in Table 3.15 was not included in the scenario development and results discussion (section 3.6.3 and 4.1); it is however considered and discussed in this section. Therefore, the discussion follows the subsequent sequence and addresses the results generated by the specified scenario.

i. BAU scenario / Scenario 1;
ii. BAU with climate change scenario / Scenario 7; and
iii. Green economy scenario / Scenario 6.

The green economy results section involve additional results generated by the model for Scenario 6, as discussed in section 4.1. This is done since Scenario 6 is considered as a possible strategy to assist the Western Cape Province in the transition to a green economy. The results are discussed by means of graphical representation of the key variables, which are total supply and demand and total annual costs for the water sector.

4.2.1 Scenario 1-BAU scenario

Figure 4.7 illustrates the BAU Scenario for the predicted growth in water demand and the available water supply. Since plotting the supply against the demand is an alternative way of indicating the risk, similar to the Water Stress Index, the reasons for the shape of the graph are the same as that previously discussed in section 3.6.3. Therefore, only a brief discussion of the dynamics of the total supply and demand graphs presented throughout this research project, are provided here.

It should be noted that the *demand* is simulated, and not the actual *consumption*. Meaning that; the total supply and demand graph (refer to Figure 4.7) does not imply that the whole of the Western Cape Province will be without water if the demand exceeds the available supply. For example, in Figure 4.7 it can be seen that the demand was slightly more than the supply in 2008 and 2009. In “real-life” a drought occurred in the Eden and Karoo districts of the Western Cape Province in 2009. However, during this time the rest of the Province still had sufficient amounts of water supplies available to satisfy the minimum water demand.

Furthermore, Figure 4.7 indicates that the demand exceeds the supply from 2014 onwards. This water shortage refers to, among others, the agricultural drought experienced by the farmers surrounding the Clan William dam, also known as the Olifantsriver Valley. According to Agri Wes-

Cape's CEO, Carl Opperman, the 2014-2015 summer has been the driest the Western Cape Province has seen in many years (Mortlock, 2015). Beaufort West, situated in the Great Karoo region, also struggled to maintain a sufficient water supply since 2010 (Matthews, 2015). Evidently, the water demand in the Western Cape Province is growing at a rapid pace and the available water supply is not predicted to increase if BAU scenario continues. This will most likely result in the entire Western Cape Province to experiencing drought within the near future. By 2040 the water supply demand deficit will be 745 billion kg in the Western Cape Province.

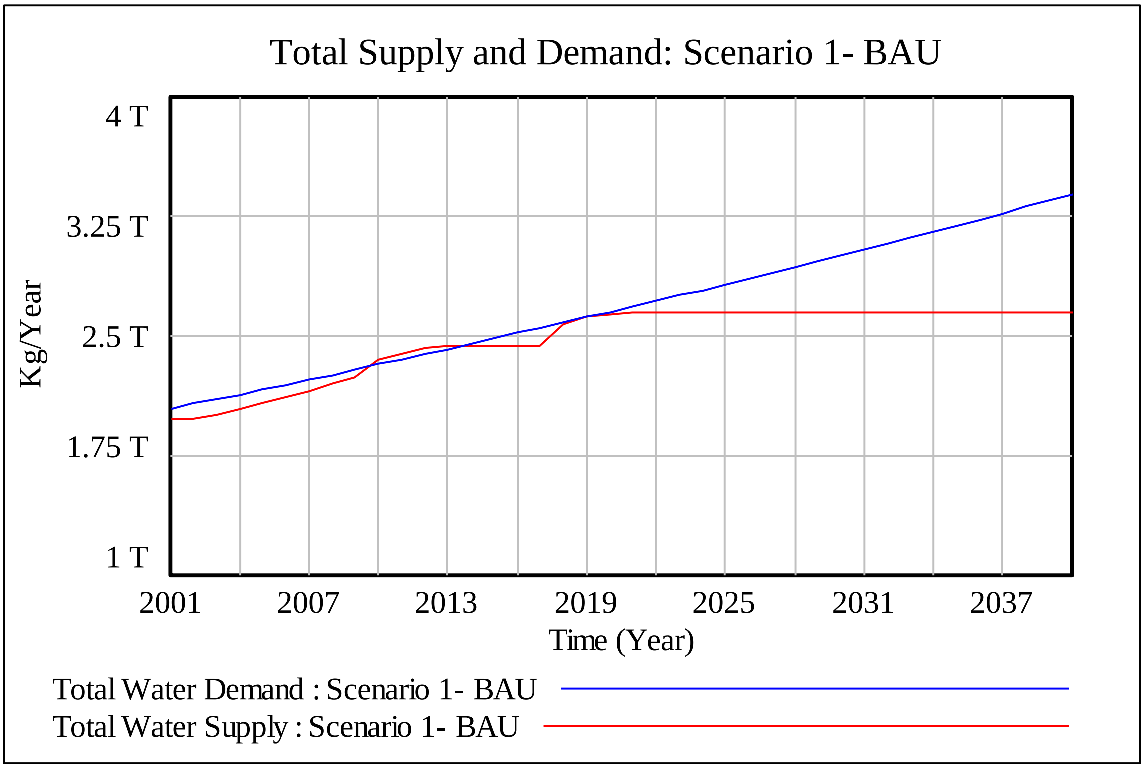

Figure 4.7: Total supply and demand: BAU

Figure 4.8 presents the annual costs associated with each implemented intervention for the BAU case. The BAU scenario assumes that currently there is little effort made to meet the water demand in the Western Cape Province and that the implemented interventions are merely maintained. As seen in Figure 4.8 the costs prior to 2015 were not taken into account as it does not influence any current or future decisions. The costs involve the implementation fees as well as the maintenance costs. Bear in mind that the costs do not depict the actual cost of the different intervention options as these costs will vary on a project-by-project basis. However, these figures were used in the model to provide an indication of the possible costs involved in the various interventions.

The costs associated with the WC/WDM are different from the other intervention costs since it does not involve rigorous maintenance throughout the lifetime of the assets used. WC/WDM requires a lump sum investment to implement pressure management, leakage repair and educational systems or campaigns, which is indicated by the sharp rise of the blue line in Figure 4.8. Furthermore, WC/WDM requires a reasonable amount of upkeep at first but will eventually become self-sufficient as the educational systems ensure that the users use water in a responsible and sustainable manner.

The department of water and sanitation listed various projects that are envisioned for the Western Cape Province (DWS, 2015a). The projects that aim to augment the supply system are not included in the research with the exception of the Clan William dam wall raising. The reason for this is that the projects are still in the feasibility or design phase. The projects that include upgrading of existing infrastructure that are in construction phase are taken into account by the WC/WDM input parameters.

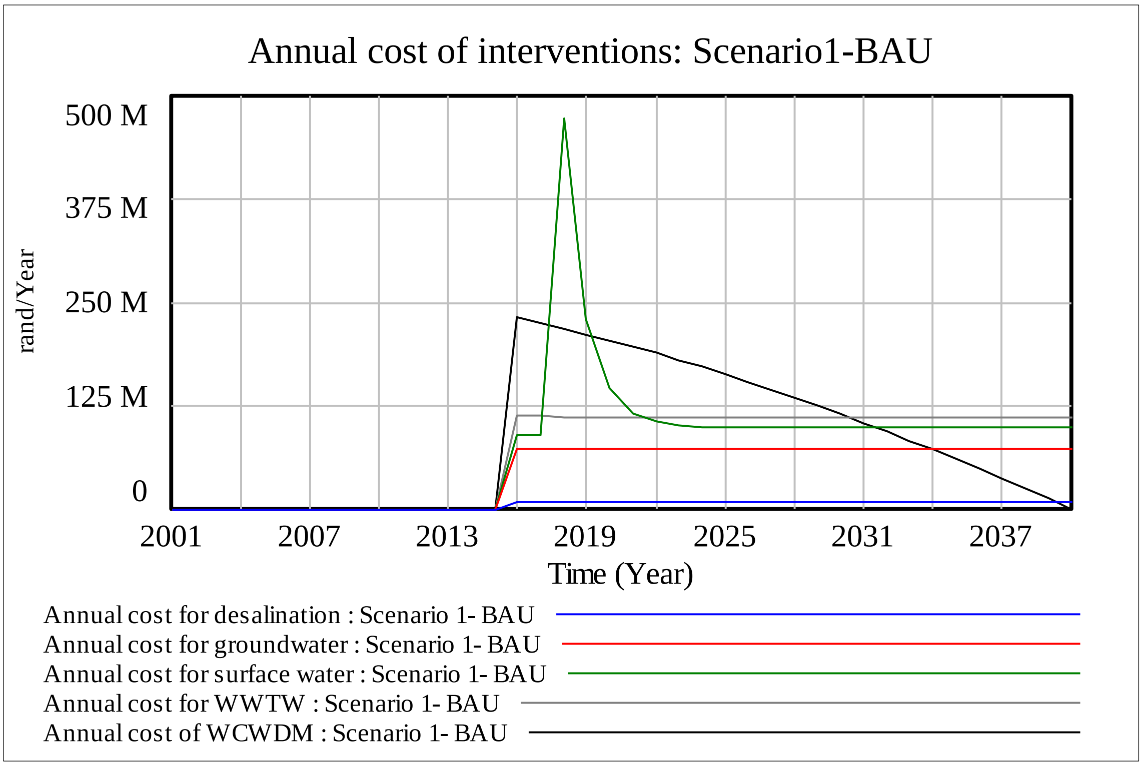

Figure 4.8: Annual costs of interventions: BAU

Despite the implementation of the Clan William dam wall raising, which is indicated by the spike of the grey line(Annual costs for surface water: BAU in Figure 4.8) in 2017, it is evident that the water supplied by the WWTW is currently the most expensive source of supply for the Western Cape Province. Desalination is currently the lowest; however, the water desalination plants require maintenance even though they are only used intermittently. This makes the desalination plants a liability.

4.2.2 Scenario 7- BAU with Climate Change scenario

This sub-section discusses the results generated by the model for the BAU case with climate change included. Climate change is predicted to increase the mean temperature, and cause more frequent and severe extreme weather conditions. Subsequently the Western Cape Province is predicted to become an increasingly water scares area. In the developed System Dynamics model, the random normal function is used to generate random numbers for the precipitation over the time horizon, as discussed previously (see section 3.4.2 and Table 3.12).

Figure 4.9 presents the results generated by the model for the BAU scenario as well as BAU scenario with climate change included. Two primary differences should be noted. Firstly, the growth in demand increases with climate change. This can be attributed to agriculture requiring more water as a result of higher evaporation rates and less rainfall. According to the results generated by the model, 295 billion kg more water will be required by 2040 than with the BAU Scenario.

Secondly, the available supply is predicted to become more variable with climate change, specifically referring to an increase in drought periods. Future drought periods are subsequently predicted to be over longer periods of time and more frequent than previously experienced. This can clearly be seen in Figure 4.9 where supply decreases abruptly in 2019, 2021, 2025 to 2029 and 2032.

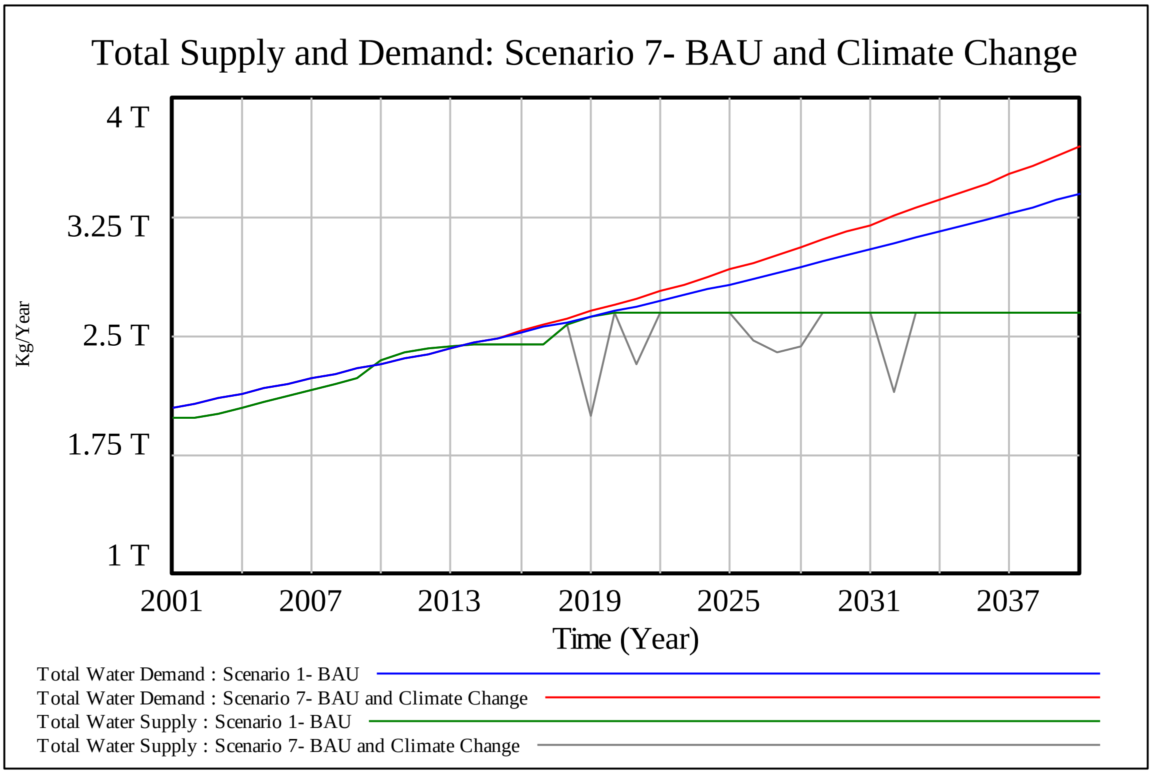

Figure 4.9: Total supply and demand: BAU and Climate Change

4.2.3 Scenario 6- Green Economy scenario

The green economy results refer to the results generated by Scenario 6, as discussed in section 3.6.3. Scenario 6 was selected as a feasible strategy to assist the Western Cape Province in the transition to a green economy, since it takes climate change into account and the interventions implemented in the scenario proves to be sufficient to ensure water supply until 2040.

The total supply and demand generated by the model for the green economy scenario as well as BAU with climate change scenario are presented in Figure 4.4. The differences between the two scenarios that are plotted in the graph are evident. Firstly, the supplies of the two scenarios are similar in the sense that the droughts occurring in 2019, 2021, 2025 to 2029 and 2032 are constant. As seen in Figure 4.4 the proposed interventions, in the green economy scenario, will not fully alleviate the droughts but will serve to reduce its effects. The supply differs in the sense that Scenario 6 shows an increase of 756 billion kg water by 2040 in comparison to BAU with climate change scenario. This increase is a result of WC/WDM and the augmentation of the supply system by means of dam construction, groundwater development, WWTW construction and desalination implementation.

The water demand of the BAU with climate change scenario is 7.5% more (or 256 billion kg water) than the water demand of the green economy scenario. This can be attributed to the WC/WDM intervention which aims to lower per capita water demand and reduce UAW throughout the supply system. It is interesting to note that when comparing the demand of the BAU scenario, presented in Figure 4.7, with the demand of the green economy scenario, the BAU demand is slightly lower.

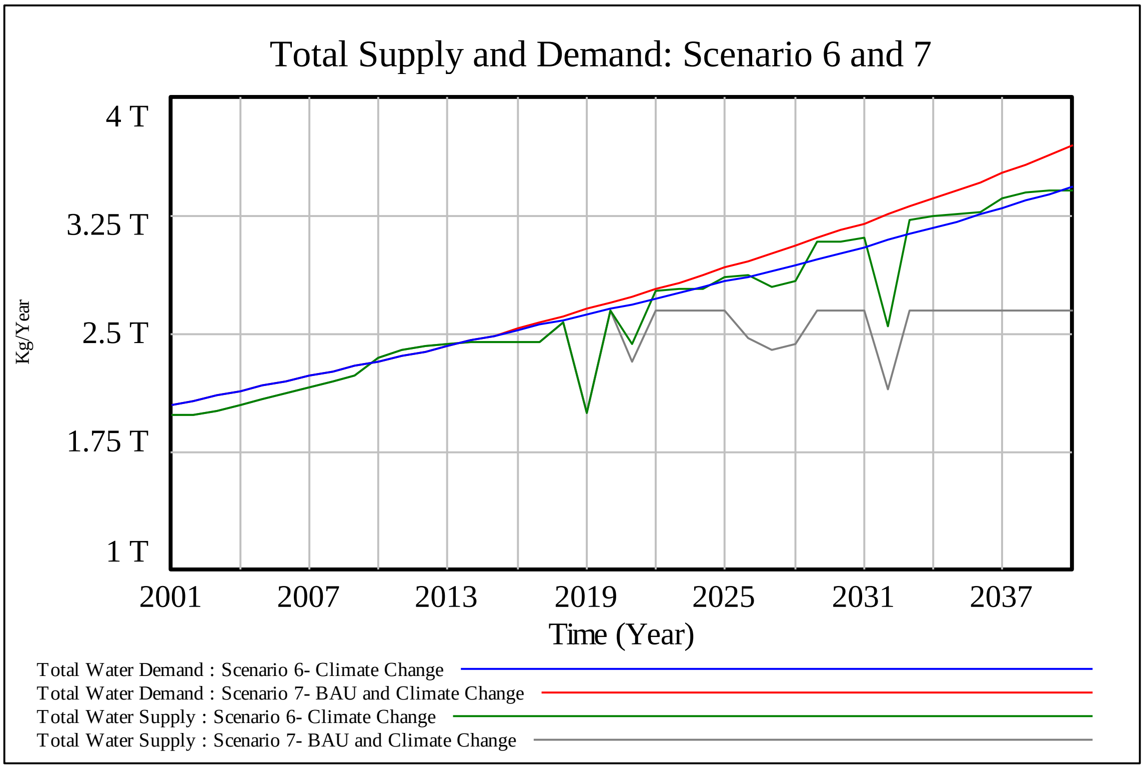

Figure 4.10: Total supply and demand: BAU with Climate Change and Green Economy

Figure 4.11 presents the annual costs associated with the various proposed intervention for the green economy scenario. By comparing Figure 4.8 and Figure 4.11 it is clear that the green economy scenario requires a larger capital investment for the management of the water sector than the BAU scenario. As expected desalination requires the most investment since it is proposed to be implemented on large scale for the green economy scenario. Groundwater also proves to require substantial investment, which can be attributed to the large change in the groundwater extraction factor. Groundwater is extracted by pump stations, and is only utilized when there is groundwater available, therefore the groundwater cost varies.

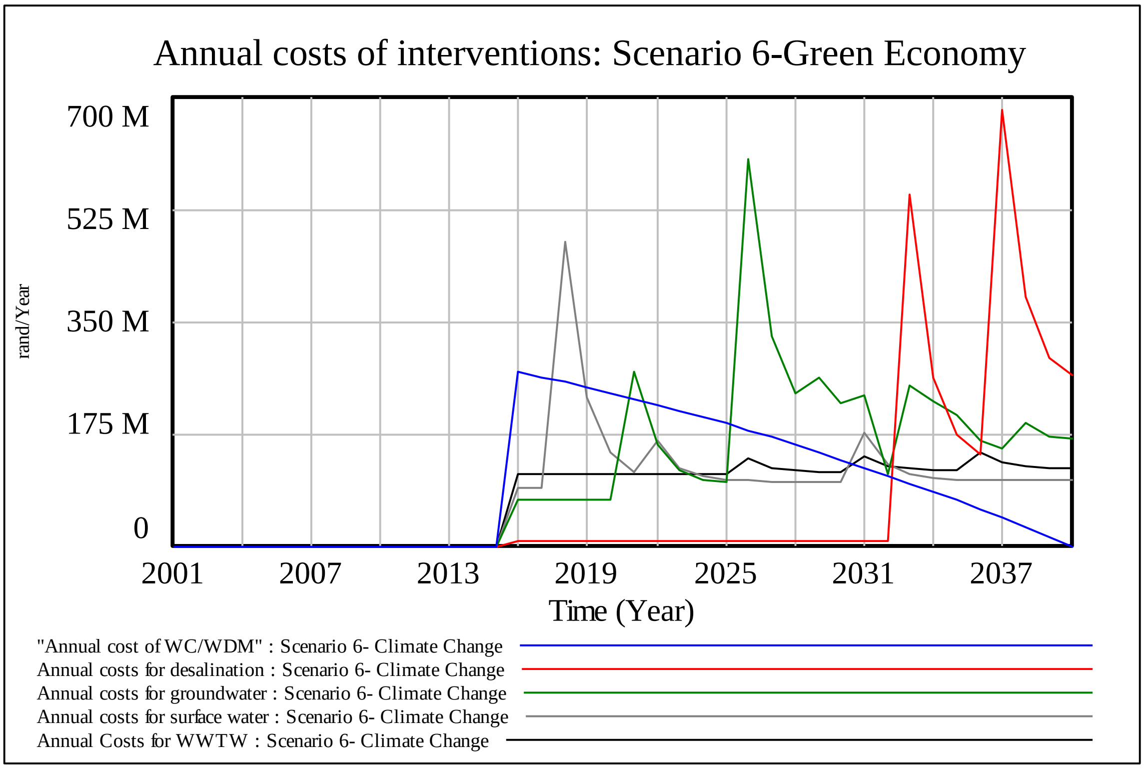

Figure 4.11: Annual costs of interventions: Green Economy

By comparing Figure 4.8 and Figure 4.11 it is evident that the transition to a green economy requires reasonably more financial aid than what is required for the BAU scenario. The annual performance plan of the DWA states that mega projects range between R400 million and R1 billion per year, large projects range between R90 million and R400 million per year and small projects cost less than R90 million and not more than R250 million (DWS, 2015a). Therefore the proposed interventions can all be classified as either large or small projects according to the results generated by the model.

It should be noted that the figures are bound to change with inflation over time. Also, as mentioned previously, the costs do not depict the actual cost of the different intervention options as these costs will vary on a project-by-project basis. However, these figures (Section 3.6.3, Figure 3.19) were used in the model to provide an indication of the possible costs involved in the various interventions.

Figure 4.12 provides a comparison of the possible total annual costs that will be required to implement and maintain the BAU scenario and the proposed interventions in the green economy scenario. The spikes of the green economy scenario (red line) can be attributed to the implementation of the various interventions. Understandably, the implementation of the interventions requires a capital investment, where after the only operational and maintenance costs are required. The amount required to implement the interventions depend on which intervention is implemented as well as on the size of the intervention. The maintenance costs depend on the life expectancy of the specific intervention.

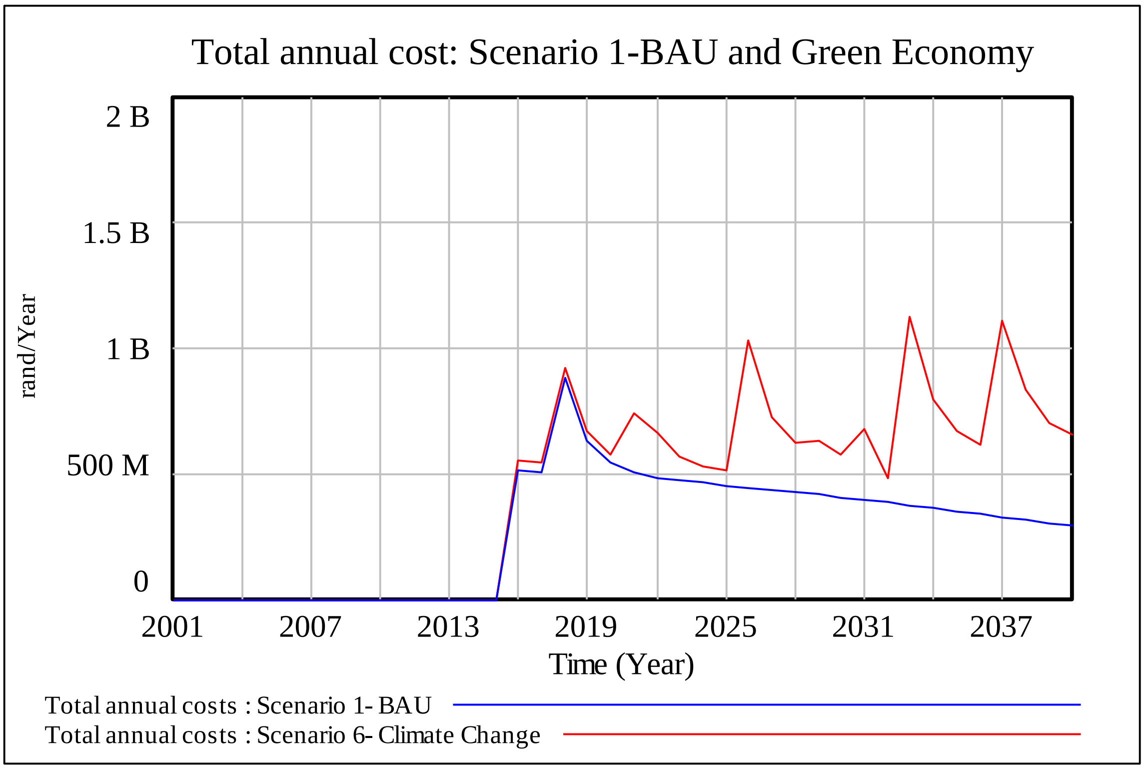

Figure 4.12: Total annual costs: BAU and Green Economy

An additional result worth mentioning is presented in Figure 4.13. It represents a comparison between the total accumulated costs for the BAU with climate change scenario and the green economy scenario. The comparison is presented to illustrate the possible trend that costs might take. Therefore the actual amount of capital required is not as important as the trend that two scenarios follow. From Figure 4.13 it is evident that the green economy costs are predicted to be approximately 68% more by 2040 than that of the BAU with climate change scenario.

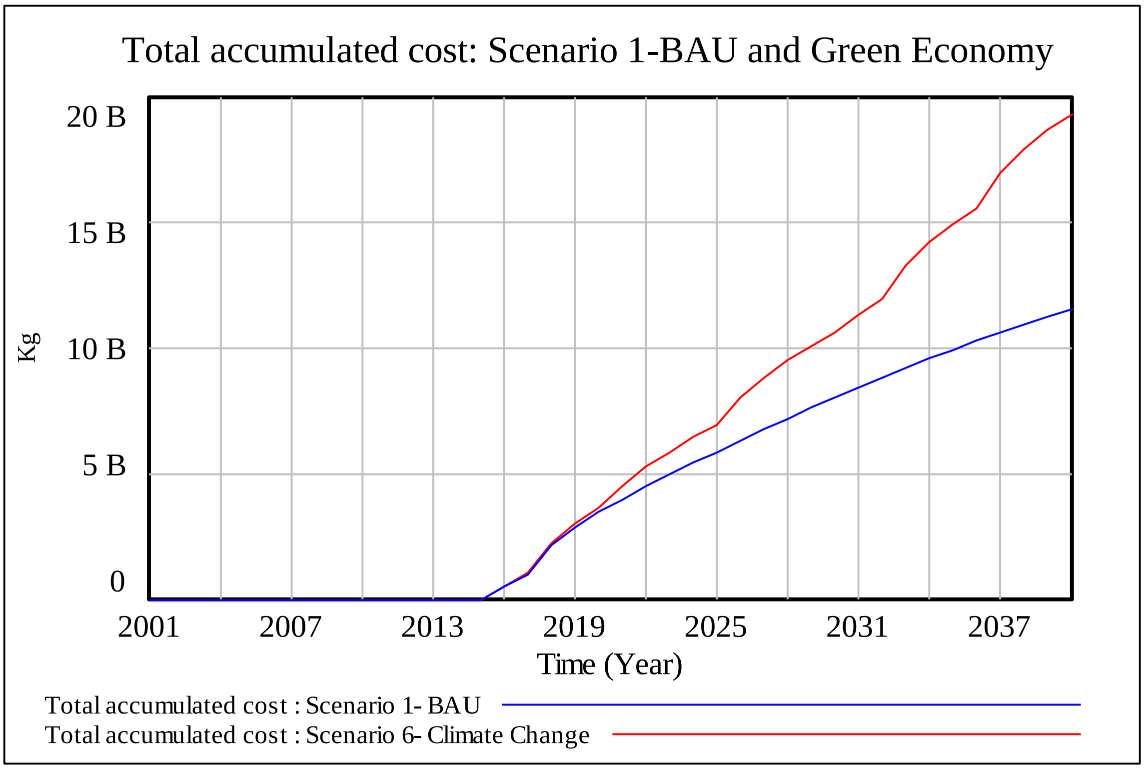

Figure 4.13: Total accumulated cost: BAU and Green Economy

4.3 Results Conclusion

This chapter discussed the results generated by the model for the developed scenarios as well as the key output variables namely, total supply and demand as well as annual costs. The key output variables were evaluated against three different scenarios which included; BAU, BAU with climate change and the green economy. The results generated for the different scenarios were evaluated in separation and in comparison of one another with the aim of attaining a full understanding of the system.

For the BAU scenario as well as the BAU with climate change scenario, the total supply and demand results indicated that the Western Cape Province might face severe droughts in the near future. The BAU with climate change scenario indicated that the Province will experience extreme drought conditions more frequently and intense. The results generated by the green economy scenario illustrated that the proposed interventions are able to provide the Western Cape Province with sufficient water until 2040 with the implication of a large capital investment, among other implications.

From the results discussed in this chapter it is concluded that the green economy scenario is the best case since it indicates sufficient water until 2040. In Chapter 5 important findings are highlighted and recommendations are made with regards to the green economy scenario. The limitations and future improvements of the model are also discussed after which concluding remarks are made.

CHAPTER 5: RECOMMENDATIONS AND CONCLUSIONS

In the previous chapter, the results obtained from the model were discussed. The green economy results indicated that there is a realistic and achievable way to ensure sufficient water supply for the Western Cape Province until 2040. Since sufficient water supply is considered as the primary goal, the green economy scenario was chosen as the best case. Consequently, the recommendations and conclusions are made around the green economy scenario.

This chapter subsequently provides a conclusion to the research. It aims to provide evidence that the research objectives stated in section 1.3, have been addressed. Ultimately, stakeholders and policy-makers can use the recommendations as a guideline to contribute towards more effective management of the transition to a green economy in the water sector of the Western Cape Province.

5.1 Recommendations and implications for policy makers

The research objectives, as described in section 1.3, were developed with the aim of providing stakeholders with support in order to improve management within the water sector with regards to the transition to a green economy in the Western Cape Province. The SDM process ensured a better understanding of the interrelationships, structure, causal factors and systemic problems of the green economy transition.

The scenario development and testing highlighted specific areas that can be targeted to assist this transition. As mentioned, the green economy scenario (Scenario 6 in section 3.6.3) was identified as the best case since it ensures sufficient water supply despite the effects of climate change. The green economy scenario involves various implications for policy makers and stakeholders. The following seven areas were identified as high impact areas that can be targeted to assist the green economy transition:

i. Financial investment
ii. Water demand
iii. Water supply
iv. Water quality
v. Management
vi. Data availability
vii. Social equity

Each of the mentioned areas is discussed in this section to indicate the recommendations surrounding it. As highlighted in section 4.3, financial cost is a key area of concern since South Africa has limited finance which is poorly managed (South African Government, 2014). Various aspects involved with managerial improvements in the Western Cape Province are discussed. Lastly, the social aspects that are inherent to water supply are discussed as it is considered to be an important implication.

5.1.1 Recommendation 1: Ensure sufficient financial Investment

The results discussed in section 4.3, showed that the accumulated costs and capital investment associated with the proposed interventions is approximately 68% more by 2040 (see Figure 4.13) for the green economy scenario when compared to the BAU with climate change scenario. It is projected by the model that an average yearly cost of approximately R700 million is required for the Western Cape Province in current monetary worth until 2040 to implement the interventions proposed by the green economy scenario. This represents the first challenge for the Western Cape Province in terms of transitioning to a green economy within the water sector.

This research ranked the proposed interventions according an indicative costing of the interventions based on a case study of the marginal cost of water sources in a municipal area (refer to section 3.6.3). WC/WDM was ranked as the least cost intensive intervention while desalination was ranked as the most cost intensive. The costs associated with each intervention that was generated by the model, depended on the frequency and magnitude of the capacity increase. The frequency and the magnitude were determined based on the Water Stress Index generated by the model as well as expert opinion. The method is accurate for current available information. However, as the technology develops, prices of interventions might change. Therefore, regular studies should be done to ensure that the proposed interventions are economically feasibility.

Given the financial requirement indicated by the model a possible solution is that the Western Cape Province’s government increase fees paid for clean and potable water supply. However, this solution might cause socio political issues due to reduced access to clean and potable water for the poor and subsequently increased inequity among the population. The social implications that are inherent to water supply are discussed in section 5.1.7. Privatisation of water is another controversial topic, nevertheless if the government fails to fund the required implementation of interventions it should be a considered as a possible solution.

5.1.2 Recommendation 2: Decrease water demand

As discussed in section 4.2.3, the results generated by the model showed that the green economy scenario’s demand is approximately 7.5% less by 2040 than the demand of the BAU with climate change scenario. Furthermore, Figure 5.1 presents the results generated by the model for the amount of UAW in the treatment system for the BAU with climate change scenario and the green economy scenario. Clearly the UAW in the green economy scenario deceases in 2020 and 2025 in comparison with the BAU with climate change scenario.

The decrease in both cases mentioned above can be attributed to the proposed WC/WDM intervention. As discussed in section 3.6.3, the WC/WDM interventions considered in this research include pressure management, leakage repair and user education. WC/WDM primarily aims to decrease UAW in the treatment system and decrease water demand. WC/WDM has been established as the least expensive and, given the context, assumptions and parameters used during the SDM, it is considered as the most essential intervention to ensure water supply for future generations.

UAW is affected by the amount of water put into the system, and the fraction of water lost though the system. The fraction of water lost through the system is attributed to poor maintenance and also unsustainable use of water. Therefore service backlogs should be addressed as soon as possible. However, from Figure 5.1 it is evident that vast amounts of water are lost despite the implementation of leakage repair and pressure management in 2020 and 2025. This happens since the model assumes that the total supply of the Western Cape Province (including all sectors) is put through the system. Therefore the more water that will be put through the system the more leakage will occur and more water will be lost.

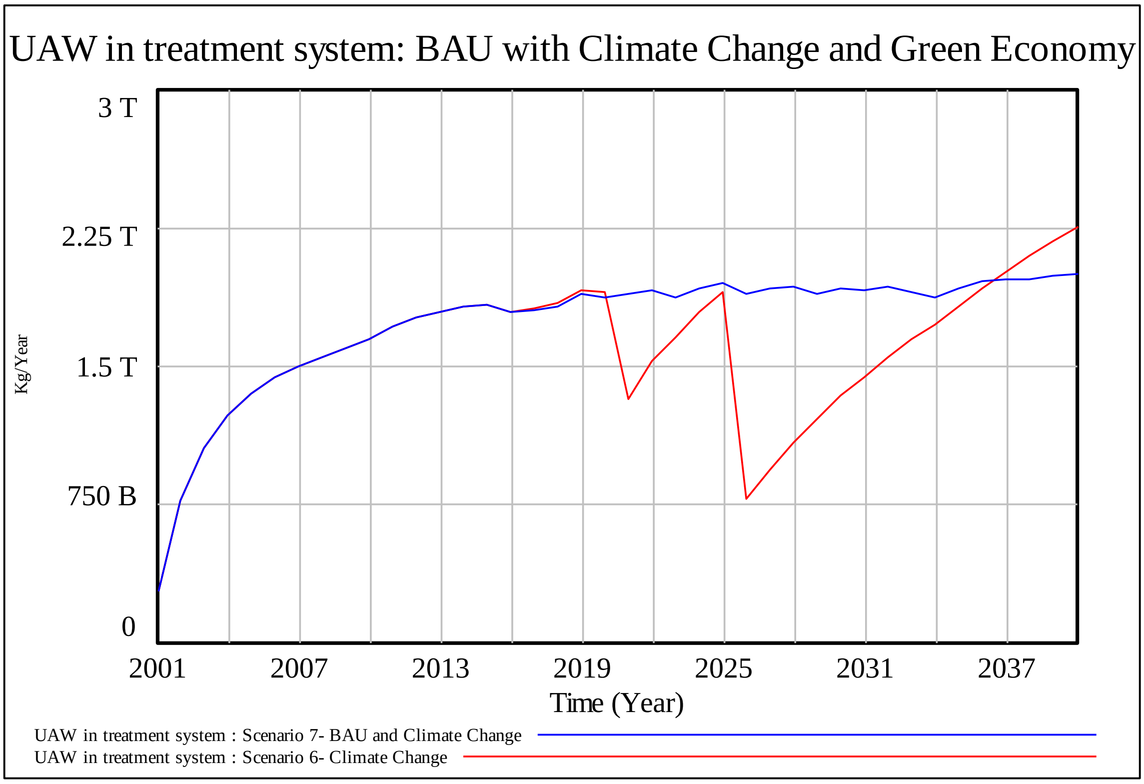

Figure 5.1: UAW in the treatment system: BAU with climate change and green economy

A proposed solution would then be to focus on decreasing demand further. To decrease the demand of the Western Cape Province, both the government and each individual water user are held responsible for the implementation of WC/WDM. The water users associations and are required to address the agricultural sector, while the water service providers are required to address the urban sector.

To decrease the per capita water demand it is recommended that the government invest heavily in user education. For private users, management of one's own demand and backup supply should be encouraged. Demand management includes reuse of grey water from baths and showers for irrigation and toilet flushing. To generate private supply of water, rain water harvesting is necessary. If "water shedding" were to be implemented in the Western Cape Province, rain water harvesting would serve to prevent any discomfort.

To decrease water demand within the industrial sector, industrial symbiosis is a possible solution. It refers to the sharing of services and by-product resources among industries in order to reduce costs and extensive extraction of natural resources. The promotion of industrial symbiosis by the water service authorities would save a lot of water.

5.1.3 Recommendation 3: Invest in water supply diversification and augmentation

Once WC/WDM interventions are in place to reduce the demand it is recommended that the DWS invest in diversifying the water mix to prevent future water shortages. According to the research the supply sources in the Western Cape Province consist of approximately 78% surface water. Many studies have established that surface water supply in the Western Cape Province has reached its capacity since all available catchments have been filled (Palmer & Graham, 2013). However, in Figure 5.2 the available groundwater after extraction is presented. Evidently, there are vast amounts of groundwater available in the Western Cape Province. Therefore it is recommended that the DWS invest heavily in the development of groundwater extraction. However, as seen in Figure 5.2, the available water is highly variable and aquifers have different recharge rates. It is subsequently recommended that extensive feasibility studies should be done to prevent over utilisation.

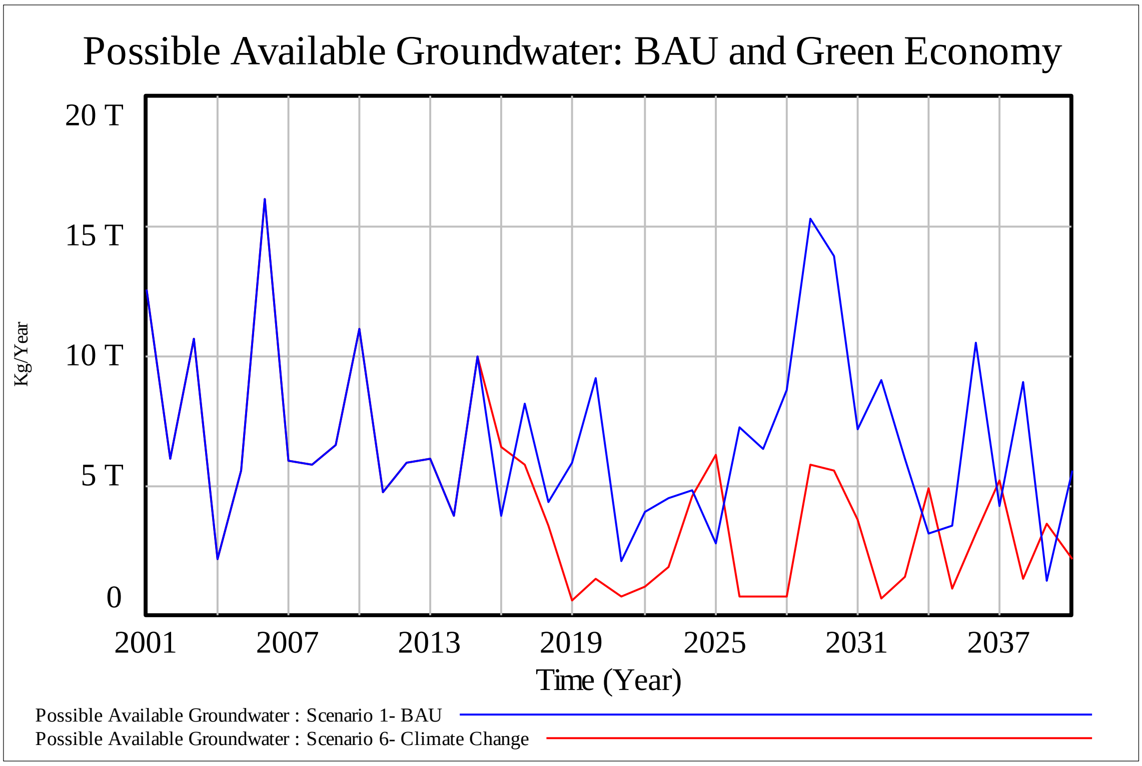

Figure 5.2: Possible available groundwater: Green economy scenario

Waste water re-use and desalination is recommended as second and third options for diversifying the water mix. Unlimited amounts of waste water and sea water is available, which will be able to satisfy the demand of the Western Cape Province. However, a mind shift will be required when waste water reuse is implemented and a large capital investment will be required for desalination.

Furthermore, it was found that most studies focus on the development of the City of Cape Town's water supply system namely the WCWSS. Major urban areas are essential to the country's economy and the DWS has to invest in the conservation and augmentation of water schemes serving these urban areas to prevent serious water shortages from adversely impacting the economy. However, the smaller towns surrounding the urban centres require an equal amount of attention to prevent the extensive migration to the urban centre. Migration to the urban centres will increase the water demand beyond the supply system's capacity.

5.1.4 Recommendation 4: Maintain water quality

Another recommendation to the DWS refers to the water quality of the Western Cape Province. Maintaining the quality of the water in the Province is a critical necessity. Water quality is variable in the sense that it cannot be defined by the measurement of only one parameter. It also varies with time and subsequently requires regular monitoring to detect possible patterns and changes over time. Turton (2008) points out that the lack of surplus water also means that South Africa has lost its capacity to dilute pollutants, and will require increasingly higher standards of water treatment that will require more expensive technologies. User education is again a possible solution since most forms of pollution are attributed to human activity.

5.1.5 Recommendation 5: Strong management structure

The model shows that the Western Cape Province's water supply will soon become insufficient given the growth simulated for the BAU scenario. Therefore, various changes regarding the current development patterns and practices are required. Important decisions will need to be made in the near future to enable and support the transition to a green economy. Consequently, a strong management structure for all sectors and specifically for the water sector is required. It has been established that restructuring is currently underway in the DWS (DWA, 2014), which should improve the management structure. Once this restructuring process is complete it is crucial that they address the recommendations to prevent water scarcity in the Western Cape Province.

5.1.6 Recommendation 6: Improve data availability and accessibility

The lack of reliable and consistent historic data on the state of the environment and for the case of this research, water demand and supply, is a major barrier to increasing the effectiveness of the management thereof. The Western Cape Province should undertake to monitor and assess their environment and integrate social economic and environmental information to inform the decision making processes. Standardized approaches to data collection are needed and the cooperation by all involved parties in this regard must be reinforced.

Improved access to information is also essential. Professionals and academics involved in water research have had difficulty in the past trying to access reliable, accurate and comparable water use statistics, particularly from the mining, power generation and industrial sectors (Heath et al, 2009). In a 2009 paper for the Water Research Commission, Heath et al (2009) reports a general industry resistance to providing information because it could affect future applications for water use and wastewater discharge. It is recommended that policies and legislation are put into place by the Western Cape Province which will force industry to make their water use patterns available to the public.

5.1.7 Recommendation 7: Monitor social equity indicators

The approaches and technologies that have been discussed are all technical and engineering matters. However it is essential to incorporate social and environmental concerns in the management of water resources in the Western Cape Province. Water supply contributes to overall human and social development. It is viewed as a human right and not a commodity. Dimensions such as poverty alleviation, equity, social inclusiveness and inclusive wealth are all affected by the supply of fresh water. A limitation of this model is that it does not measure and demonstrate how the transition to a green economy and more specifically, sufficient water supply, would affect these social equity indicators.

The social implications that clean and potable water supply might have are highlighted here. The first important impact that improved access to clean and potable water will have is improved sanitation. Sanitation subsequently reduces health problems and mortality. Another impact is improved nutrition throughout the population as sufficient supply of water is bound to increase agricultural yield which implies that more food will be available for consumption.

The process of transforming to a green economy and enhancing the water sector will create job opportunities since a dedicated and skilled workforce will be required. Higher employment rates will result in reduced poverty and increased social equity. An induced impact that might affect the social equity includes higher economic growth. As mentioned in the CLD development in section 3.3, GDP will grow with more available water to support economic activities such as agriculture, industry and services. However, it is important to take account of the “rebound effect”. Since higher GDP and more water supply might result in increased urbanisation and ultimately higher water consumption.

Lastly, as stated by Aston et al (2008) it is important that the imbalance between urban, semi-urban and rural communities be accounted for when water resource policy makers make trade-offs between equity, efficiency and sustainability objectives at different scales. Properly informed decisions need to be made and acted upon to sustain and strengthen social resilience in the Western Cape Province.

5.2 Assumptions and model limitations

The model limitations discussed in this section include aspects that could potentially have increased model accuracy. The variables that were not considered in the model due to time constraints, research scope or modelling difficulty are highlighted. Also, the lack of data for certain variables is discussed as well as assumptions made throughout the modelling process.

The first limitation of the model is the data used for water supply and demand of the Western Cape Province as a whole. As mentioned previously it was found throughout the research that most studies focus on the City of Cape Town’s water supply system, which is known as the WCWSS. Most data only resemble the statistics of this specific system and neglects to take the smaller towns, surrounding the urban centre, into account. Therefore the data used in the model is not time series data but rather data that represents the supply and demand only for the year of 2000. Time series data for the Western Cape Province as a whole would have increased the confidence in the model.

Water demand in the model is assumed to grow directly proportional to GDP growth of the specific sectors. Ideally, models calculating the water demand of the agricultural, industrial and domestic sectors should be built to feed into the WeCaWaRM. Given the absence of such models, GDP growth is deemed the appropriate variable to estimate demand growth. The impact of climate change is another assumption that was made, of which the impact could not be accurately calculated since climate change is still uncertain and unpredictable.

The costs associated with the interventions, as specified in section 3.6.3, are assumed to be similar to the costs calculated by a case study of marginal costs of water resources in a municipal area. The costs are accurate for the current available information. However, it would be more accurate if an in-depth case study of each project, in its specific location and with its specific characteristics, could be done to determine the URV for each project. With an accurate URV of each project the ranking of the interventions might change.

The potable water inflow is only dependent on the total water supply. To improve the accuracy of the amount of water that is made available for treatment, the allocations to the different sectors in the Western Cape Province are required. In the model it was assumed that potable water (water used in households) is the highest priority and therefore the total amount of water supply is allocated for this purpose.

Goal based scenarios are implemented in the model, which tends to make the model more discrete. Due to the difficulty of modelling a feedback loop which would be able to implement the decision rule described in section 3.6.3, and subsequently implement the interventions as required based on the Water Stress Index, the goal based scenarios were used. However, the model remains dynamic as various feedback loops do exists.

5.3 Suggested future research

Future research possibilities that have been identified throughout the research are discussed in this section. It includes improvements on the model itself based on the limitations discussed in the previous section, as well as scope adjustments.

As mentioned previously, this model forms part of a larger Western Cape Green Economy Model (WeCaGEM). The aim of this model is to assist the Western Cape Province in the transition to a green economy by modelling various important sectors. The sectors included in WCGEM are; agriculture, transport, biofuels, energy and water. By including these additional sectors a better understanding of the implications involved in the transition to a green economy can be gained.

With regards to the scope; the model is simulated for the Western Cape Province as a whole. The scope can be adjusted to focus on smaller parts of the Province since data might be more readily available. Also, to assist South Africa with the transition, future research could potentially focus on the other eight provinces of the country. Either one of the suggested scope changes will decrease the lack of literature and data surrounding the transition to a green economy. This could assist policy makers of South Africa to make informed and accurate decisions when transforming the country to a green economy.

A possible interesting research project would be to look into waste water generation in the various sectors. The various water use sectors, such as agriculture, mining and industry as well as domestic, generate different amounts of waste water. Some of the waste water can be re-used while some are lost to the system. It the amount of re-usable waste water generated could be calculated, planning for waste water treatment works can be done well in advance, without the risk of extensive financial loss due to a lack of waste water to be treated.

Lastly, the limitations mentioned in the previous section could be addressed to improve this model. Simulating historic time series data for supply and demand for the whole of the Western Cape Province and including water demand form the specific sectors (therefor not relying on

GDP growth) is suggestions made in the previous section that would increase the model accuracy significantly.

5.4 Concluding remarks

In South Africa and specifically the Western Cape Province it has become inevitable that our current way of living should change. Climate change is affecting the Western Cape Province for the worst (van Weele and Gumbi, 2013) and the limited finances are poorly managed (South African Government, 2014). It is our obligation as human beings, and especially as planners, to work toward the objective of sustainability and the green economy. The system dynamics modelling process ensured a better understanding of the implications involved for the water sector when transitioning to a green economy in the Western Cape Province.

The results generated by the model showed that the Western Cape Province will experience extreme water shortages in the near future if the current development patterns as well as current consumption and production practises continue. However, it was established that, with sufficient investment and effective management, the demand of the Western Cape Province could be met. After thorough research, and careful consideration, various interventions were proposed and simulated in the model against a climate change scenario. Since the proposed interventions proved to be sufficient to supply water until 2040, it was suggested as a possible strategy for the Western Cape Province.

Ultimately, this research ensured a better understanding of the complexities and implications involved in the transition to a green economy. Therefore, the research lays the platform for future studies in this field and can hopefully assist the Western Cape Province in becoming the lowest carbon province in South Africa and the leading green economy hub on the African continent.

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APPENDICES

APPENDIX A

A. Sub-model sketches

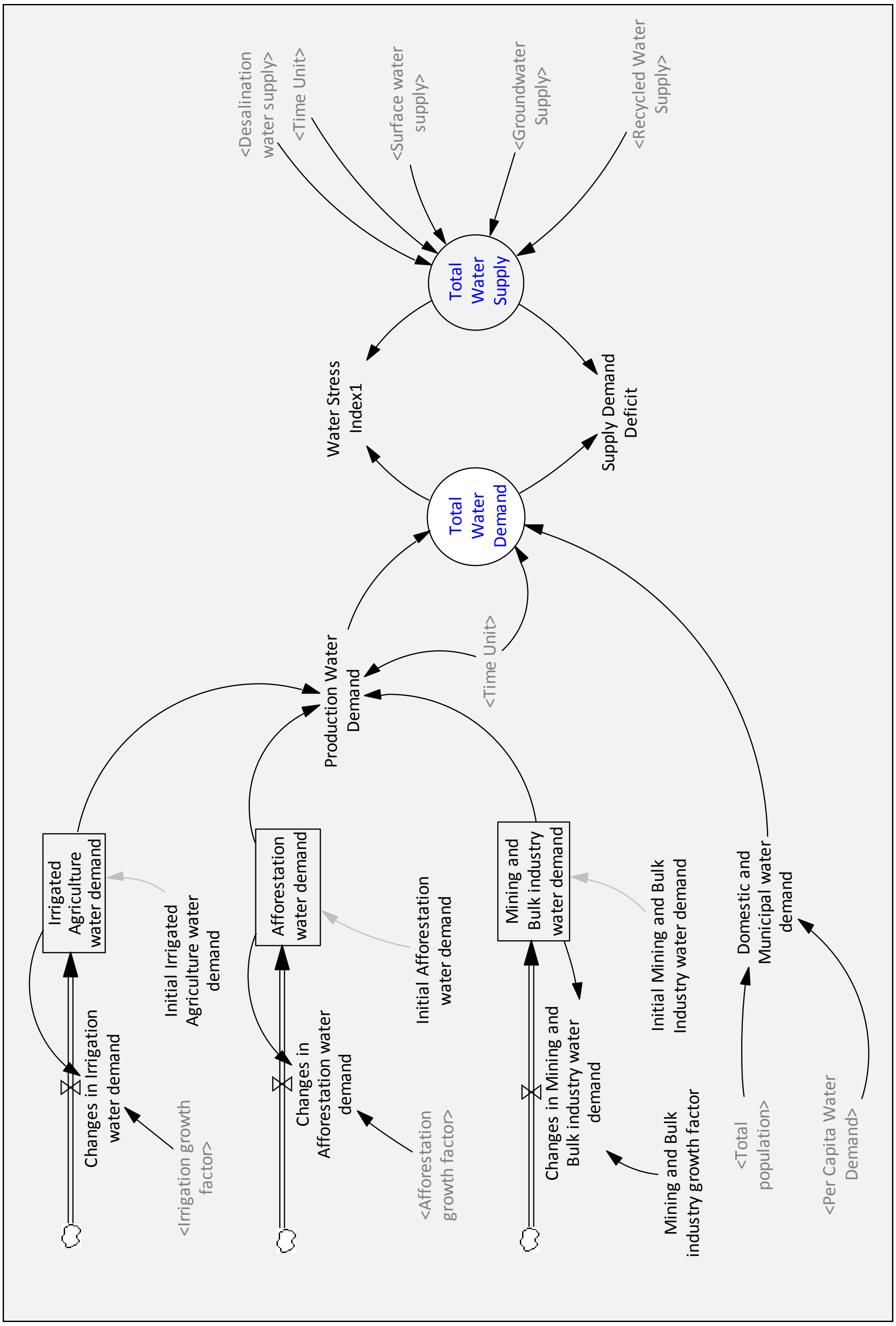

Figure A-1: Supply Demand model sketch

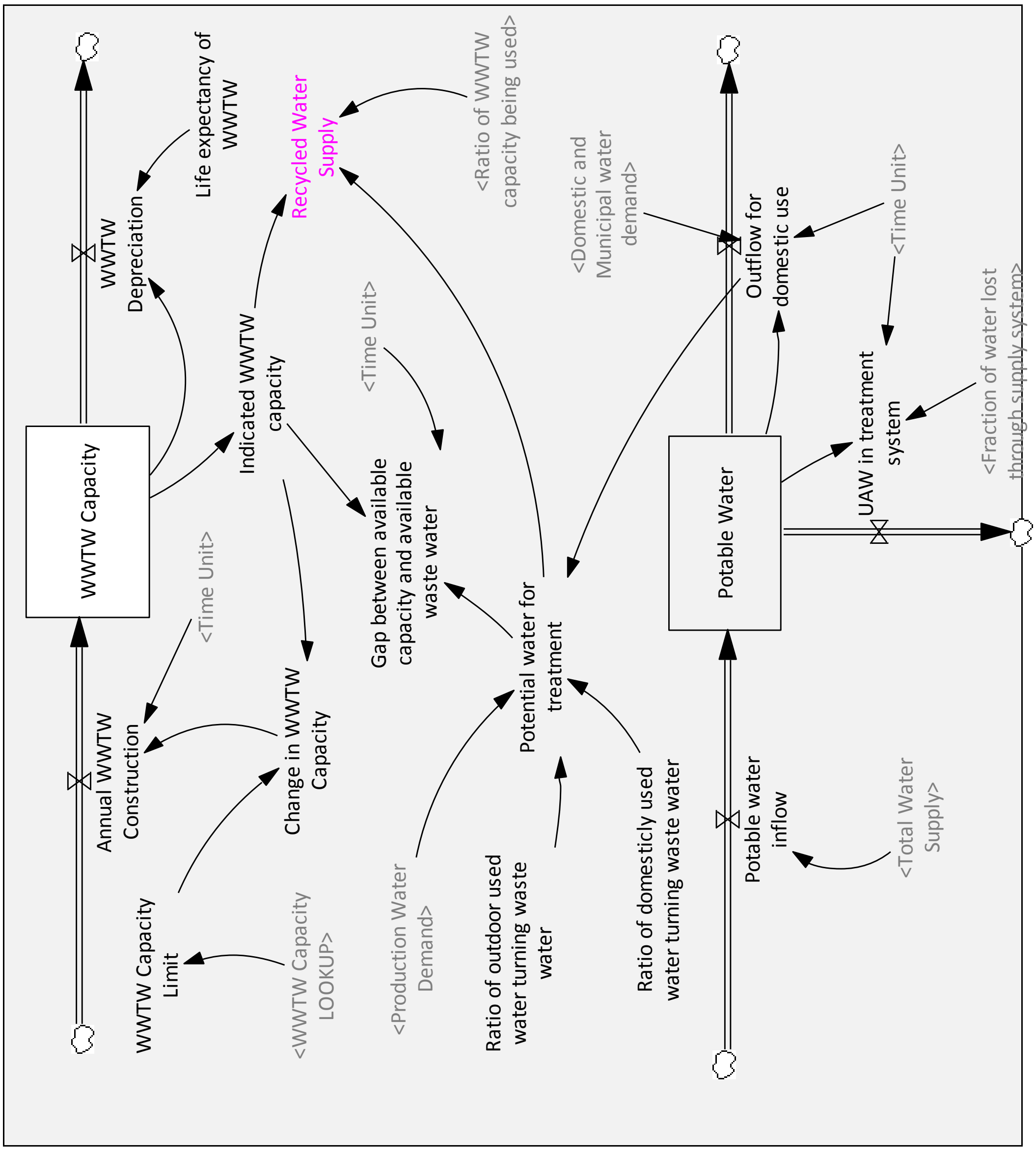

Figure A-2:Waste water model sketch

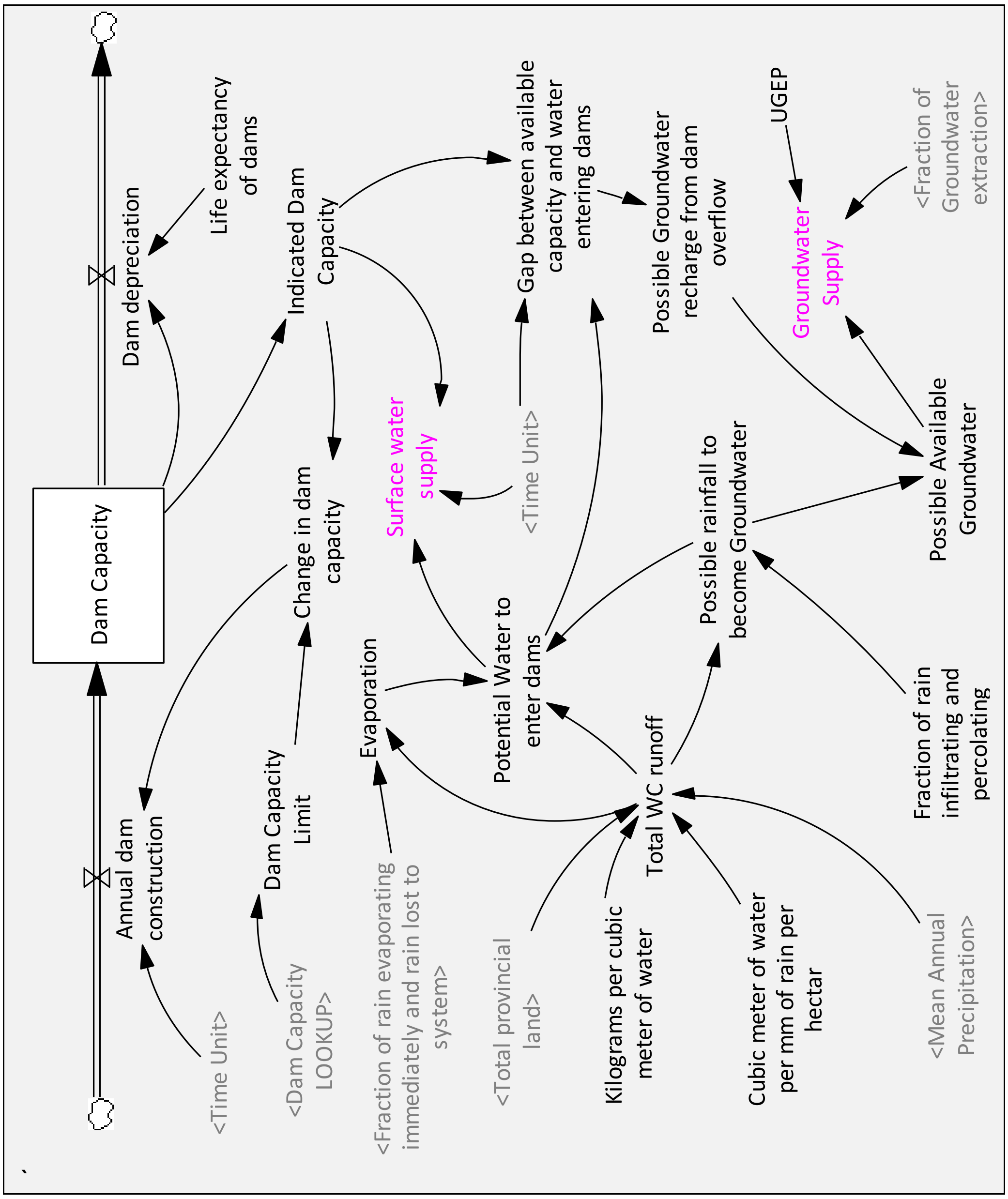

Figure A-3:Surface water and groundwater model sketch

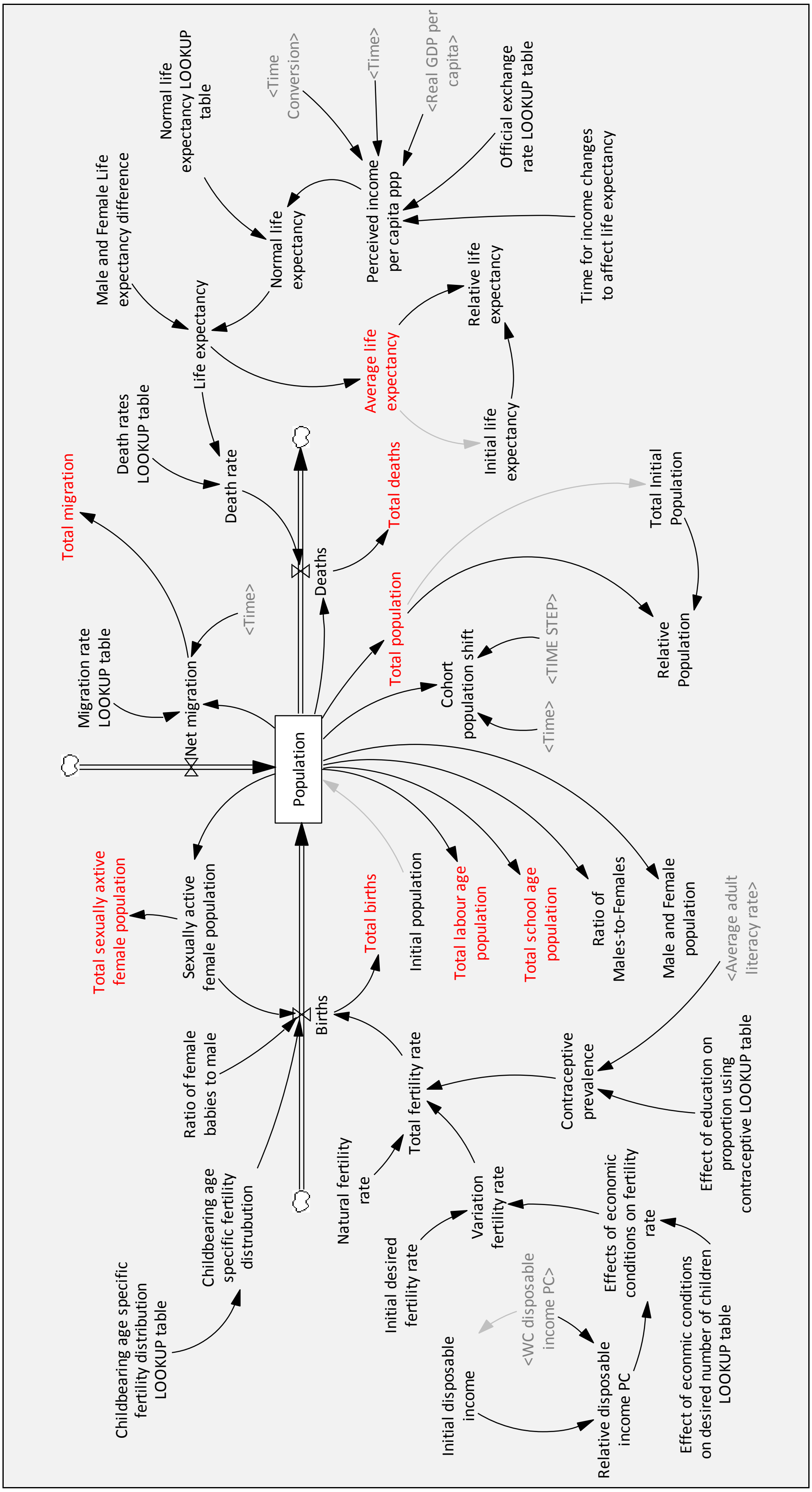

Figure A-4:Population model sketch

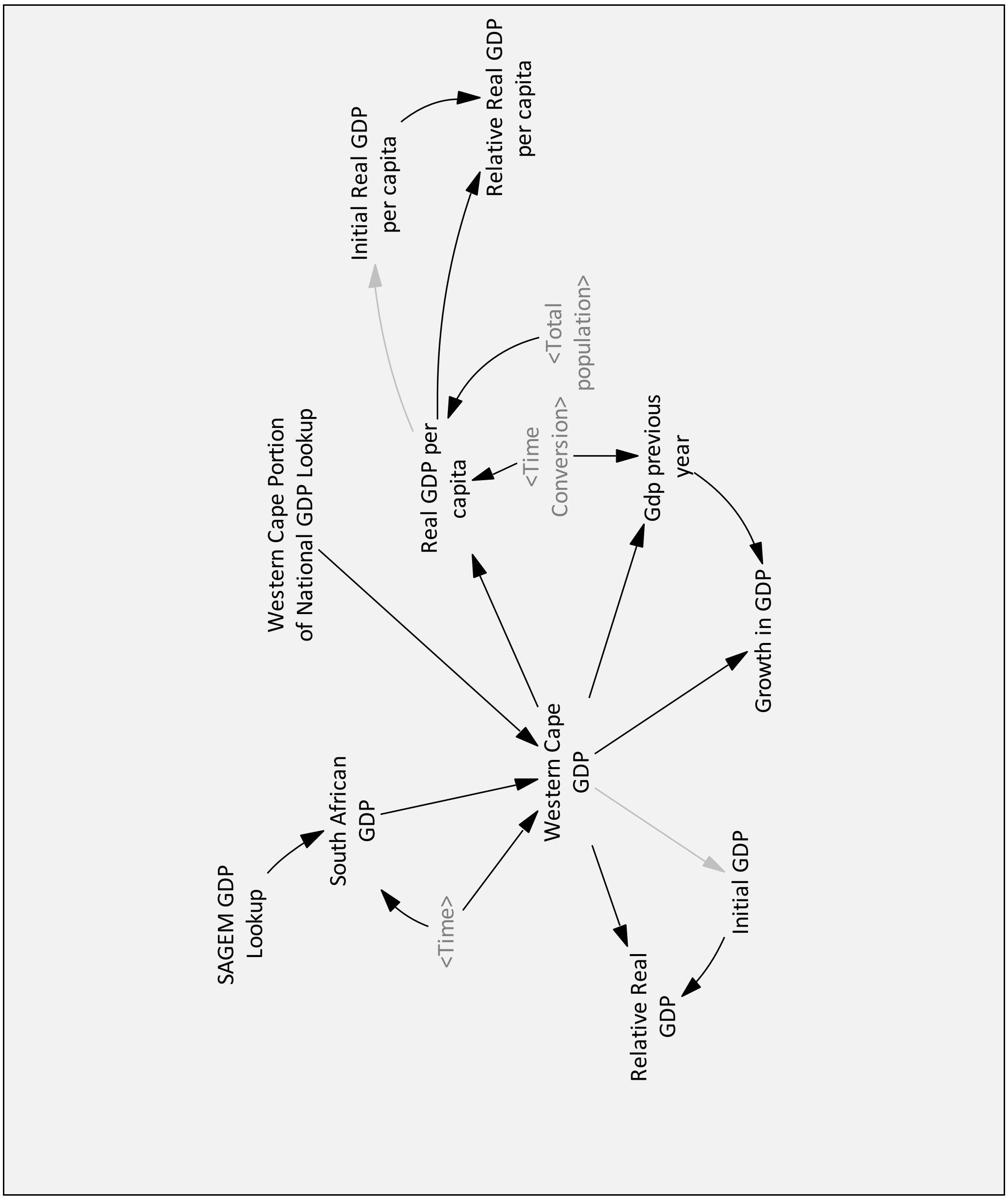

Figure A-5:GDP model sketch

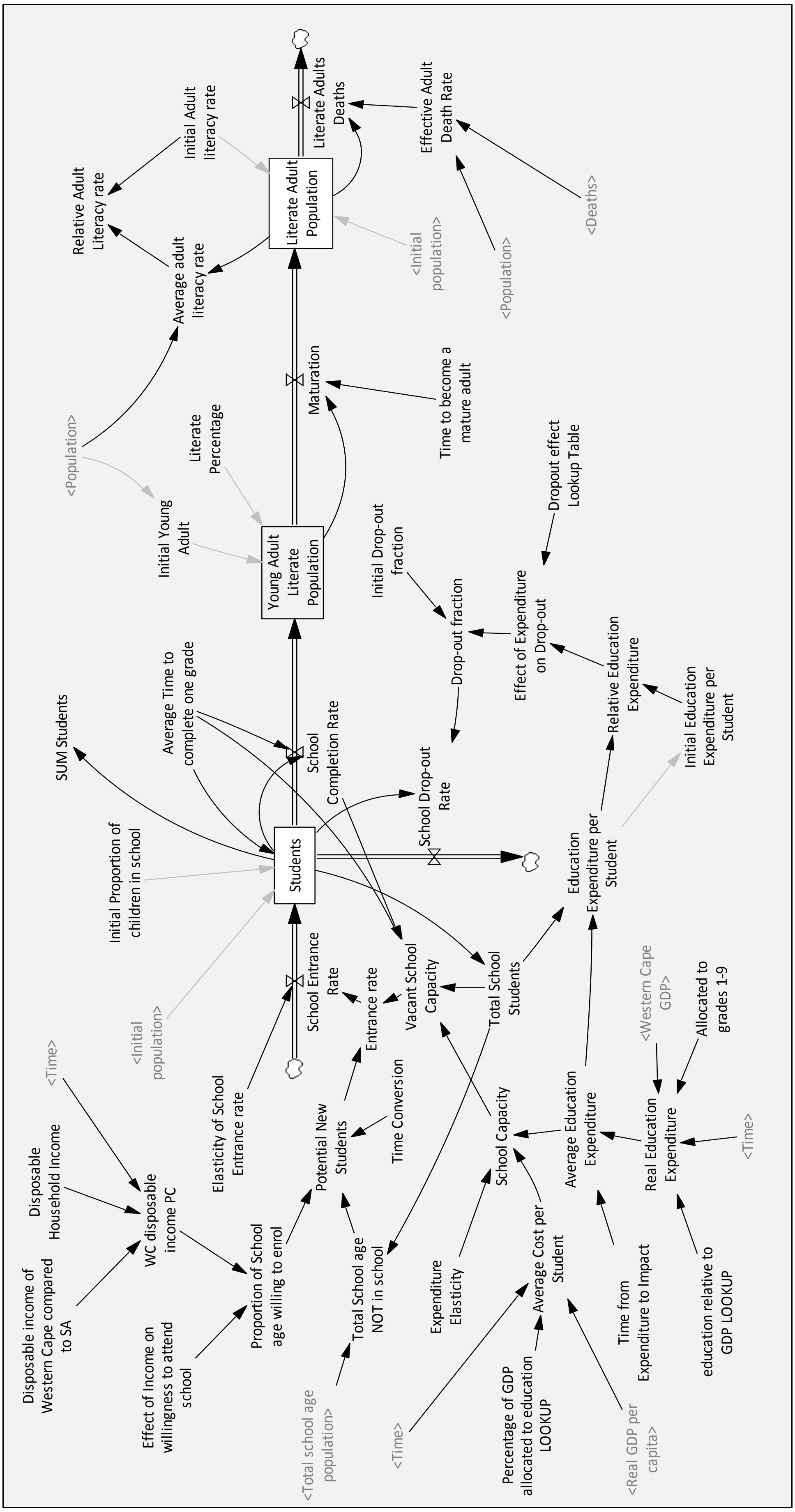

Figure A-6: Education model sketch

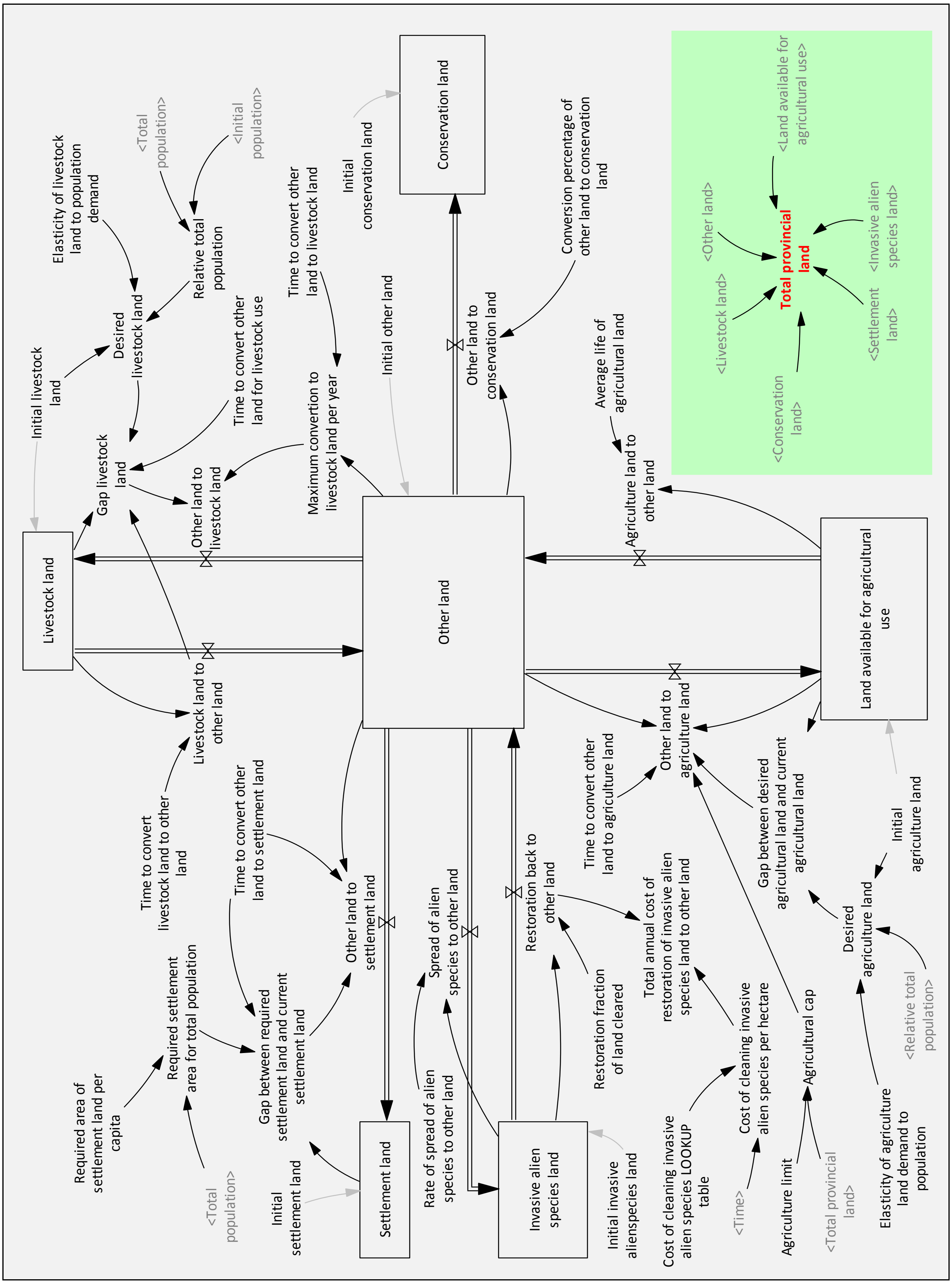

Figure A-7: Provincial land model sketch

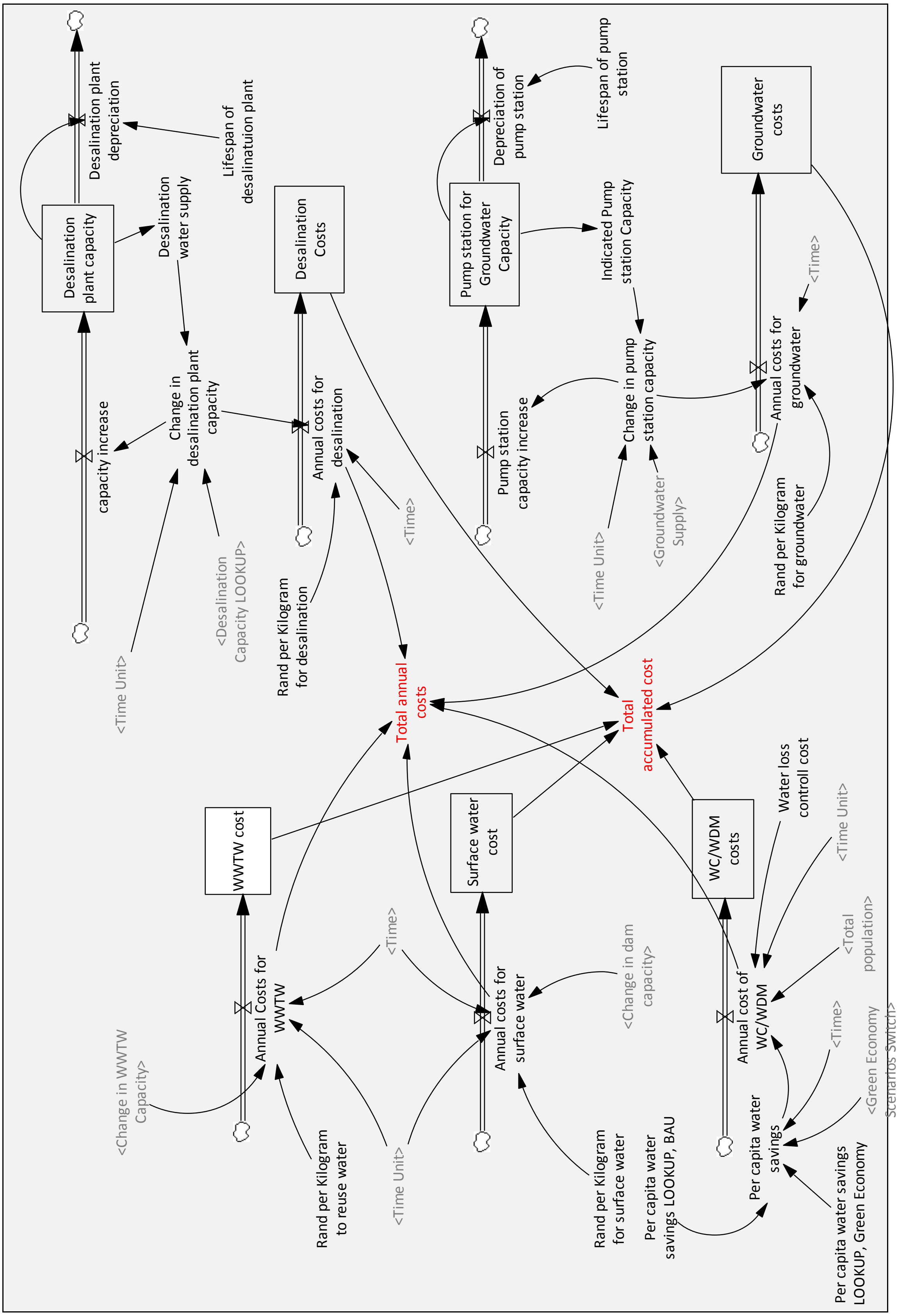

Figure A-8: Investment model sketch

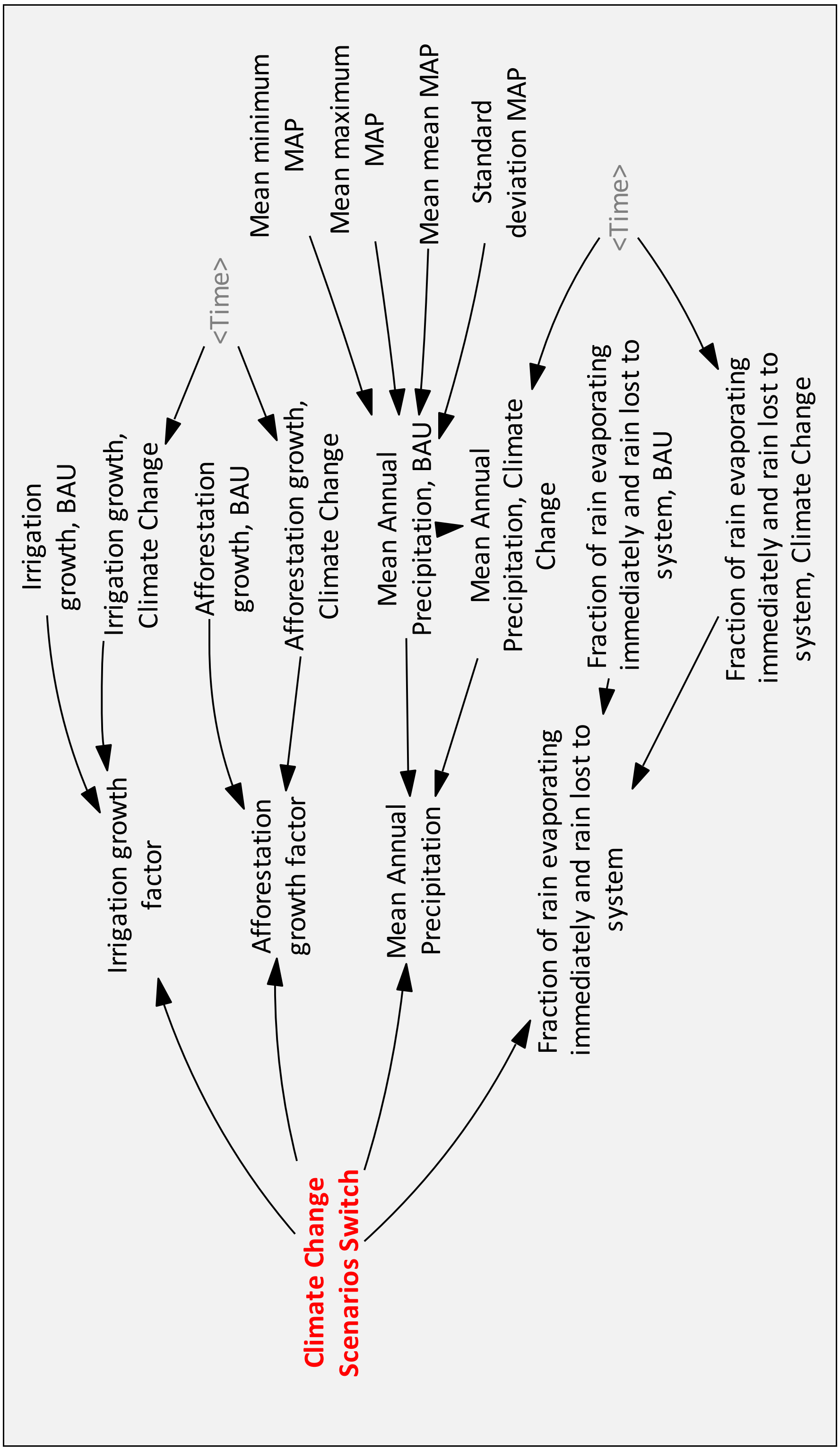

Figure A-9: Climate change switch model sketch

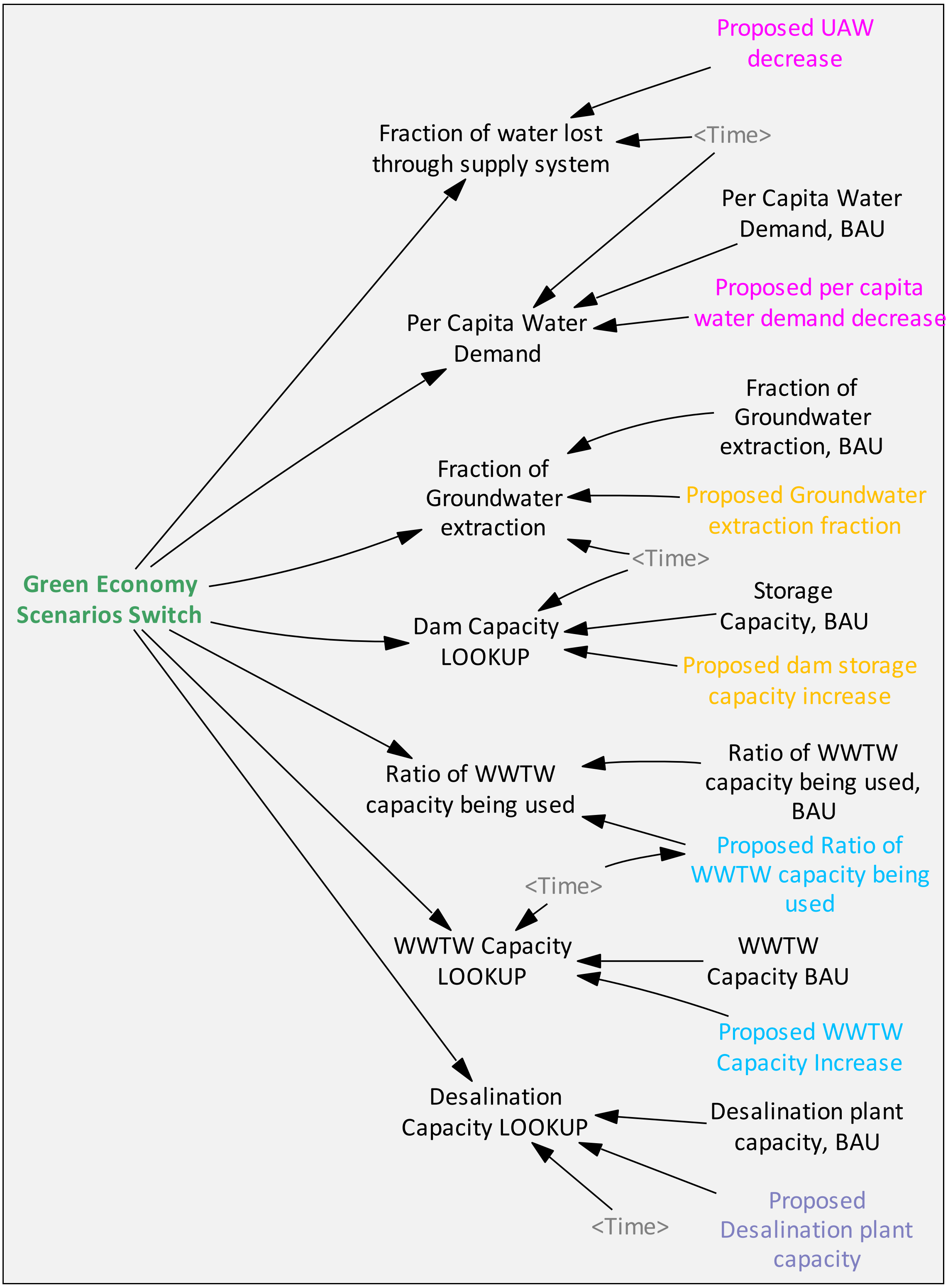

Figure A-10: Green economy switch model sketch

APPENDIX B

B. VENSIM Settings and important data

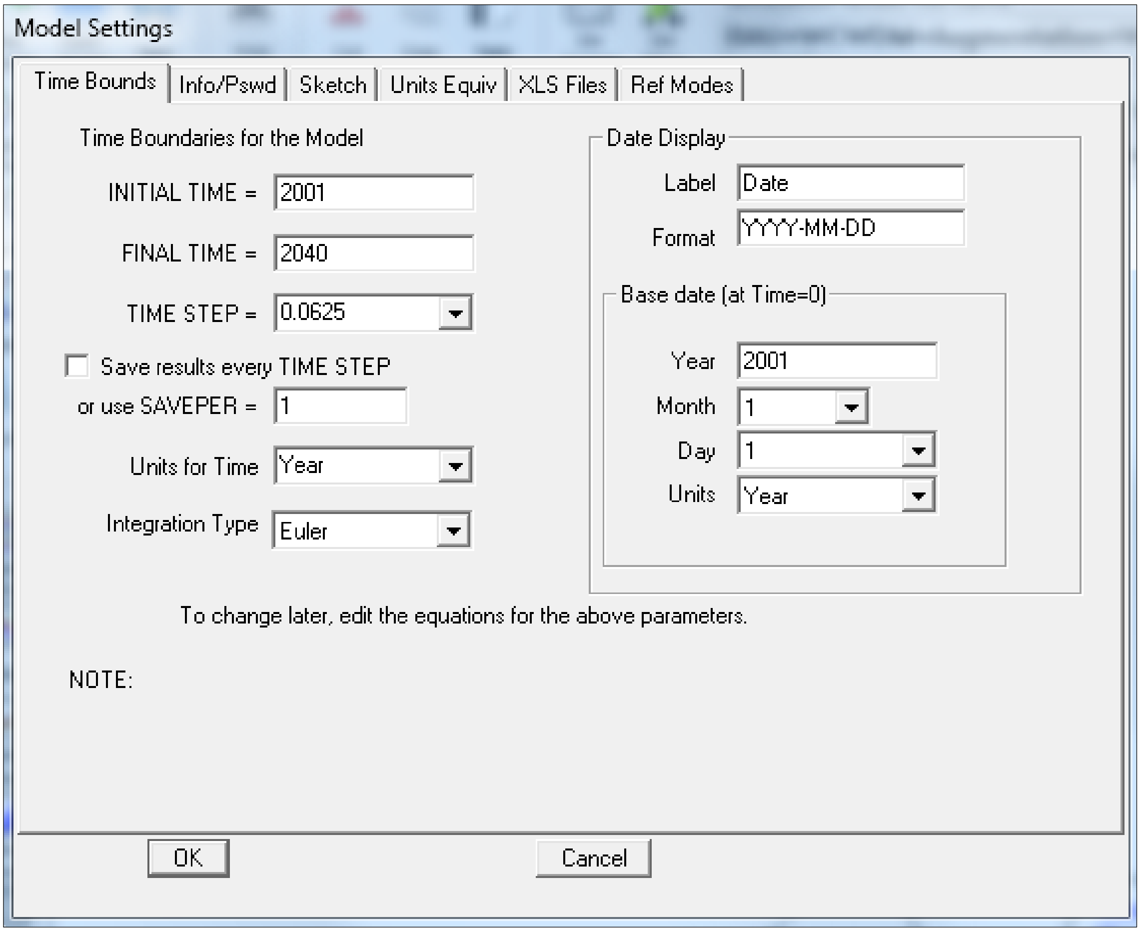

Figure B-1: VENSIM settings

PRECIPITATION DATA AND CALCULATIONS

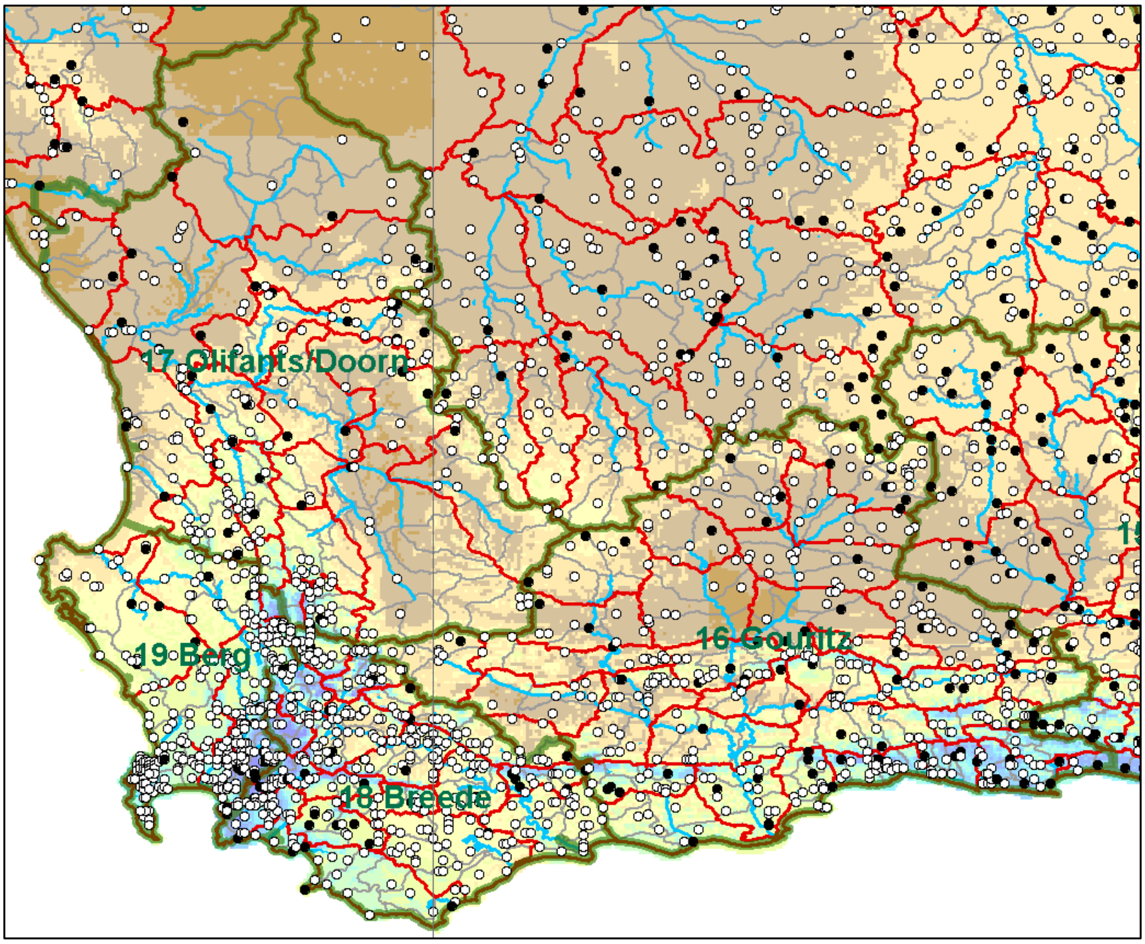

Figure B-2: Western Cape Province Rain Fall Stations

Table B-1: MAP per WMA

	Gourits MAP	Olifants MAP	Breede MAP	Berg MAP	Average
MIN	98	84	293	225	175.026
MAX	997	899	2141	1630	1416.75
Average	398.96	267	648	713	506.83
Standard deviation	225.69	150	373	372	280.31

GDP GROWTH GRAPHS

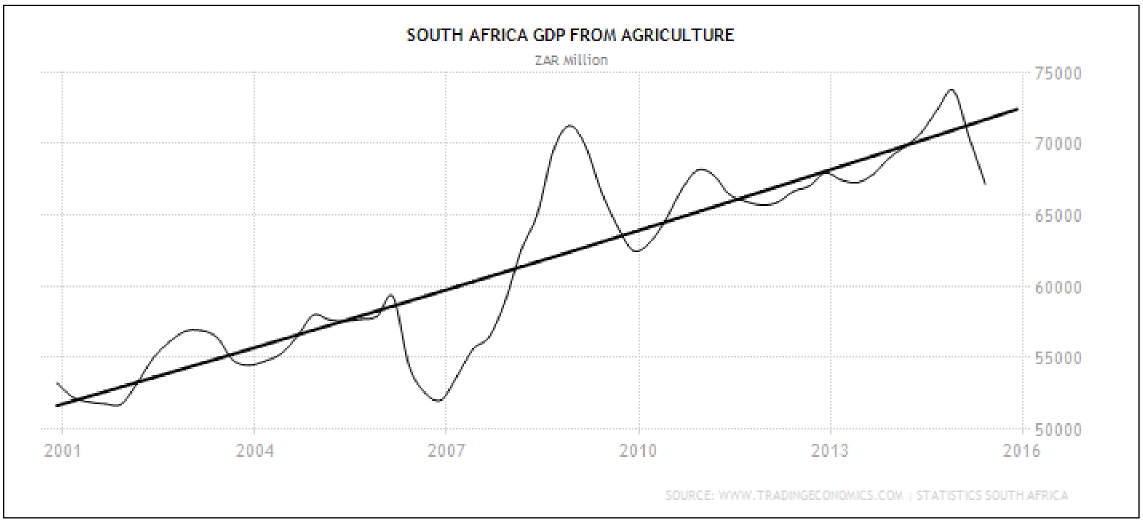

Figure B-3: South African GDP from agriculture

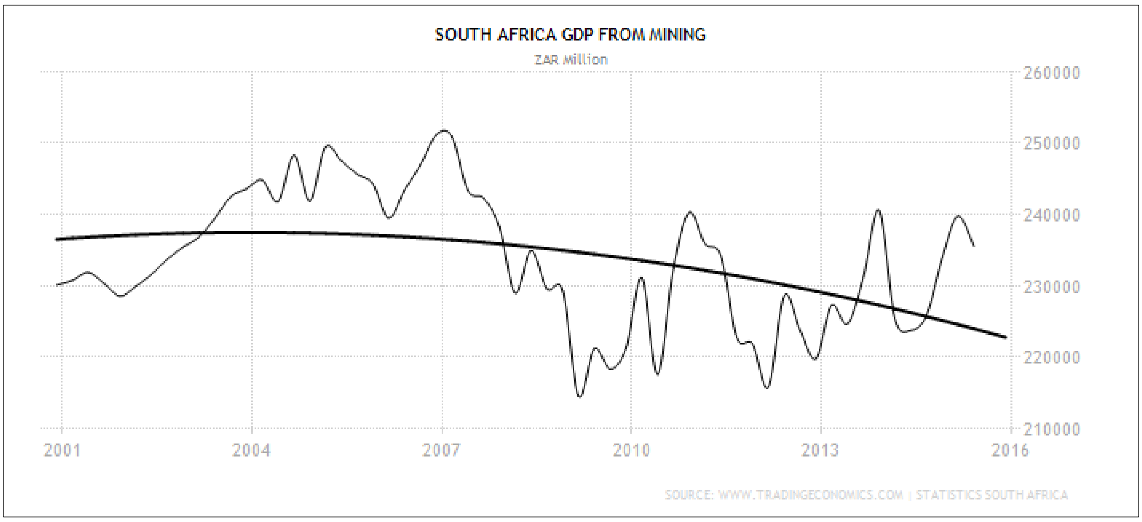

Figure B-4: South African GDP from mining

APPENDIX C

C. Model validation

C.1 Historical Data Validation

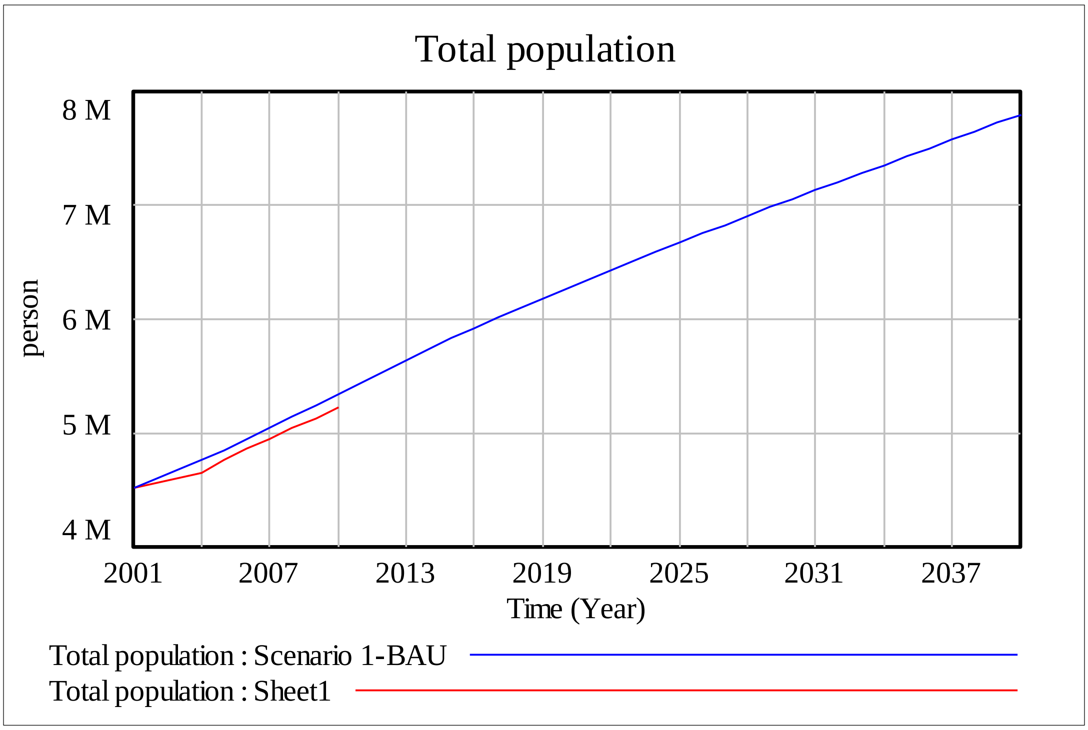

Figure C-1: Total population: Historical data and simulated results

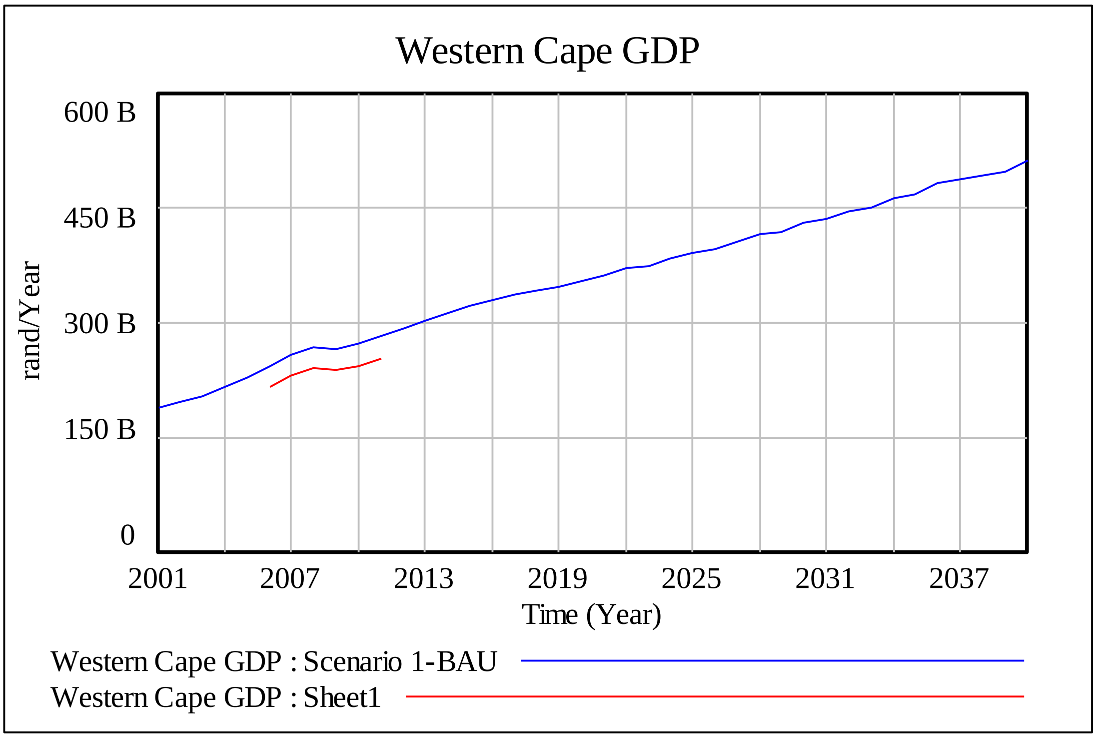

Figure C-2: Western Cape GDP: Historical data and simulated results

C.2 Sensitivity analysis tests results

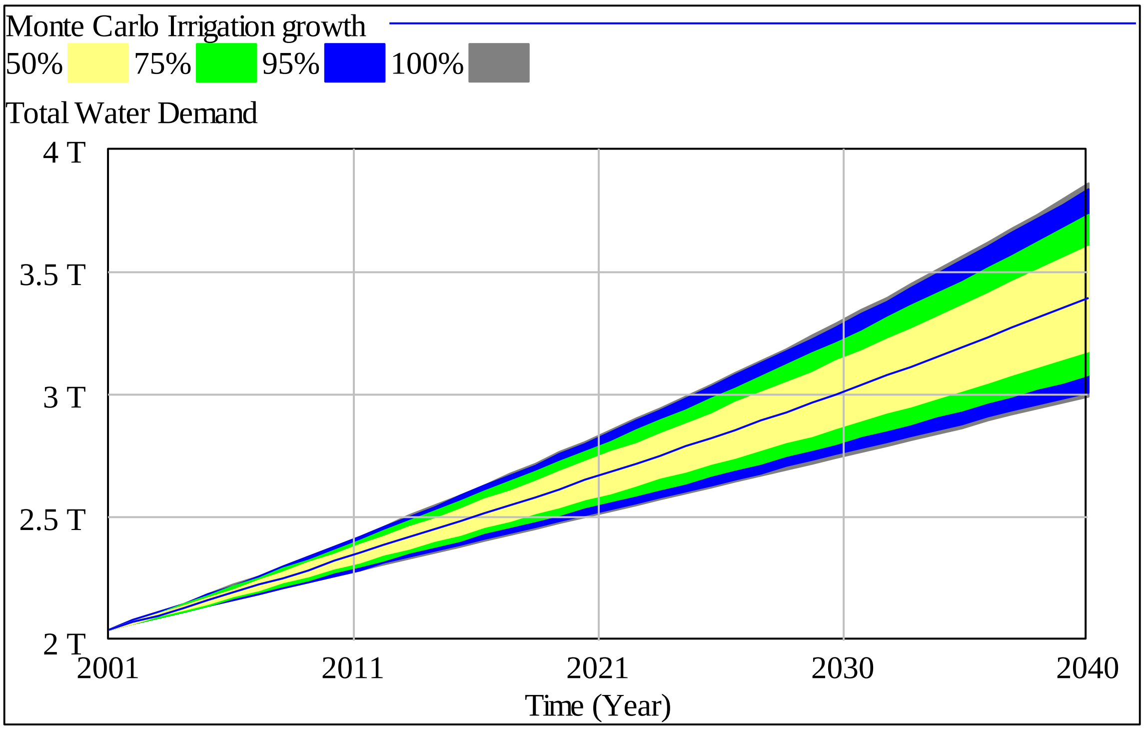

Figure C-3: Total water demand when the irrigation growth factor is changed

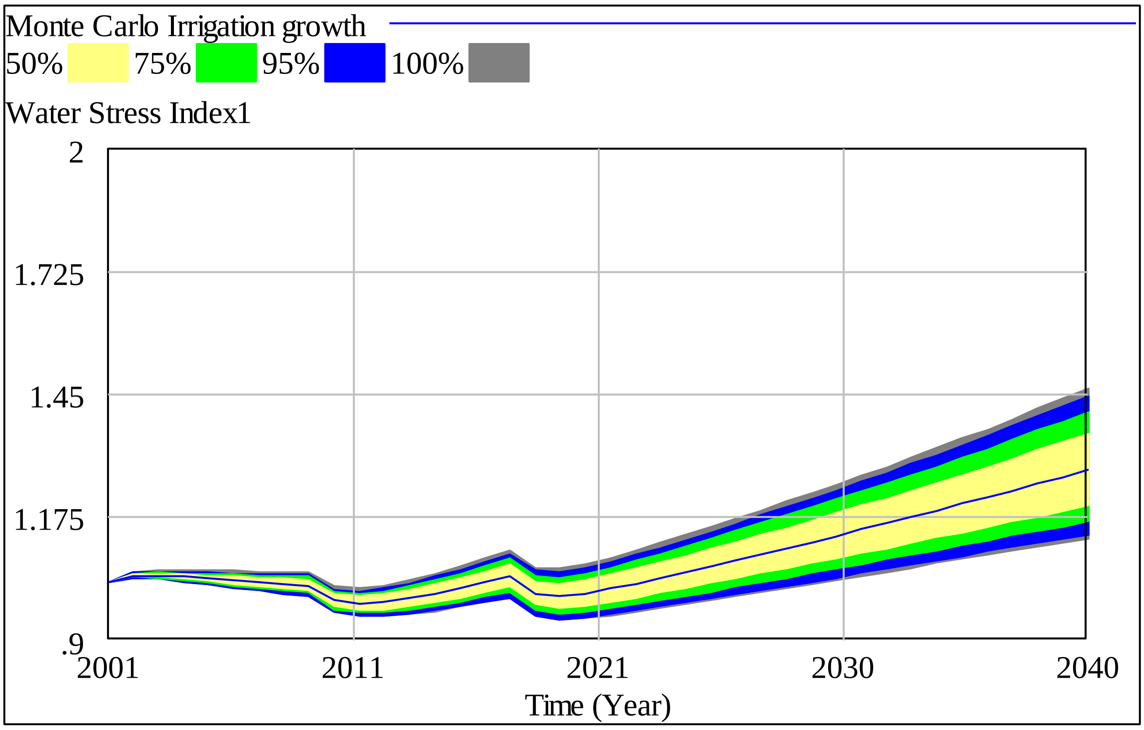

Figure C-4: Water Stress Index when the irrigation growth factor is changed

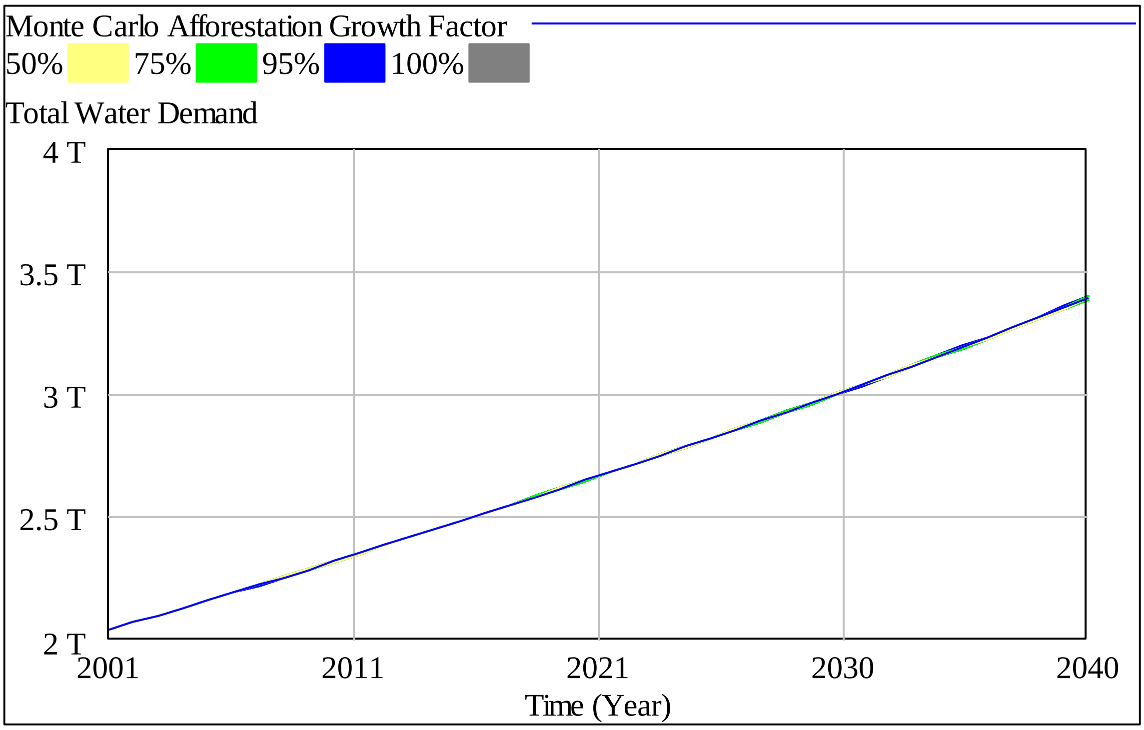

Figure C-5: Total water demand when the afforestation growth factor is changed

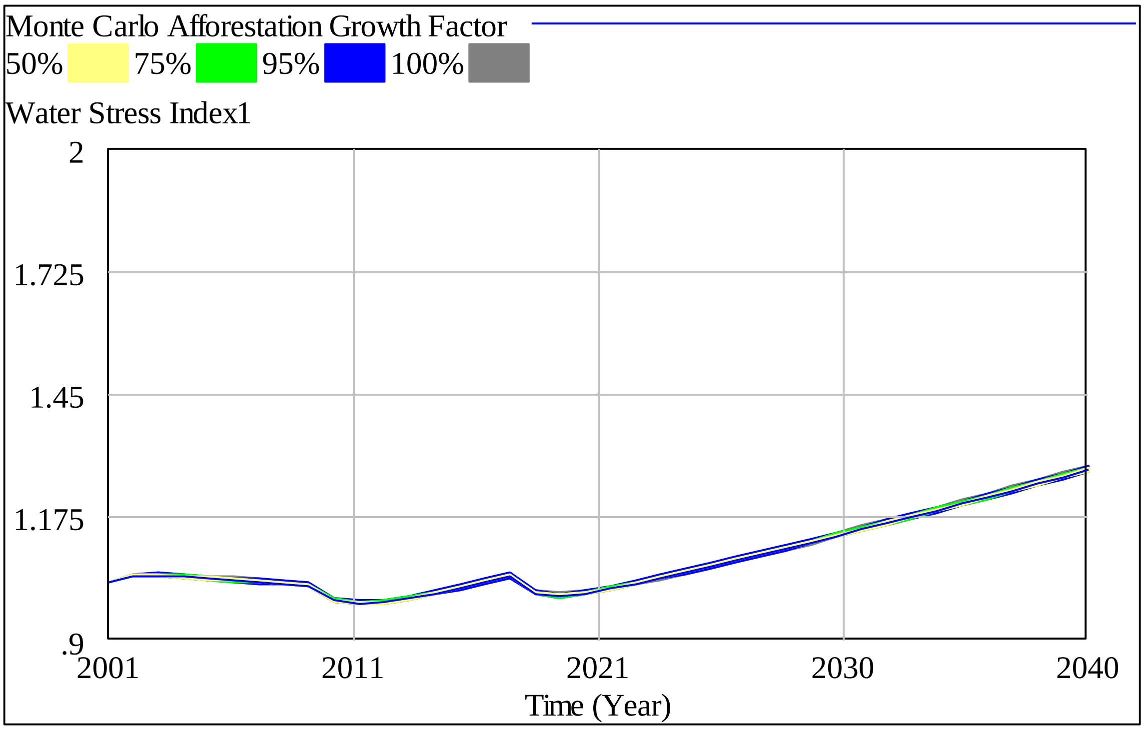

Figure C-6: Water Stress Index when the afforestation growth factor is changed

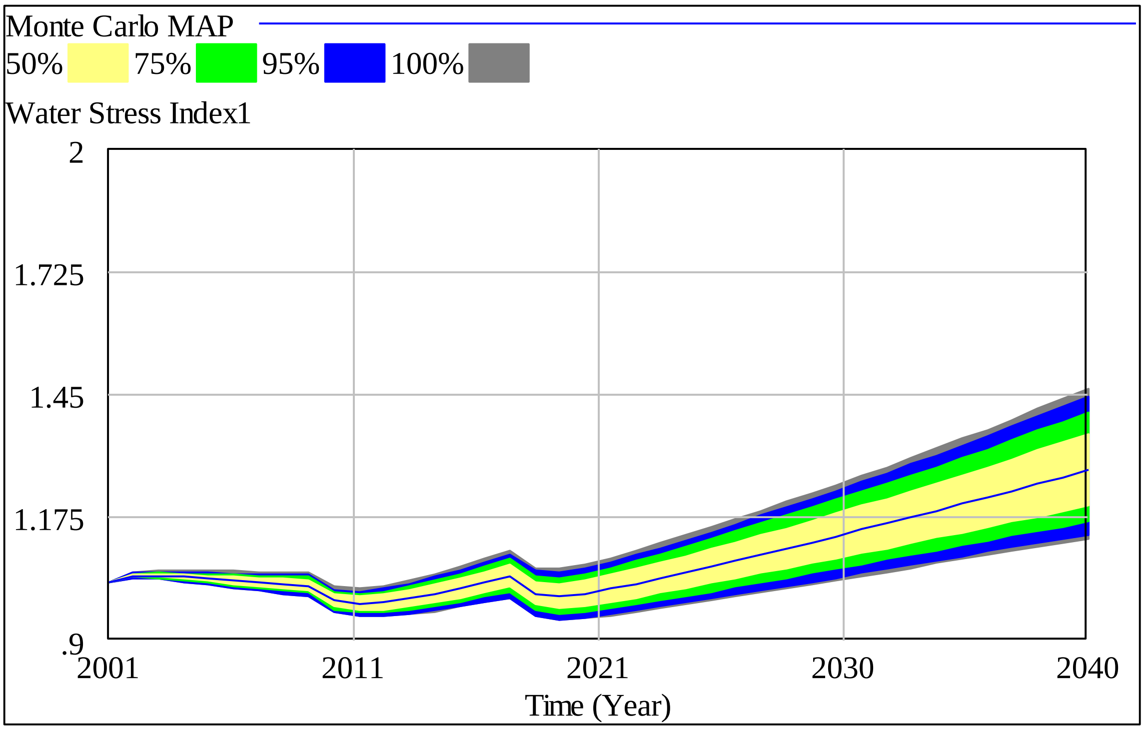

Figure C-7: Water Stress Index when MAP is changed

APPENDIX D

D. Total supply and demand results for each scenario

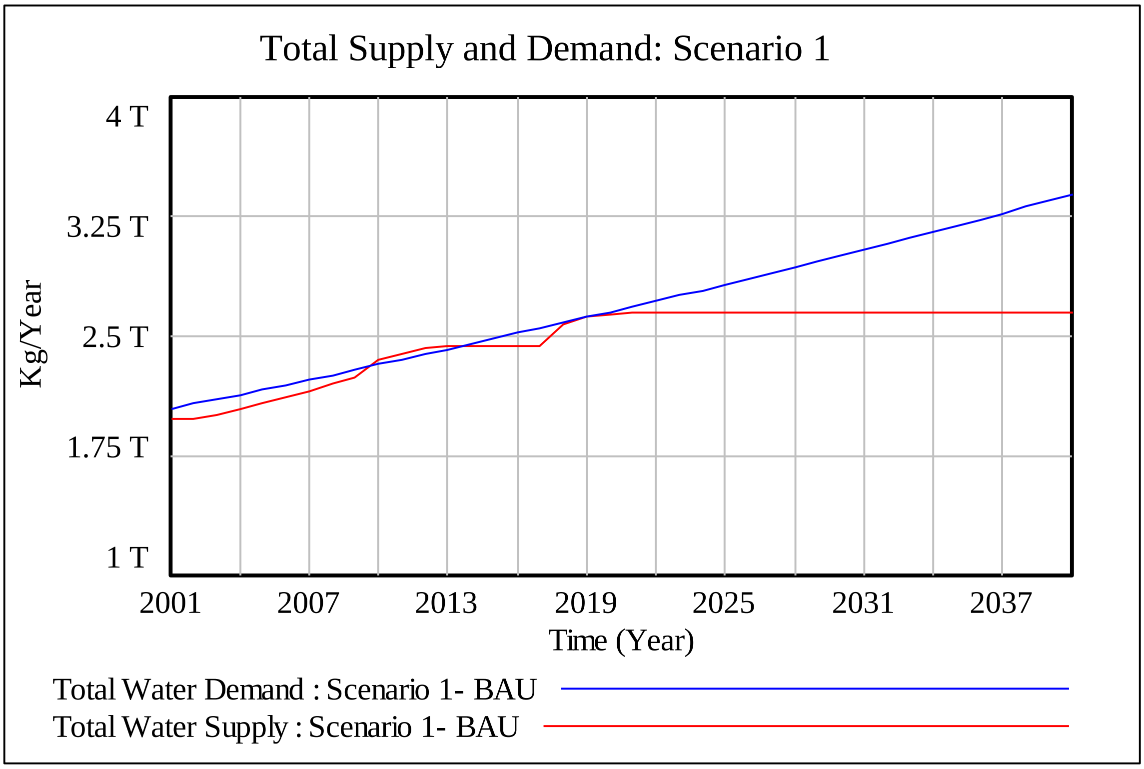

Figure D-1: Total Supply and Demand: Scenario 1

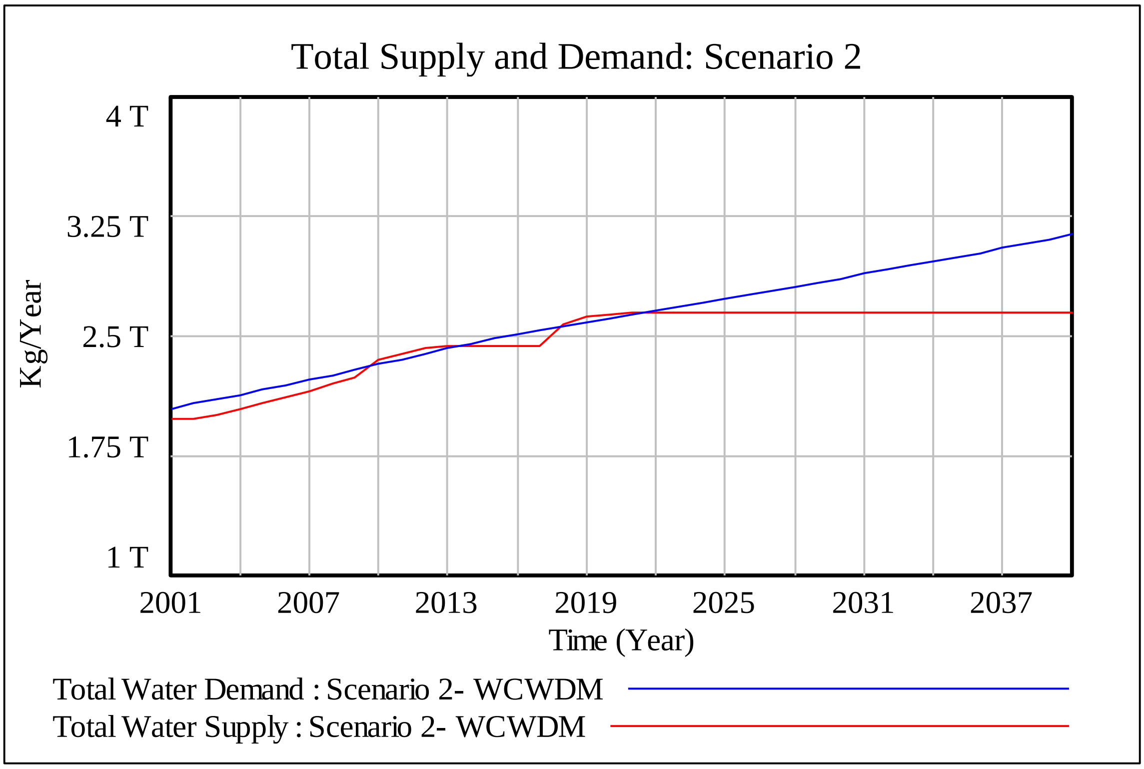

Figure D-2: Total Supply and Demand: Scenario 2

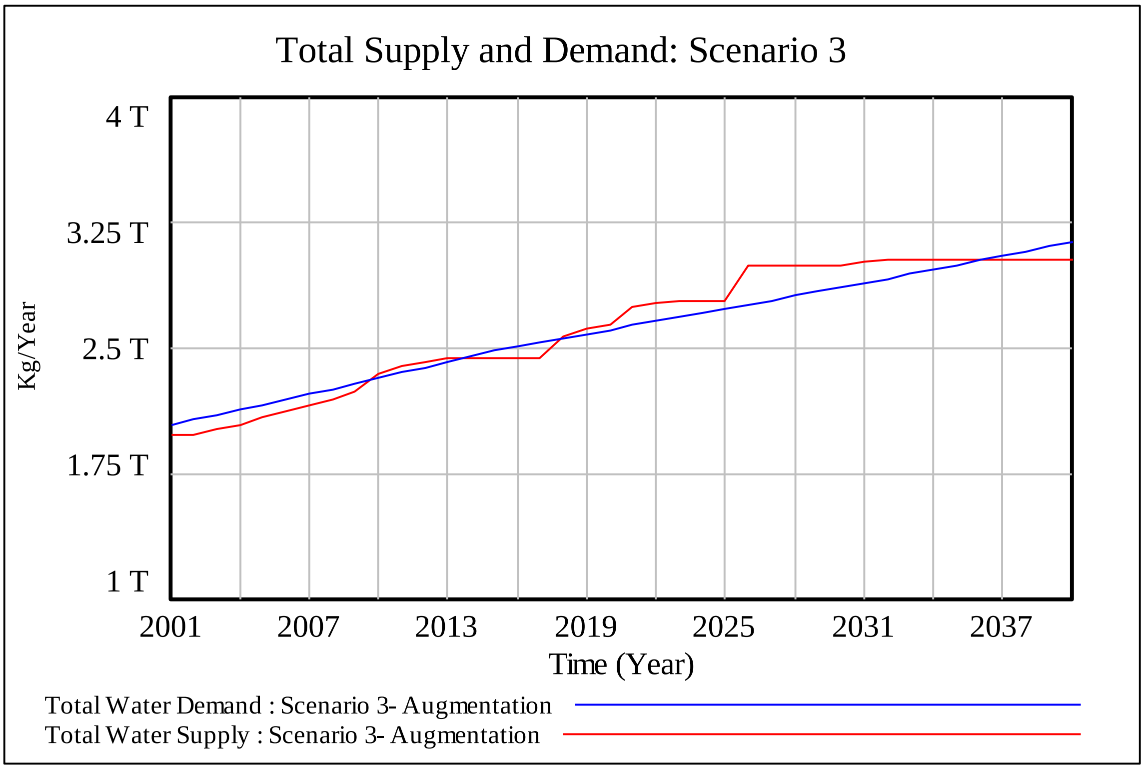

Figure D-3: Total Supply and Demand: Scenario 3

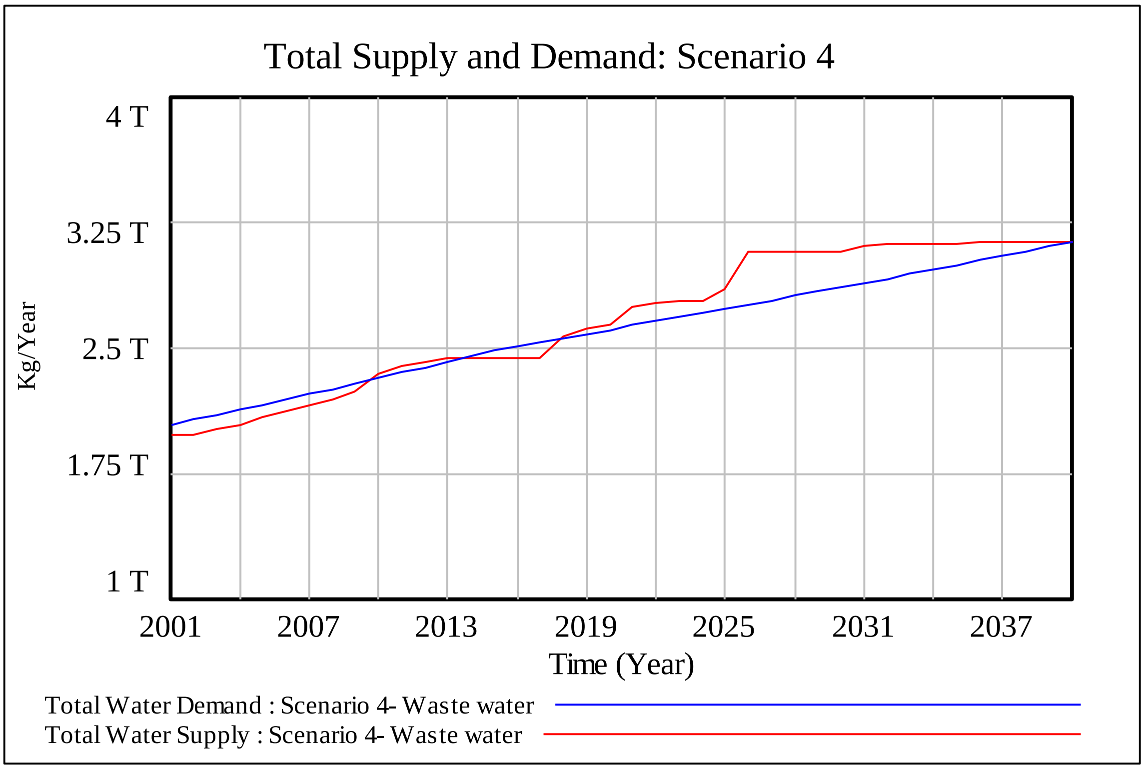

Figure D-4: Total Supply and Demand: Scenario 4

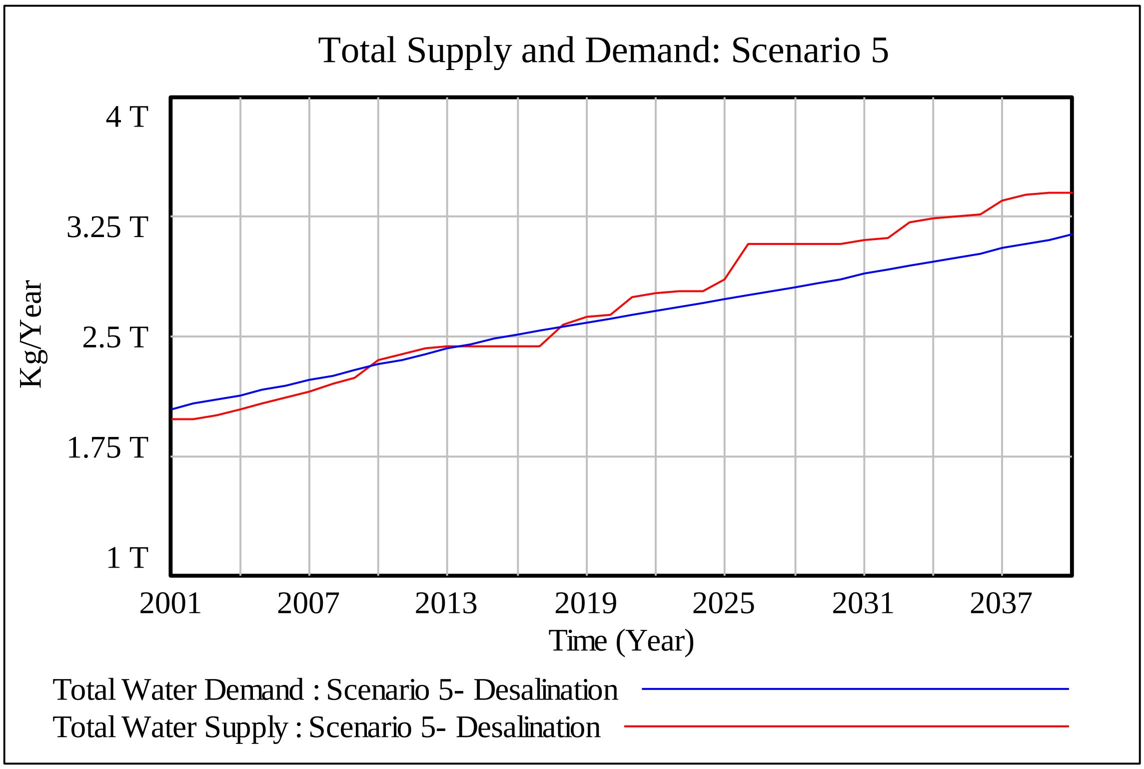

Figure D-5: Total Supply and Demand: Scenario 5

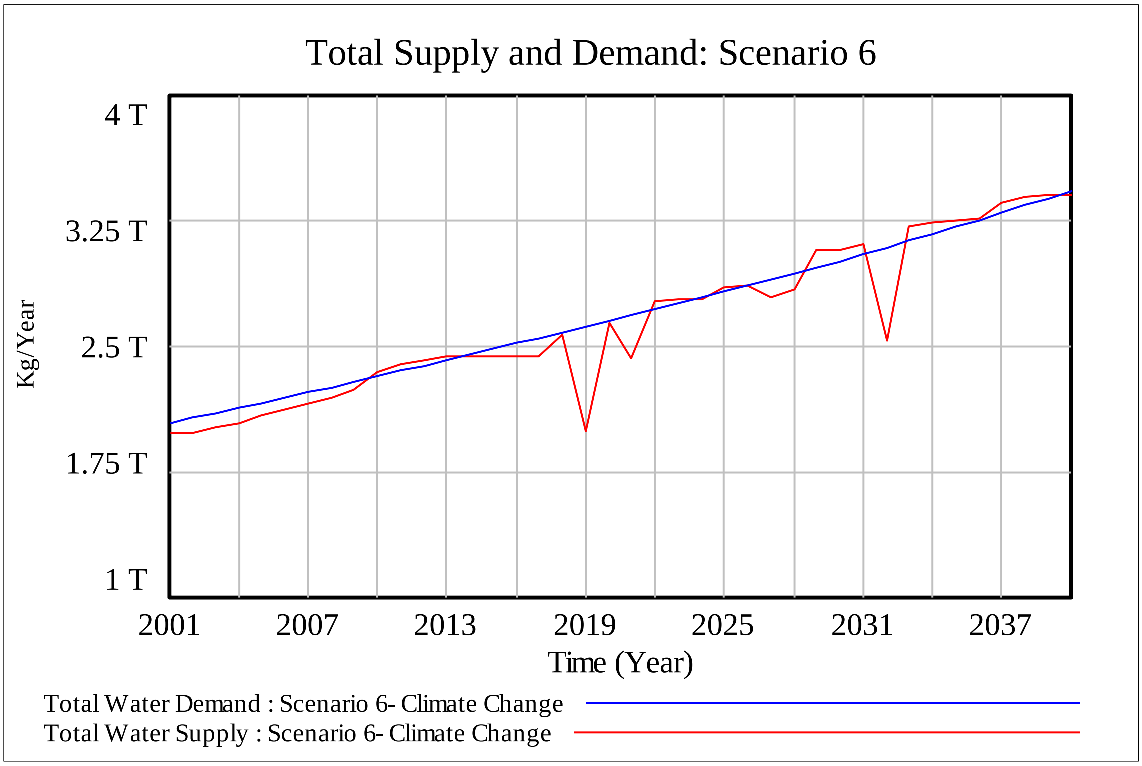

Figure D-6: Total Supply and Demand: Scenario 6