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THE ROLE OF OPEN-ACCESS HYDROLOGICAL INFORMATION SYSTEMS IN WATER SECURITY RISK ASSESSMENT IN CAPE TOWN

by

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DECLARATION

I, MARIUS VAN DER MERWE, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed____________________ Date 18 November 2021

ABSTRACT

The City of Cape Town (CCT) faces the prospect of an uncertain water future due to climate change, increasing demands, and delayed interventions. Augmentation and diversification of water resources have been mostly reactive, which resulted in the drought experienced since 2015 and culminated in the threat of “Day Zero” in 2018. The impact of the drought was experienced across domestic, business and agricultural domains, with immeasurable direct short-, medium- and long-term financial implications.

With water being a mobile common pool resource, achieving water security (WS) requires a flexible and dynamic approach. The aim of this research was to assess the water security *status quo* versus the impact of the proposed water augmentation projects of the New Water Programme, and to determine the relative risk impact of the augmentation projects to water security by identifying and ranking the related risk factors.

The research followed a quantitative systematic empirical investigation within a positivist paradigm to produce a water security risk assessment using open-access hydrological information systems (HISs). Archival data collection was adopted as instrument to review secondary quantitative data resources available in the public domain, with no human participation and no significant ethical implications.

The findings present a dynamic water security risk assessment for the CCT that confirms water security during normal rainfall years through augmentation projects reducing Cape Town’s dependence on supply from the Western Cape Water Supply System (WCWSS). The risk analysis found population growth as the biggest threat to WS and water re-use as the most positive contributor to future WS.

The research results are aligned with the objectives of the Western Cape Water Supply System Reconciliation Strategy, which are to reconcile future water requirements with supply for a 25-year planning horizon, and to provide a framework for decision-making with regard to both securing supply and managing demand.

Keywords: Water Security, Dynamic Framework, Integrated Water Resource Management, Open-Access Hydrological Information Systems, Relative Risk Model

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GLOSSARY

Acronym/Abbreviation	Full Word/Term
A	Agriculture Water Use Indicator
CCT	City of Cape Town
CHANS	Coupled Human and Natural Systems
CW	Consumption Water Indicator
DFWS	Dynamic Framework for Water Security
DWS	Department of Water and Sanitation
ERA	Environmental Risk Assessment
FAO	Food and Agriculture Organisation
GWP	Global Water Partnership
HIS	Hydrological Information System
HWYA	High Water Yield Area
I	Industrial Water Use Indicator
IWRM	Integrated Water Resource Management
MODIS	Moderate Resolution Imaging Spectroradiometer
N	Natural Ecosystem Indicator
NIWIS	National Integrated Water Information System
NWP	New Water Programme
(P+I)	Precipitation and Imported Water Indicator
PW/(P+I)	Water Resources Utilisation Intensity Indicator
PW	Production Water Indicator
Q	Water Flow from Basin Indicator
RQ	Research Question
RRA	Relative Risk Assessment
RRM	Relative Risk Model
MAIS	Water Monitoring & Assessment Information System
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SAWS	South African Weather Service
TT	Trade and Technology Indicator
U	Non-Agricultural Water Use Indicator
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WCWSS	Western Cape Water Supply System

Acronym/Abbreviation	Full Word/Term
WHYCOS	World Hydrological Cycle Observing System
WMA	Water Management Area
WMO	World Meteorological Organisation
WRC	Water Research Commission
WS	Water Security

CHAPTER 1: INTRODUCTION

1.1 Introduction

The declaration of a provincial disaster by the national government in March 2018 placed the focus on how deeply dependent humans and the environment are on the availability of water. This declaration led to the introduction of severe water restriction for the City of Cape Town (CCT) and larger Western Cape. The societal and economic disruption created by these restrictions need to be prevented through careful planning and pro-active political governance. The successful determination of Water Security whereby dynamic indices are incorporated and available human-natural hydrological information is utilised, will support quality short- and medium-term decisions.

The term ‘Water Security’ abbreviated as ‘WS’, has evolved ever since its debut on the world stage in the 1990s. Grey and Sadoff (2007:2) identified WS as “the reliable availability of an acceptable quantity and quality of water for health, livelihoods and production, coupled with an acceptable level of water-related risk”. The new millennium saw the introduction of an integrative WS definition by the Global Water Partnership (GWP), which includes the affordability of water, social requirements and environmental wellbeing (Cook & Bakker, 2016). Tindall and Campbell (2010) posit that the most likely water insecure places are those with low, variable rainfall and rapid population growth.

The definition of WS has been expanded over a 15-year time period, from 2006 to 2020, to include the concepts of ‘broad’ and ‘applied’ (section 2.2), where broad is defined as including four themes, namely: (i) water availability, defining the volume of exploitable water resources available; (ii) human susceptibility to water-related threats; (iii) human requirements specifically focused on food security and developmental needs; and (iv) sustainability of the water resource in relation to these demands made on it (Pahl-Wostl et al., 2016:3). Applied is defined in terms of the exploration of challenges at regional level, all within the geographical spatial domain of the CCT (Pahl-Wostl et al., 2016:3).

According to Chevalier and Chase (2016), Southern Africa in particular is vulnerable due to its highly seasonal and variable rainfall. From a South African perspective, our freshwater resources are predominantly surface water, which is totally dependent on an annual average precipitation of 490 mm per year, less than half of the world’s average precipitation by comparison (World Wildlife Fund, 2016).

Almost all, in fact 15 billion m^3 or 98%, of South Africa's available water supply has already been allocated for use at a high assurance of supply with demand estimated to grow to 17.7 billion m^3 (116%) of current supply capacity by 2030 (City of Cape Town, 2018b; World Wildlife Fund, 2016). The CCT relies on rain-fed dams of the Western Cape Water Supply System (WCWSS), a cohesive provincial surface-water scheme administered by the nationwide Department of Water and Sanitation for 96% of its raw water supply (City of Cape Town, 2019a). Cape Town's water is supplied via comparatively minor catchments which are susceptible to regional dry periods. Studies conducted from 2010 to 2016 demonstrate that limited precipitation is just one element of the dilemma (Muller, 2017; Visser, 2018). The increased water consumption is just as important as the limited rainfall (City of Cape Town, 2017a).

This research is significant because according to the CCT Water Strategy of 2019, the only viable supplementary supply options still available to the CCT are increased inter-catchment transfers and storage, desalination, groundwater abstraction, water re-use and sectoral re-allocations (City Of Cape Town, 2019a). However, increased surface storage capacity will be negatively affected by the rate of potential evaporation that is estimated at three times the average rainfall for South Africa (World Wildlife Fund, 2016).

The principle aim of this research was to explore the status quo of WS for the CCT by using the Dynamic Framework for Water Security (DFWS) and the role of open-access hydrological information systems (HISs) in a WS risk assessment for Cape Town. The research expands the WS framework (Table 3.5) by incorporating the effect of the Western Cape Water Reconciliation Strategy (City of Cape Town, 2017b) and the proposed CCT water augmentation projects.

1.2 Background to the Water Security (WS) of Cape Town

Since 1995, Cape Town's inhabitants has increased by 79%, from roughly 2.4 million to an estimated 4.3 million in 2018. Over the equivalent period, water storage capacity has improved by 15% (Bohatch, 2017). Strategic water resource management is based on the balancing of supply and demand, therefore one of the keys to strategic water resource management lies in effective demand-side approaches (Siebrits et al., 2014). The relationship between water supply and demand translates to WS. WS can be defined as an indicator that pursues a equilibrium among the driving forces of society, economy and the natural environment (Muller, 2018; Somlyódy & Varis, 2006; United Nations, 2015a). To achieve this, a better understanding of how water is currently used is required to incentivise the use of resources in smarter ways (De Lange et al., 2010; Srinivasan et al., 2017).

WS is a multi-faceted challenge going beyond the simple weighing of supply and demand (Cook & Bakker, 2016). Previous endeavours to quantify WS depended on static index-based methodologies, water resource availability, rainfall and water demand. These earlier efforts neglected to acknowledge WS in the light of outcomes caused by anthropogenic impact on a water system. Previous attempts to the quantification of WS failed to represent the expanding spatial specialisation in the contemporary world. Whatever people consume and what they produce are progressively unconnected (Hoekstra & Mekonnen, 2011).

The conventional approach to WS as conceptualised by global agencies such as the United Nations Development Programme (UNDP) and Global Water Partnership (GWP) was to measure WS as a marker or indicator. This indicator signified a picture at singular location and timeframe, therefore providing no historical reference or predictive insight – a limitation questioned by scholars (Savenije, 2000; Savenije & Van Der Zaag, 2002). The quantification of WS in different spatial spheres, applying different frameworks and diffident indices is not new. In fact, several authors (Sullivan, 2002; Padowski et al., 2015; Hoekstra et al., 2018) have used different frameworks and indices.

Despite the existence of emphatic environmental and climate change legislation in South Africa, it is not enough to solve the demand challenges. Required is functional local knowledge engagement with a variety of role-players through mutual and transgressive learning (Vogel et al., 2016; Srinivasan et al., 2017; Meissner et al., 2018a; Rawlins, 2019). Changes to sustainability can take place if citizens have the understand of making adjustments at slight action level, which can lead to broader collective shifts and government transformations, in particular if such methods of understanding develop to be more collective (Muller, 2017; Lotz-Sisitka et al., 2016). Radical societal changes and transformation are considered necessary for a meaningful climate change response to achieve sustainability. Thus, citizens the world over will be required to transform their lifestyles in ways that are socially just, peaceful and ecologically sustainable (Lotz-Sisitka et al., 2016; Ololade et al., 2017; McNabb, 2019).

A narrow interpretation of WS focuses on the needs of a singular focus group or sector, whereas in its broadest incarnation WS can help create an understanding of the complexity, non-linearity, teleconnections and systemic nature of the water-human system (Pahl-Wostl et al., 2016). A broader application of WS may assist in providing a better systemic understanding of the issue, even though researching or implementing such a broad application may be complex (Cook & Bakker, 2016). The achievement of this goal may complement the Integrated Water Resource Management (IWRM) paradigm (Cook & Bakker, 2016).

To comprehensively understand the true WS status of Cape Town, further studies are required applying spatial scaling to the Water Management Area of Cape Town, inclusive of all regional and non-regional water receipts (Mekonnen & Hoekstra, 2016; Rushforth & Ruddell, 2016; Muller, 2017; Visser 2018). The scale of hydrological variability greatly influences the analysis of WS. Vörösmarty et al. (2010) describe the importance of scaling in comparing inter-country scaling where a country can be considered as water secure to intra-country scaling, while a region in that same country may be considered water insecure. Srinivasan et al. (2017) developed a dynamic approach to framing WS as a connected human-water approach to answer the critique of stagnant indicators and explain the interaction between human and water systems as well as the numerous routes by which these structures co-develop.

It is thus equally sensible and correct for the CCT to consider the hazards of general weather transformation during its strategising. Planning should be done along the universal best-practice methodology for seaside cities, where the CCT's resilience is augmented via the transformation of dependence for water supply away from surface water exclusively. This can be achieved by aiming in the direction where the Metropole acquires a bigger percentage of its supply from aquifers, water re-cycling and desalination (City of Cape Town, 2019a). Accordingly, a water-resilient city will then be enabled to augment and sustain its existing water supply through the integrated management of more diverse sources. In the case of the CCT, these supply sources can be divided into four distinct supplies, namely: storage facilities created by wetlands and dams fed by rainwater and urban storm water run-off, water from aquifers (with recharge), recycled raw and wastewater, and purified seawater (City of Cape Town, 2017a; News24, 2018; Luker & Rodina, 2017; Malaza & Maduba, 2019; Muller, 2017; Visser. 2018; City of Cape Town, 2019a).

Despite the adequate storage capacity of the six major dams of the WCWSS of about 900 million cubic meters of water, all are rain-fed and thus exposed to the vagaries of rainfall and potential evaporation because of climate change. Of the 'new sources' of water earmarked by the water augmentation projects (groundwater, wastewater recycling and desalination), only desalination is completely unaffected by precipitation (Western Cape Government. 2012; City of Cape Town, 2017b). The volume of supplementary resources considered necessary to realise a reliable resource depends predominantly on an assessment of risk tolerance and expectations associated with the rainfall potential across the High Water Yield Area (HWYA) catchments. Comprehensive modelling has been carried out established on accessible historic precipitation data, and hydrological data established on future macro-, meso- and microclimate change projections. The current projection results propose that using a process involving a randomly determined sequence of events, supplementing current volumes with 50 to 100 million litres per day, would be adequate. This scenario assumes a 1 in 200 level of assurance based on part rainfall data and does not consider probable precipitation fluctuations (City of Cape Town, 2017b).

If the exceptionally limited precipitation of the previous three-year period is projected to persist into the foreseeable future, an additional 200 to 250 Mℓ/d (megalitres per day) will be required. This additional volume is essential if a minimum dam level of 25% at the end of summer is required to offer a margin of security against late or less rains during the ensuing rainy season. Any increase over and above 25% would improve levels of assurance and result in *excess water* to downstream users and the ecological reserve via recurrent dam spillages during the wet season. This presents a risk averse scenario that appears to provide the CCT with a suitably higher confidence of supply status, preventing the method of water-restrictions presently experienced from being applied in the near future (Pohl et al., 2014).

Additional modelling that utilises precipitation forecasts from world-wide climate models is at this time being undertaken by various agents to inform the City’s decision making. This is achieved by considering the pattern of shifting weather impacts with environmental unpredictability. This, in turn, represents a combination of the climate change risk assessments with randomly determined sequences of time series rainfall events. Moreover, the CCT’s water supplementation plans are based on extended-term expansion projects aiming to produce 350 Mℓ/d (Parliamentary Monitoring Group, 2018; City of Cape Town, 2019a).

1.3 Problem statement

Unforeseen drought, demand increases, and delayed interventions contribute to the current (2017-2019) water crisis in the Western Cape and, more specifically, in the greater CCT region (Cameron & Katzschner, 2016; Fisher-Jeffes et al., 2017). Moreover, Ziervogel (2019) states that inadequate support from national government through delayed responses, funding and lack of leadership has further exacerbated an already tenuous situation. During the course of the drought, it was evident that precipitous alternative management input was required to successfully mitigate a fluctuating water system and shifting water demand. Furthermore, the lack of coordinated decisions based on quality information contributed to the water shortage problem. This is despite the fact that large open-access hydrological information exists for decision makers to utilise.

The impact of the drought, delayed interventions and doubtful decisions led to severe economic and social challenges for the people of Cape Town. Debate exists about the efficacy and timing of several interventions. These vary from supplementary new surface storage facilities and aquifer exploration, as well as waste water recycling and re-use to the purification of seawater. All these options are presently in play to mitigate the present situation, even though they are mostly reactive (Siebrits et al., 2014, Meissner & Jacobs, 2016; Muller, 2017). Siebrits et al. (2014) argue that South Africa will continue to experience a water deficit that necessitates critical management interventions. This is supported by Meissner and Jacobs (2016), stating that WS concepts in South Africa are directly related to other material needs such as energy and food. Muller (2017) contends that for the next couple of years, the CCT and other consumers dependent on the Western Cape Water Supply System (WCWSS) for raw-water provision will be exposed to the unpredictability of climate-change.

Srinivasan et al. (2017) suggest that the sum of the cross-dependencies among human-natural systems every so often lead to evolving patterns of form, function and dynamics. This dynamic combination then results in surprises not predictable from the expertise of the behaviour of the individual components. Although issues relating to WS has featured prominently in the South African media, not many academics have published about WS in the general from a South African and CCT perspective (Funke et al., 2019).

In presenting the DFWS, Srinivasan et al. (2017) recommend the application of the framework to different spatial scales. No literature on the application of the DFWS incorporating the risk assessment methodology of the Relative Risk Model (RRM) with specific reference to the CCT, could be found during the literature review. The accessibility and diverse open-access sources of water-related data from statutory HISs allow for cost and time effective data collection over a longitudinal time frame of 20 years. As such, the role that open-access HISs can play in the interrelatedness of human-natural influences on the decision-making processes, is unclear.

1.4 Aim and objectives of the research

1.4.1 Aim

The aim of this research was to explore how open-access hydrological information systems can be used for decision making on WS. A second aim was to explore the effect of the water augmentation projects proposed by the New Water Programme. The research furthermore explored the related risk factors of water produced and consumed within the spatial boundaries of the CCT. A further aim was to explore how the open-access hydrological information systems can be applied to the interrelatedness of the human-natural influences on the decision-making processes.

1.4.2 Objectives

i) To examine the influence of the coupled human-water system, utilising the DFWS to determine the WS status in order to expand the timeframe of the framework to incorporate the water augmentation projects of the New Water Programme by integrating all open source hydrological information and producing an integrated WS status for Cape Town.

ii) To bridge this knowledge gap by applying and expanding the Dynamic Framework over a 20-year time frame to address historical as well as possible future WS for Cape Town, and to address these indices for their risk to WS for the CCT through the Relative Risk Model.

iii) To address critiques of static indices by accounting for both the interconnectedness between human and water systems and the varied pathways by which these systems co-evolve over the chosen time period.

iv) To frame and propose WS as an outcome of a coupled human-natural water systems along the precepts of Srinivasan et al. (2017), who proposed that human adaption to environmental change and increasing spatial specialisation in the modern world necessitate a more flexible and dynamic view of WS.

v) To determine the risk elements associated with the WS status of the CCT and contribute to the IWRM of the CCT by means of a proposed guideline or improved DFWS to contribute and build on the knowledge base and a better understanding of the economic, social, biophysical, technological and institutional influencers of the current and future WS of the CCT.

1.5 Research hypothesis

This research is based on the hypothesis that the extremity of the drought conditions experienced by the CCT during the 2015-2018 period has been caused by climate change, human action, dependence on a singular source, and a lack of source diversification.

The reactivity to mitigate the drought impact could have been averted with WS risk assessments in the spatial domain of water produced versus water consumed by utilising open-source HISs. The implementation of the WS risk assessment may contribute to timeous and effective diversification of water resource planning.

1.6 Research questions

1.6.1 Research Question 1 (RQ1)

RQ1: What is the current WS status of the CCT versus the WS impact of the proposed augmentation options as proposed by the New Water Programme?

The objective of RQ1 was to examine the WS indicators available from the latest literature and their applicability to the Water Management Area (WMA) of Cape Town, and then to select and examine the influence of these indicators on the coupled human-water system of Cape Town. The determined WS status may enable water managers to apply focus and resources more effectively.

1.6.2 Sub-Research Question 1 (Sub-RQ1)

Sub-RQ1: What is the impact or influence of the augmentation projects of the CCT's New Water Plan on the historical and current WS status of the CCT?

The objective of Sub-RQ1 was to examine the influence of augmentation projects on the historical and current status of WS by including indicators representing the coupled human-water influence on the water supply network of Cape Town. The method employed was a quantitative systematic empirical investigation of WS indicators using a DFWS.

1.6.3 Research Question 2 (RQ2)

RQ2: What are the risk elements associated with the WS status of the CCT's augmentation options proposed by the New Water Programme?

The objective of the question was to examine the WS indicators selected and determine and rank the risk elements of the WS status of the CCT using Relative Risk Assessment (RRA). The method employed was a Regional-Scale Risk Assessment analysis using the Relative Risk Model (RRM).

1.7 Research design and methodology

The word paradigm originated from the Greek word *'paradeigma'* meaning *pattern* and was originally used by Thomas Kuhn (1962) to represent a theoretical framework. This framework, used collectively by a group of scientists, provided them with a suitable model for studying problems and discovering solutions. Kuhn (1962:176) characterises a paradigm as "an integrated cluster of substantive concepts, variables and problems attached with corresponding methodological approaches and tools". The term paradigm implies a research culture with a set of common beliefs, values, and assumptions shared by a community of researchers regarding the nature and conduct of research (Kuhn, 1977). A paradigm henceforth suggests an outline or configuration, a composition and structure or arrangement of scientific and academic concepts, principles and beliefs, according to Olsen et al. (1992). This research followed a quantitative systematic empirical investigation within a positivist paradigm into the WS of the Water Management Area of the CCT.

The methodology was applied as an outcome-based or solution-oriented business information technology research method. Data were collected from open-source HISs, census surveys, and other relevant data in the public domain, and then assimilated to produce an integrated WS status for the CCT. Precipitation (P), water entering the Water Management Area (WMA) of the CCT either naturally or through Infrastructure (I), Agricultural Water Use (A), Industrial/Commercial Use (U), Water Outflow from the WMA of the CCT (Q), Ecosystem Usage (N), and Trade and Technology (TT) investment have been determined from data sources available in the public domain.

The data were abstracted using an annual interval to represent changes over time. Water-related parameters were expressed in units of volume and infrastructure investments in units of currency, and results expressed as ratios were used. The expression of results in ratio rather than difference enabled reporting to be scale independent, per internal and external water theory as offered by Hoekstra and Mekonnen (2011). Plotting the variables PW, CW, PW/(P+I) and TT against each other provided a graphical representation of WS.

The Relative Risk Assessment (RRA) includes several major steps, which parallels the accepted Environmental Risk Assessment (ERA) process. These include, firstly, the identification of the decision criteria as defined by the RQ; secondly, the gathering of information from the data available in the public domain; and thirdly, interpreting the information by processing using the Relative Risk Model (RRM), such as the Monte Carlo Analysis (MCA). RRA risk assessments may be utilised to calculate the probability of potential (prospective) outcomes or calculate the probability that outcomes are produced via historical influence by stressors (retrospective).

WS from a positivist paradigm refers to measurable and tangible water-related risks. These include, but are not limited to risks such as droughts, floods, pollution and water demand as management practice.

1.8 Research philosophy

1.8.1 Ontology

This research was viewed via the philosophical approach of ontology and epistemology. Business research through the ontological perspective can be defined as the science or research of being and it deals with the nature of reality (Blaikie, 2010). The ontological belief system represents an individual’s perspective on what constitutes a fact.

Between the central questions of whether social entities should be perceived as objective or subjective, this research followed the objective approach. Objectivism represents the view that social objects exist in reality isolation from social actors concerned with their presence (Saunders et al., 2012). Alternatively, objectivism is an ontological position stating that societal singularities and their meanings have a presence autonomous of social actors (Bryman, 2012).

The objectivist research philosophy (ontology) guided the researcher’s interpretation of the nature of realism or being, believing that the reality of WS exists externally, objectively, and independent of social actors. The WS status of the WMA/WCWSS of the CCT is discoverable and comprehensible. The WS reality exists objectively and externally and an objectivist ontology for this research was therefore followed.

1.8.2 Epistemology

The positivist research paradigm was followed in the belief that knowledge is acceptable if founded on interpretations of the external reality and that these observations are independent of social actors. The positivist paradigm selected for this research is suitable in its approach as it relies on facts and quantitative data.

WS in the positivist paradigm context is measurable as the lack of risks based on the presence of real and independent risks (Harrington, 2013). Using the positivist approach to guarantee WS, quantifiable parameters are required and utilised to inform and improve water conservation/water demand management. The researcher was independent of the subject and could objectively measure WS without affecting it.

1.8.3 Research approach

The deductive research approach for this research was preferred because of the availability of open-access information sources, both current and historical, the short time frame available to complete the research, and because it was suitable to explore a known phenomenon and test the WS theory in the Water Management Area of Cape Town.

1.8.4 Research strategy

This research followed a quantitative research strategy, accessing primary databases containing open-access hydrological information and using exact water and water-related indicators, combined with secondary research data from published works and online data to measure WS within the spatial domain and geographic boundaries of the CCT. Factors affecting WS were identified and the threats to WS were predicted, identified and managed. Research activities included the recognition of variable indicators and indices to calculate the real water status in terms of WS and processing these indicators and indices through the DFWS, as proposed by Srinivasan et al. (2017).

1.9 Unit of analysis

The unit of analysis was identified as WS, represented by a ratio (Ratio Scale) to make it scale-independent, and by the relative risk (RR) measurement.

1.10 Data collection

The data collection method was a rigid, well laid out procedure that focused on quantitative research resources available in the public domain. The procedure followed focused on secondary data collection from institutional archive repositories, libraries and online resources. This was done by examining data and records of environmental data, physical resource data, and infrastructure and economic records.

Parameters explored in the open-sourced hydrological data include population census, financial and infrastructure data, as well as water volumes associated with precipitation, infrastructure, agriculture, non-agriculture, outflow, water used by natural ecosystems, production water footprint, direct human-beneficial abstraction, consumptive water use footprint.

A longitudinal time horizon was determined after the data were tested over various time frames, and the data gaps were identified. Applicable current and historical data available in the public domain were identified and mined. Annual cumulative data were collected for the period 1998-2017. This time frame was identified as a critical period for water management decisions for the CCT by both the South African National Biodiversity Institute in 2005 and the 2010 DWA analysis of the Integrated Water Resource Planning for South Africa.

1.11 Sampling

Samples were collected from open-sourced, publicly available HISs, including HPS-WINS, SASSCAL, SANCIAHS-MAIS, MODIS, WHYCOS, academic institutions, national and local government, and published work. The research was conducted using a non-random sampling process. The data source was relatively large and selected to enable the generalisation of findings. The sampling universe consisted of all open-sourced hydrological, environmental and census data applicable to the WS of the CCT. The samples collected covered annual totals of the WS parameters for the period 1998-2017, which consisted of 11 parameters tabulated in Appendix B, measured over 20 years, from 2006-2026.

1.12 Data analysis

Data available through open-access HISs were collected, analysed and presented in a twofold deliverable. To supplement the available bio-physical data, related data available from grey and published-peer reviewed data were collated. The data were analysed by first applying and expanding the DFWS as proposed by Srinivasan et al. (2017) (Table 3.4; Table 3.5). A second processing of the findings of the DFWS was then done through a Regional-Scale Risk Assessment using the BN-RRM methodology (Ayre & Landis, 2012; O'Brien & Wepener, 2012). The second deliverable explored the associated risk elements by further processing the results through a probability risk assessment process as described by the Regional-Scale Risk Assessment methodology. Data obtained from the Dynamic Framework for Water Security (DFWS) was further analysed using the RRM assessment tool in order to rank the risk factors contributing to the WS status of Cape Town.

1.13 Ethics

This research had no significant ethical implications as stated by the Ethics Committee of the University of Cape Town’s (UCT) Faculty of Commerce (UCT, 2019):

i) No human participants were used as a data source for this research.
ii) The possibility that this research could be harmful to any person or third party is negligible.
iii) This research did not involve any community participation.
iv) No service to a community was provided by this research.
v) This research was not sponsored, therefore no conflict of interest was declared.
vi) This research did not involve the field of Health nor did it have any association with it.

1.14 WS risk assessment for Cape Town

The multi-faceted aspects of the challenge to determine the WS status of any one place require a dynamic approach that must be delineated, calculated and comprehended beyond only physical water scarcity (Srinivasan et al., 2017). The shortcomings of early definitions and indices of WS include ignorance of cross-scale feedback between people, groundwater, and surface water systems (Srinivasan et al., 2013). Because production and consumption of energy, food, goods and services are not bound to a local water footprint and population numbers, what Srinivasan et al. (2017) termed as ‘spatial specialisation’ where production and consumption regions are geographically distinct, had to be considered; water embedded in these products and services were included in determinations of the DFWS (Hoekstra, 2008; Mekonnen & Hoekstra, 2016).

The water footprint indicates the extent of water use relative to consumption by the population. The water footprint of an person, society or enterprise is characterised as the total volume of blue, green and grey water utilised to generate the commodities and services utilised by the person or society or produced by the enterprise (Mekonnen & Hoekstra, 2010).

Further shortcomings of earlier definitions of WS include a lack of historical reference and predictive insight, in that it focused on a global scale to develop WS indices to identify regions requiring interventions but without identifying what those interventions should be (Srinivasan et al., 2017). Savenije (2000) criticises the singular view of WS framed in a static state, which fails to acknowledge a anthropogenic influence in the water cycle (Wagener et al., 2010).

The DFWS used in this research was developed by Srinivasan et al. (2017), who addressed these static indices by accounting for the interrelation of human-water systems and the extensive quantity of dynamic pathways these systems co-develop.

The dynamically framed approach to WS are produced in a three-step sequential methodology, namely:

i) By a number of indices or measures that convey to anthropogenic water utilisation to available water capacity.
ii) By indicators used to map to different types of WS for Cape Town.
iii) By a number of casual components that represent anthropogenic utilisation versus available water capacity, resulting in where the indices can be demonstrated in a framework of anthropogenic hydrological structures (Srinivasan et al., 2017:3).

In addition to determining the status quo of the WS of Cape Town, the DFWS has been expanded by the addition of:

i) The contribution of Cape Town's water augmentation projects for implementation from 2019-2026 and its effect on the overall WS of Cape Town.
ii) The risk assessment of the water augmentation projects applying a Relative Risk Methodology.

1.15 Delineation and exclusions

The research was limited to the defined system boundaries of the CCT Metropolitan Municipality Water Management Area inclusive of all internal and regional water sources. Information used for the research was limited to open-sourced, publicly available hydrological information available from literature, government, local authorities, tertiary institutions, public entities and business.

The researcher realises that data quality and accessibility could be restricted due to the unwillingness of local authorities and other entities such as corporations to disclose data on water. Key initiatives have been launched, notably by the World Water Assessment Program and UN-Water, but in general, the architecture for water monitoring is evidenced by an absence of coordination and collaboration across entities (Lindhe, 2010; Lindhe 2008):

i) Present supplementary sources consist of fountains and tributaries, the Atlantis Aquifer, and three small-scale interim seawater desalination plants, which, for this research, was considered as part of the current bulk supply.
ii) The influence of alien vegetation on run-off in the WCWSS is reported to be significant but has not been quantified in available literature and was thus not considered for this research.

iii) The research exclusively utilised water-related secondary and grey data Information freely available in the public domain.

Notwithstanding the complexity of water systems and the insufficiency of data, effort was focused on unsophisticated indicators where the fundamental data were clear rather than complicated, weighted compound indicators. Consideration was given to naming and articulating indicators applicable within the spatial unit, as they are as much political and communications tools as they are analytical devices.

The researcher is aware that the selected risk assessment methodology using the Relative Risk Model might have been affected by data gaps due to data not made available in the public domain. This methodology has only been tested in first world countries and in spatial units of a singular watershed, not across system boundaries and not in developing countries.

1.16 Findings

The headline findings confirm that the CCT will be water secure under normal rainfall circumstances. The WS risk assessment underlines the long-term threat to Cape Town’s WS in terms of dependency on rain-fed surface water supply by urbanisation and population growth. Water re-use was found to be the most robust and rainfall-independent augmentation project of the New Water Programme (City of Cape Town, 2019b).

The WS risk assessment utilising open source HISs produced results that underscore the impact of the augmentation projects and the risks associated with it. The DFWS found that the augmentation projects proposed by the New Water Programme, if implemented as planned, will add 48.8% water supply capacity independent to the WCWSS. The following statements can be made from the headline findings:

1.16.1 WS status of Cape Town

i) Storage capacity of rain-fed surface water is sufficient during normal rainfall years as indicated by the Water Resources Utilisation Intensity indicator PW/(P+I); therefore, there will be no risk to WS for Cape Town.

ii) The Trade and Technology (TT) indicator displays a downturn in spending on water storage and supply infrastructure, which represents a threat to long-term WS for Cape Town.

1.16.2 Influence of augmentation projects on the WS of Cape Town

1. i) Augmentation projects will add an additional capacity of 48.8 % by 2026 to the current surface water storage capacity if implemented according to the New Water Programme. This will make the CCT less dependent on supply from the WCWSS and increase WS.
2. ii) The PW/CW indicator displayed results that support a continuance of the predominant economic activity as industrialised versus service sector-oriented. Consumption far exceeds the PW footprint; the result therefore confirms that the spatial unit measured is a nett importer of water from outside its boundaries.

The findings support the utilisation of open-access HISs as a data source and the framing of WS indicators through the DFWS in combination with the implementation of the Relative Risk Model to inform the WS risk for Cape Town.

1.16.3 Risk assessment

The risk assessment of the augmentation projects delivered the following significant findings:

i) Supply of water for agricultural use will be most at risk from the current WCWSS, thereafter industrial/commercial water use, and then domestic water use as well as environmental reserve in sequence of relative risk ranking, respectively.

ii) A sensitivity analysis of the augmentation projects resulted in water re-use and ground water as the most prominent contributors to the average water potential and therefore the WS for Cape Town.

iii) The sensitivity analysis of the WS indicators identified population and water re-use as the two most significant high-risk elements for WS for Cape Town.

In light of the preceding results and findings of the WS risk assessment, the use of an open-access HISs approach supports the practicality of the methodology and data sources. The presentation of the results enables interpretation of the findings over a long time frame and the uncomplicated incorporation of a variety of indices. The methodology utilised the availability of open-access secondary data from hydrological information sources. The findings of the WS risk assessment support and underpin a diverse approach to the management of water resources by ranking the WS risk factors attributed to the augmentation projects and thus present mitigation actions for consideration.

1.17 Conclusion

The quest of the CCT becoming a water-sensitive and water-resilient city will require society as a whole to commit through collective action to implement the required strategies as proposed by science and water utility experts and not allow water to become a political instrument. The findings disclose that the effective use of data from open-access hydrological information sources processed via the DFWS and RRM can deliver a composite view of WS for the CCT. By considering all three components presented in the findings, namely, water resource utilisation, human demand or consumption, and human development, the WS status for the CCT in relation to the objective of RQ1 was successfully determined.

1.18 Contribution

The key contribution of this research is the combination of the DFWS and the Relative Risk Model using open-access hydrological data to measure WS and the associated risk elements for Cape Town. The efficacy is evident in the results and findings, and this contributes to academic discourse on three of the five commitments proposed by the CCT Water Strategy, namely: (i) the wise use of water; (ii) the sufficient, reliable supply of water; and (iii) the aim of becoming a water-sensitive city.

1.19 Summary

The drought experienced from 2015-2018 exposed Cape Town's vulnerability to rain-fed water sources, climate change, and its dependency on a singular supply from the Western Cape Water Supply System. The New Water Programme proposes mitigation by augmentation of water supply through exploring and utilising alternative sources.

The aim of this research was to explore how open-access hydrological information systems can be used for decision making on WS by determining Cape Town's WS status, the impact of the augmentation projects proposed by the New Water Programme, and to assess the risk associated with it. The RQ objectives were met by the methodology employed, which consisted of a dynamic framework to determine the status and impact of the augmentation projects on the WS for Cape Town. The risk assessment, uncertainty and sensitivity analysis were achieved by utilising the Relative Risk Model.

This research adopted a positivist research paradigm, within which a deductive research approach was employed because of the availability of open-access information sources, and a quantitative research strategy was selected. The unit of analysis was identified as WS and risk was measured in relative risk units. Data collection was a well laid out, rigid, non-random procedure focusing on quantitative water-related resources available in the public domain. Secondary data were collected via open-access HISs. There was no human or community participation, therefore no significant ethical impact and no conflict of interest was declared.

Findings were produced in graphical format, and results were interpreted and presented using WS indices and relative risk scores. WS results were discussed in terms of water resources utilisation intensity, trade and technology, and production water and consumption water indices, while risk scores were discussed in terms of sources, exposure to stressors in various habitats, and their impact on selected management endpoints.

The research was limited to the spatial boundaries serviced by the CCT Metropolitan Municipality and excluded the influence of regime changes for the determination of WS. The risk assessment excluded the establishment and testing of a hypothesis for future field and laboratory investigations to confirm the risk ranking results.

It was concluded that the WS risk assessment of the CCT utilising open-access HISs can add value as a resilience measurement instrument. The methodology requires clarification, and the concept needs buy-in from all role-players to be a meaningful instrument. Achieving WS in the urban areas of developing nations will only be achieved by improving institutional capability and public capacity in a progressive approach to collaboration, trust and a more responsible attitude to building a robust, long-term plan.

1.20 Overview of chapters

Chapter 1: Introduction

Chapter 1 presents and frames the thesis by reviewing the historical environment of the conundrum studied, which is then encapsulated into a conventional problem statement. The research objectives are developed from the problem statement and the limitations of the research are determined. The layout of the investigation and approach employed to investigate and consequently execute the aims of this study is depicted.

Chapter 2: Literature Review

Chapter 2 presents a wide-ranging assessment of literature relating to the problem statement stated in Chapter 1. This chapter begins with an outline of WS, focusing specifically on the evolution of the WS concept, the impact of water conservation and water demand management, application of the definition of WS, the spatial implications of WS, and the anthropogenic human-water influence.

This is followed by an assessment of the key water scarcity measurement models to distinguish the primary measurement components to be addressed in the determination of WS for the CCT. Subsequently, the evidence is reviewed in respect of suitable indices and indicators. This chapter additionally examines various data presentation structures and the methodology usually required to complete applying the data.

Chapter 3: Research Methodology

Chapter 3 explains the determination of WS using and expanding on the DFWS through a composite index in a dynamic view of WS for the CCT established on the outcomes of the literature assessment in Chapter 2. The recommended solution is offered as an outline that can be used to encode evidence using information from open-access Hydrological Information Systems through a Regional Risk Methodology to quantify risks and inform water management decisions.

The extension and requisite characteristics of the structure is reviewed, supported by the steps determined by the framework. Wherever feasible, every phase is portrayed in terms of its aims and objectives, its hypothetical foundation, and as an output, supported by the value it adds to the framework.

Chapter 4: Data Analysis, Results and Findings

Chapter 4 discusses how the proposed solution was validated with the help of accessing and analysing secondary data available from open-access sources from various data-intensive organisations to provide input for the framework.

Chapter 5: Discussion

Chapter 5 is a detailed presentation of the results and findings in relation to the literature review done in Chapter 2. Descriptive analysis of the results and findings is done to motivate the positive or negative contribution, and the significance to the RQs, aims and objectives of the research.

Chapter 6: Conclusion and Recommendations

Chapter 6 presents the conclusion and recommendations derived from the research. The section embarks with an outline of the study to recap, condense and contextualise the results. The chapter closes with a statement of the constraints encountered during the research and suggestions are made for potential research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Chapter 1 contextualised the research. The origin and historical aspects of the phenomena under study was explored and the problem statement was presented. The aim and objectives were stated and the design of the study was discussed.

In this chapter, literature on the role of open-access hydrological information systems in water security risk assessment is reviewed. Key words and key concepts are explored. A summary of published academic papers and grey literature in the form of documents and reports from government agencies and non-profit organisations is included. In addition, a blend of electronic literature examinations and records published by the CCT as well as the utilisation of official and unofficial reports, reviews and documents distributed among the academic and local water authority communities was assessed. The literature review was aimed at providing a comprehensive overview of literature supportive of the topic and available for further study, dissertation and critique.

The objective of RQ1 was to examine the WS indicators available from the latest literature and their influence on the coupled human-water system of the CCT. A DFWS was applied to determine the historic and current WS status as the primary deliverable, where after the impact of the New Water Programme (NWP) augmentation projects on the future WS was determined as the secondary objective of RQ1.

Srinivasan et al. (2017) contend that the resultant WS indicators will enable water managers to apply interventions and resources more effectively through a range of benefits. Benefits include the provision of both historical and predictive insight, coupled human-WS, WS trajectories under anthropogenic influence, forecasting and predicting of water in/security and mapping physical resource availability within infrastructure and economic choices.

RQ2, as described in section 1.6.3, aimed to determine the risk elements associated with the WS status of the CCT augmentation options as proposed by the New Water Programme. Here, the objective of RQ2 was to examine the WS indicators selected in the secondary objective of RQ1, and then to determine and rank the risk elements of the WS of the CCT by using Relative Risk Assessment for the assessment.

Key words and key-concepts were used to explore resources such as the World Bank, World Wildlife Fund (WWF), World Water Forum, United Nations Education, Scientific and Cultural Organisation (UNESCO), Water Research Commission (WRC), Statistics South Africa (Stats SA), UCTD, National ETD portal (NRF), Department of Water and Sanitation (DWS), the CCT, South African Weather Service (SAWS), Hydrological Information System (HIS) databases such as SADC-HYCOS, and the online library of the Cape Peninsula University of Technology. Databases such as Google Scholar, Scopus, Emerald and ERBSC host were explored.

This chapter begins with an outline of WS with emphasis on the evolution of the WS concept and the application of WS to Cape Town. Secondly, it provides the background to the CCT's water crisis, CCT's water security, and the CCT Water Strategy. Thirdly, the background and application of the Security Risk Assessment for the CCT considering the spatial implications of WS and the anthropogenic human-water influence is discussed.

Subsequently, by presenting an outline of the major WS frameworks, the most crucial factors that have to be directed in the determination of WS for the CCT process are distinguished. Next, WS is discussed with regard to indices and frameworks. The chapter concludes with describing the DFWS and its application to the CCT by measuring the WS status quo versus the impact of the proposed water augmentation projects of the CCT Water Strategy on the WS and then determining the WS risk indicators via the Relative Risk Model (City of Cape Town, 2019c; O'Brien et al., 2018).

2.2 Hydrological Information Systems (HISs)

The major sources of data for this research were derived from open-access Hydrological Information Systems (HISs) as presented in Table 3.2. Sustainable water resources management requires an understanding of the hydrological cycle. Adequate meteorological, hydrological, and other related data were considered necessary to assess the level of water availability in spatial-temporal parameters defined by the RQs (WIAG, 2011; World Meteorological Organisation, 2012).

Reports by international development agencies on water resources development have identified, among other factors, the lack of knowledge of the hydrological cycle as an impediment to developing water resources in those countries. As a consequence, this has weakened their attempts to alleviate poverty and achieve the United Nations Millennium Development Goals. Owing to insufficient hydrological information, numerous water resources development schemes are designed sub-optimally and their sustainability is thus compromised (WIAG, 2011).

2.2.1 Mission

The mission of the UN Millennium Development Goals was to facilitate a better understanding of the global hydrological cycle. Moreover, to encourage a thorough comprehension of its variability, with an improved knowledge of the status and trends of the world's freshwater resources (United Nations, 2015a).

2.2.2 Objectives

The objectives of the hydrological information systems were to create a world-wide system of national hydrological observatories that could deliver data of reliable value (HydroNet, 2020). This information could be communicated in real- or near real-time to domestic, regional and international archives. A further objective was to improve the methodological and functional capabilities of hydrological facilities to gather and distribute hydro-meteorological data and information. This was to be achieved via the development of suitable general water resources information systems. In this manner, enabling their usage for sustainable socio-economic development, also enables local and global collaboration and stimulates data distribution at the local and international levels (HydroNet, 2020).

The purpose was to conduct scientific research on climate change and its impact on water-related issues. Moreover, it promoted the use of information technology and space-based observations as a complementary mode of providing information on water-related issues by improving national and regional capacities. Lastly, to improve collaboration between nations and hydrological services sharing regional water bodies by encouraging and improving the accessibility, accuracy and distribution of hydrological data and information.

Each HYCOS element evolved in answering a request that emanated from the area in one or several of the subsequent key performance areas:

i) Water supplies evaluation;
ii) flood predicting and alerts;
iii) aquifer monitoring and evaluation;
iv) evaluation of surface and ground water quality;
v) water information systems development; and, consequently,
vi) development and support of integrated Water Resources Management.

South Africa participates in the WHYCOS program under the SADC-WHYCOS initiative facilitated and supported by the World Meteorological Organisation's Hydro-Hub programme. The intent of the SADC-HYCOS project was to develop regional collaboration (WIAG, 2011). This cooperation transcended throughout the disciplines of water asset information, flood and drought administration. It also included land management, watershed safeguarding, and the administration of shared common watercourses of the nations in the Southern African Development Community (SADC). The venture targeted the improvement and/or consolidation of the national and district capability in the disciplines of water supplies monitoring, evaluation and administration. This required the establishment of water supply statistics and evidence in the format required for assessment on all facets of combined water resources development and administration.

Data were collected from various diverse and independent open-access hydrological information sources available from various governmental, regional as tertiary institutions as well as NGO’s in South Africa, and especially in Cape Town. The aim of this research was to focus on open-sourced, publicly available, HIS systems such as HPS-WINS, SASSCAL, SANCIAHS-MAIS, MODIS, WHYCOS, academic Institutions, national and local government, and published works.

HIS systems are web-based decision support systems that empower researchers with integrated online water management information (HydroNet, 2020). Spatial-temporal specific data availability enables well-informed, transparent, and accountable information on water resources easily accessible and communicated with stakeholders.

The National Integrated Water Information System (NIWIS) was developed by the Department of Water and Sanitation (DWS) with the purpose of providing water information products in the form of water information dashboards. The presentation of data using dashboards facilitates efficient analysis and reporting across the water value chain in South Africa. Trends over time relating to the number of measuring stations, different site types and positions are available on these HIS dashboards.

Regular publications of surface water monitoring point measurements by the CCT in the form of weekly water dashboards containing water use and dam level data were used as sources for site specific financial, census, population and hydrological information in order to address the aims and objectives of this research (Department of Water and Sanitation, 2019; City of Cape Town, 2019a).

Long-term data were available in graphical format ever since organised hydrological monitoring began in South Africa in the early 1900s. It likewise indicates the proportion of trustworthy data produced per location and offers a link to the online DWS HYDSTRA data portal for users to access the information. Metadata linked to each monitoring location is also supplied. Moreover, users may evaluate the accessible monitoring sites relative to their requirements (Department of Water and Sanitation, 2019). As such, data from open-access HISs can be utilised to distinguish zones where improvement can be made to avoid potential data gaps in the accessibility of hydrological information.

2.3 Coupled human-natural influence

The coupled human-water system, also known as a coupled human-natural system (CHANS), exemplifies the dynamic two-way interactions among human and environmental systems. The human system represents the economic and social aspects and the natural systems, the hydrologic, atmospheric, biological and geological aspects of the anthropogenic impact of human-water system (Turner et al., 2003; Jaeger et al., 2019). This human-nature connection articulates the perception that the progress of humans and environmental systems may no longer be viewed as distinct or isolated systems, contrasted to former periods in human history when human-natural interactions were weak and linear (Werner & McNamara, 2007).

The term coupled human-natural system is found in literature from 1999, stating that social and natural systems are inextricable (Sheppard & McMaster, 2004). Research into the anthropogenic effect is expanding in investigations about sustainability and preservation of environments and humanity (Turner et al., 2003; Ferraro et al., 2018).

2.4 Water Security (WS)

WS has gained growing consideration and recognition in the policy, business and scientific communities in recent years (Link et al., 2016; WWAP, 2016). Cook and Bakker (2016) contend that the notion of WS along with its conceptualisation first appeared in academic literature from the 1990s and was mostly framed from an engineering and natural science perspective. The social science paradigm only followed later in 1999. The first political framing followed in 2000 at the 2nd World Water Forum in The Hague, from where it progressed in stature to be the central theme in framing its nexus position in relation to food and energy from various scientific and political perspectives (Gleick & Cain, 2005).

Pahl-Wostl et al. (2016) argue that the progress in the framing and prominence of WS among various role-players may have been attributed to the pressing sustainability needs in land and water management experienced world-wide. Fischhendler and Nathan (2016) and Gupta et al. (2016) view the increased prominence of WS as a vehicle in raising water and water-related concerns on the political agenda. Despite the emphasis placed on water and its pivotal role by the concept of WS at various spatial and temporal levels, consistent framing of the concept still eludes academics and policy makers (Pahl-Wostl et al., 2016; Funke et al., 2019).

Definitions and interpretations varied from narrow versus broad and academic versus applied (Cook & Bakker, 2016, Pahl-Wostl et al., 2016). Patrick et al., 2016:333) state that the working definition of the WS paradigm is “one that seeks a balance between the driving forces of society, economy and environment”. This broader definition has affected the evolution of the definition of WS in the employment of Integrated Water Resources Management (IWRM).

2.5 The evolution of the WS concept in academic and policy circles

The discourse on the WS postulation has seen a marked increase since the 1990s when first used by Savage (1991). The geopolitical impact of water supplies in dry and semi-dry countries was further reported by Cook and Bakker (2016). Their analysis found that a broad scope of disciplines, ranging from social sciences, environmental science, engineering sciences, agriculture and geographical sciences, public health, and atmospheric sciences, all contributed diverse paradigms in types and scales to the research of WS.

WS is multivariate, evolving from the contest of harmonising human and ecological water requirements simultaneously with intricate social and political frameworks (Vörösmarty et al., 2010). Pursuing WS necessitates insight into the dynamic interaction between humans and natural-water systems from a regional to global range as well as timeframes from days to millennia (Lall et al., 2017).

Current research compared to historical data found that topics for the last 20 years remained constant with a steady growth in knowledge but done in isolation, not taking different disciplines into consideration (Brown & Matlock, 2011; Cook & Bakker, 2012; Siebrits et al., 2014; Cook & Bakker, 2016; Funke et al., 2019).

WS has attracted so much academic interest over the last decade that several dedicated books such as the *Handbook on WS* and publishers such as Elsevier have published many articles as shown in Table 2.1. The first journal, published in July 2017, was established with the express purpose to reflect on the changing mosaic of WS. It invites research projects offering methodologies, theories, types and data sets that help comprehend the environment and origins of WS. The WS journal describe four themes, namely shortage, flooding, governance and health, and sanitation, in which they desire to encourage deliberation, supported by science along robust interdisciplinary relationships (Lall et al., 2017)

Table 2.1: Evolution of WS (adapted from Steyn et al., 2019:4)

Author(s)	Date	Viewpoint
Savage	1991	Geopolitical
Anderson	1992	Geographic, political, economic and diplomacy
Shuval	1992	
Livingston	1995	Efficiency of water institutions
Allan	1997	Economic systems determine WS, not Hydrology or Infrastructure or engineering systems
Falkenmark & Lindqvist	1998	Resource management across domestic and international borders
Van Wyk	1998	The first person to introduce the WS concept in a Southern African context of water resources
Simonovic & Fahmy	1999	Propose modelling of WS to analyse water resource policies in terms of economic and social indicators
Falconer	1999	Appear to be the first to scientifically investigate WS in terms of human health risk
Global Water Partnership (GWP)	2000	Propose the first formal definition of WS: “WS at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced”
Falkenmark	2001	Contend that policy makers and scientist need to link WS with environmental and food security, being the first argument to identify the nexus link between water, environment and food from a policy perspective
Allan	2003	Virtual water, the water, food and trade nexus
Deveraux & Edwards	2004	Climate change and food security
Postel & Thompson	2005	Watershed services to enhance WS
Nuzzo	2006	Biological threat to WS
Kahinda et al.	2007	Enhancing rural WS
Savenije & Van der Zaag	2008	Integrated Water Resource Management: Concepts and issues
Muller et al.	2009	WS in South Africa
Hanjra & Qureshi	2010	Water for food security
Stockholm Environmental Institute (SEI)	2011	At the Bonn Conference, “The Water, Energy and Food Security Nexus: Solutions for a Green Economy”. The purpose of the conference was “to present evidence to enhance water, energy and food security by increasing efficiency, reducing trade-off's and building synergies and improve governance across sectors” (Hoff, 2011:4)
Food and Agriculture Organisation (FAO)		
GWP		
World Bank (WB)		
Cook & Bakker	2012	Multi-disciplinary paradigm of WS

Author(s)	Date	Viewpoint
Bakker & Morinville	2013	Governance dimensions of WS
Foster & MacDonald	2014	The WS dialogue from a ground water perspective
Loftus	2015	WS from a water rights perspective
Kurian	2017	The Bonn Conference in 2011 introduced the water, energy and food nexus concept to academic and policy circles and placed it on the agenda of international discussions on sustainable development
Donnenfeld	2019	Institute for Security Studies. Rains have washed away memories of Cape Town's crisis, but the country's water future is still precarious
Funke et al.	2019	Understanding WS at local government level in South Africa

2.6 Definition of WS and applications in WS

2.6.1 Definitions

Some of the prominent writers in the field of WS, including Cook and Bakker (2012), posit that the problem of no single working definition for WS persists in different disciplines with various definitions veering between 'broad' versus 'narrow' and 'academic' versus 'applied'. Throughout the evolution of WS, several researchers from different paradigms, for example Gareau and Crow (2006), Donohew (2009) and Reed and Bruyneel (2010), shared similar sentiments.

The Global Water Partnership (2000:7) defines WS as "enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced". The World Water Forum contends that:

> "…ensuring that freshwater, coastal and related ecosystems are protected and improved, that sustainable development and political stability be promoted, that every person has access to enough safe water at an affordable cost to lead a clean, healthy and productive life, and that the vulnerable are protected from the risks of water-related hazards" (Global Water Partnership, 2000:1).

Grey and Sadoff (2007:458) defines WS as "the availability of an acceptable quantity of water for health, ecosystems and production, coupled with an acceptable level of water-related risks to the people, environments and economies". Bakker (2012:914) identifies WS as "an acceptable level of water-related risks to humans and ecosystems, coupled with the availability of water of sufficient quantity and quality to support livelihoods, national security, human health, and ecosystem services".

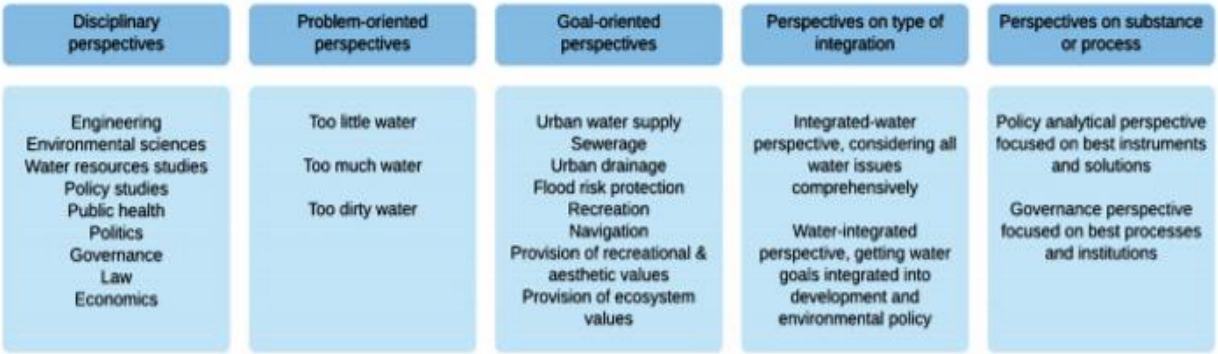
The United Nations Water Agency states that,

> "WS is the capacity of a population to safeguard sustainable access to adequate quantities of an acceptable quality of water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water, 2016).

Movik et al. (2016:456) opine that a working definition of the WS paradigm can be "one that seeks a balance between the driving forces of society, economy and environment". Cook and Bakker (2016:19), in their analysis of trending WS research, isolated four analogous pivotal themes, namely: (i) water quality and availability; (ii) sustainability; (iii) water-related hazards and vulnerability; and (iv) human needs.

More recently, WS is perceived in terms of explicit real objectives to be attained to improve Water Resources Management (Marttunen et al., 2019). UNESCO states that, "to achieve WS, we must protect vulnerable water systems, mitigate the impacts of water-related hazards such as floods and droughts, safeguard access to water functions and services and manage water resources in an integrated and equitable manner" (UNESCO, 2014). In a study on urban WS, Hoekstra et al. (2018) categorised the multiple perspectives of urban WS as presented in Table 2.2 below.

Table 2.2: Multiple perspectives on urban WS (Hoekstra et al., 2018)



Disciplinary perspectives	Problem-oriented perspectives	Goal-oriented perspectives	Perspectives on type of integration	Perspectives on substance or process
Engineering Environmental sciences Water resources studies Policy studies Public health Politics Governance Law Economics	Too little water Too much water Too dirty water	Urban water supply Sewerage Urban drainage Flood risk protection Recreation Navigation Provision of recreational & aesthetic values Provision of ecosystem values	Integrated-water perspective, considering all water issues comprehensively Water-integrated perspective, getting water goals integrated into development and environmental policy	Policy analytical perspective focused on best instruments and solutions Governance perspective focused on best processes and institutions

For this research, WS is considered as the balance between water availability and sustainable use, the risk implications of the anthropogenic human-water influence and the vulnerability to climate change.

2.6.2 The spatial implications of WS

Critics of the narrow WS definition as far back as Molle (2008) believe that water management plans should be more catchment specific in order to be effective. Muller (2014) adds that sustainability will require an acceptance of an anthropogenic environment. This is supported and taken further by Bailey and Pitman (2016), who call for more detailed studies to be done in water management areas in order to generate improved data and information.

Mekonnen and Hoekstra (2016) posit that previous global water scarcity assessments conducted annually failed to capture seasonal fluctuations because existing hydraulic information were isolated in silos, thus creating hydraulic information gaps. Furthermore, De Assis et al. (2020) argue that frictions and disputes over water use are progressively common, and is a consequence of either extreme water scarcity or elevated water demand exceeding availability, or a combination of both. This failure, combined with the criticism of it being limited to a snapshot glimpse of WS in a place and point in time, having neither a historical paradigm nor predictive insights, adds to the limitation of early WS definitions in terms of relying on static indices, thus failing to acknowledge the human-water influence (Srinivasan et al., 2017).

2.6.3 The human-water influence

The National Research Council Policy Division Board on Sustainable Development published the concept of ‘coupled human-environmental systems’ in literature during the 1999s. Sheppard and McMaster (2004) concurred, noting that social and natural systems are inseparable. The human-water influence, also known as the coupled human-environmental system describes a two-way interaction between human systems, such as economic and social interaction, with natural systems of hydrologic, atmospheric, biological and geological nature (Carter et al., 2014).

Patrick et al. (2016) and Rushforth and Ruddell (2016) expand on the WS debate by adding that boundary issues challenge the understanding of WS and therefore all local and non-local water should to be included in the spatial domain. They identify the failure of IWRM, as defined by the Dublin paradigm, as a result of the exclusion of human-water influence (Suhardiman & Giordano, 2012).

From the literature it can be surmised that WS should consider each WMA as unique, define spatial boundaries of water produced and water consumed, account for an anthropogenic environmental outcome. and more significantly, consider WS as a product of a connected human-water approach.

2.7 WS from a CCT perspective

2.7.1 Background and history

The importance of water availability in South Africa was highlighted as far back as 1970 in a report by FA Venter, an independent researcher, appointed by the Department of Water Affairs at the time. The report indicated that pro-active actions were required to avoid water demand exceeding supply by the year 2000 (Ismail, 2018; Visser, 2018).

In 1990, the Water Research Commission (WRC) reported that the CCT's total available water resources was projected to be fully committed by 2007 (Streek, 1990), and in the late 1990s, Davies and Day (1998) warned that South Africa was swiftly approaching water shortages where demand will outpace supply due to a rapidly increasing population. The authors cautioned that South Africa had a very low translation of rainfall into usable run-off water compared to other countries, and that the risk of 'permanent drought' conditions could be between 10 and 15 years. As such, Davies and Day (1998) motivated for an acceleration of community engagement through education and the implementation of water demand management instead of water supply management strategies.

It was reported by Barnes (2016) that the CCT water scarcity experienced in 2015-2018 had been projected by weather and environmental experts for more than ten years. This ruling administration was forewarned of this hazard for numerous years. Turton (2015) refers to a 1970 statement of the Commission of Enquiry into Water Affairs that predicted severe scarcities unless the conservation, augmentation and re-use of water supplies in the best effective way have been explored and successfully implemented. By 2018, the CCT experienced a third successive year of significant below average rainfall, combined with a robustly established El Nino weather pattern and affected by an unabated annual metropolitan populace increase of 4% (SADC, 2016; Visser, 2018).

The historical precipitation for the CCT area averaged 520 mm annually, mostly during the winter months of June to August, according to the World Meteorological Organisation (2019). The CCT benefits from a Mediterranean weather pattern with an median summer time temperature of 26˚C and 16˚C in winter and is home to an estimated population of more than 4 million (Visser, 2018). The bulk (>90%) of the City's water is transported from a number of catchment zones via an elaborate scheme of dams and reticulation schemes identified as the Western Cape Water Supply System (WCWSS). The WCWSS is controlled by either the CCT or the state's Department of Water and Sanitation (DWS) (City of Cape Town, 2018a). The

WCWSS likewise delivers raw water to municipalities neighbouring to and on the fringe of the larger CCT Metropolitan area. It moreover supplies water to agricultural water supply schemes in the Western Cape, with the result that close to eight million inhabitants are dependent on the WCWSS as the predominant fresh water supply system (City of Cape Town, 2018a; Visser, 2018).

The application of the CCT's Water Conservation and Water Demand Management (WC/WDM) Strategy imposed level 2 water restrictions in January 2016 with the aim to achieve a 20% water-saving among residential and business users. The agriculture sector was exempted from this restriction together with poorer households who received a basic daily allowance of 6 Kℓ free water. By November 2017, the water restrictions were increased to level 3 (Muller, 2017; City of Cape Town, 2018a; Visser, 2018).

In February 2017, with the drought persisting, the City's largest supply dam, the Theewaterskloof dam, dropped to 34%. This resulted in the enforcement of level 3B water restrictions whereby the City hoped to decrease water use by a further 30%. The CCT penalised large volume water users by installing flow restriction devices. (Muller, 2017). At this point the CCT still considered desalination as too expensive (Muller, 2017).

During March 2017, the provincial government of the Western Cape proclaimed the province a disaster region to avoid a collapse of the water supply. The Water Management Strategy switched from Water Supply Management to Water Demand Management (Muller, 2017). The water restrictions increased to Level 4 in June 2017 and widespread pressure reducing measures were introduced to decrease supply (City of Cape Town, 2017a; Nienaber, 2017).

Level 4B restrictions were implemented when it became clear that precipitation for 2017 was going to be lower than the expected average. The CCT encouraged people to limit their daily personal water use to 87 ℓ/day to achieve a cumulative volume of 500 Kℓ/day for the Metropole. The 6 Kℓ free water for poor families was terminated except for indignant families registered with the CCT (City of Cape Town, 2017a; Nienaber, 2017). To put the water demand in perspective, the population growth since 1995-2017 was 55% versus the increase in water storage capacity of only 15% (City of Cape Town, 2017a; Visser, 2018).

By the last quarter of 2017, the water restrictions were increased to level 5, requiring commercial users to lower usage by another 20% and residential users were restricted to 70 ℓ/person/day. However, even though water use was decreased by

27%, it continued to be 137 megalitres (Mℓ) in excess of the aimed for 500 Mℓ/d (Breytenbach, 2017).

During October 2017, substantial emergency water expansion projects such as boreholes and temporary desalination that were announced two months previously, were still not commissioned. These schemes were to supplement current supply with 200 Mℓ to 450 Mℓ of raw water per day (Visser, 2018). Confidence in the CCT's leadership and service capability suffered when it became known that the proposed supplementary supplies could merely produce less than 50% of the volume promised (May, 2018).

December 2017 saw the introduction of level 6 water restrictions. this meant non-residential users were to restrict their water use by a further 45% and DWS decreased the allocation to agriculture by 60%. By late January 2018, the City's Disaster Risk Management Centre went into action (Meyer, 2018) and by February 2018, level 6B limitations were instituted, which limited water usage to 50 ℓ/person/ day (City of Cape Town, 2018a).

The CCT communicated their "Day Zero" plan for actioning when supply in the 6 major supply dams would decrease to a storage capacity of <13.5%. The City's Disaster Risk Management Centre would in such a case action phase 2 of their plan, where water restrictions would be increased from level 6B to level 7 and 75% of the Metropole's taps would be closed off (May, 2018; Winter, 2018).

The drought negatively affected the entire spectrum of human activities. Commercial car wash companies were barred from using drinkable water, no new landscape or sport field projects were allowed, the hospitality trade suffered a decline in visitor statistics for the summer season, and shipping agents were not allowed to bunker drinking water to visiting vessels in the harbour. In addition, the cricket season for schools and clubs were shortened by two months and restaurants started to charge for tap water, which was previously served free with meals (Visser, 2018). A drop of approximately 5.5% in estate values were experienced over the period (Barnard, 2018; Nel, 2018).

Day Zero led to the panic buying of containers, tanks and bottled water which subsequently resulted in private trade in water and water-related goods with the selling of potable and non-potable water to a seemingly unquenchable quantity of clients (Schoeman & Marais, 2018). During the 12 months of 2017, the quantity of new private boreholes registered in the CCT Metropolitan area rose from 1,500 to 23,000 (De Kock, 2018).

Based on figures (City of Cape Town, 2018a) published in October 2018, the reduction in water consumption caused the CCT revenues to drop as a result. The CCT's projected water budget shortfall was calculated at R1.7 billion for the 2017-2018 fiscal year (City of Cape Town, 2018a; Visser, 2018). This was viewed in the light of the estimated R1 billion/year required to finance emergency water schemes, essential water supply and sanitation services over the next three years and as such, put the effect of the drought on the CCT in a dire perspective (City of Cape Town, 2019a; Visser, 2018).

The drought created destruction on the Western Cape economy, none more so than agriculture. DWS cut water allocations to agriculture by 60%. In the 2017-2018 fiscal year, production in this sector dropped by 20.4%, resulting in approximately 30,230 job losses. Fiscal damages were projected to be in the range of R5.9 billion and damage because of the drought was put at R14 billion (Boonzaaier, 2018; Theron & Brits, 2018). Ultimately, in March 2018, the National Administration categorised the drought in the Western Cape as a general disaster, which offered access to R165 million for drought alleviation projects (Essop, 2018; Meyer, 2018; Nienaber, 2018).

2.7.2 Water security

Liu et al. (2017), in their review of WS assessments, concluded that the variation in measuring water supply and usage on an annual basis calls for the assessment of WS in a singular supply system dimension. Liu et al. (2017) also stated that such an assessment would need the collaborative engagement of hydrologists, economists, social scientists, and environmental scientists to create incorporated methodologies to address the multi-faceted character of water scarcity (Liu et al., 2020).

Steyn et al. (2019) reported that South Africans' historic capability to manage water scarcity was largely due to the construction of large water infrastructure projects like dams and extensive irrigation schemes. The motivation for this hydro-ingenuity was initiated in the late 19th century, motivated by the goal to establish sustainable commercial agriculture. Moreover, the fact that South Africa's WS challenges can still be ameliorated in this way is unfortunately still part of the dominant water resource management discourse. In their research, Steyn et al. also found that the health and sustainability of ecosystem services have become more prominent in considering the threat to their ability to contribute water for socio-economic progress, as is a mandatory requirement of the Water Act (Act 36 of 1998). Steyn et al. (2019) further reported that they support the government initiative of establishing wastewater treatment and water purification plants to operate on the Green and

Blue Drop programmes, and also verified the challenges and influences of climate change in the face of urbanisation and the 4th Industrial Revolution.

The WS paradigm of water management requires both transformation and the ability to adapt to change for South Africa to establish sustainable water sensitive cities (Steyn et al., 2019). Gunda et al. (2019) add that WS research has progressed from focusing on physical availability to incorporating social factors such as governance, resulting in an improved understanding of diverse physical and social impacts. This, in turn, has led to a more wide-ranging notion of WS, which is described as the sufficient allocation of clean freshwater to support both people and ecosystems. Despite the clear acknowledgment that WS incorporates quantity, quality, and societal factors, debates often emphasise these aspects in isolation.

Gunda et al. (2019) opine that this practice often disguises critical ways in which water quality issues interconnect with water quantity issues as well as social factors for many WS challenges, and therefore water management practices should include source protection, point-of-use monitoring, wastewater recycling, water conservation, desalination, and managed aquifer recharge.

2.7.3 Indicators

In a review of a variety of indicators that have been developed to capture different characteristics of water scarcity, Liu et al. (2017) found population, water availability, and water use as the key elements of these indicators, which are applied in the quantification of water availability and usage to develop spatially explicit models. Challenges persist on applicable integration of green water (soil moisture), water quality, environmental flow requirements, globalisation, and virtual water trade in water scarcity assessment. These challenges and requirements are supported and addressed to a limited extent by the DFWS applied in this research (Srinivasan et al., 2017).

2.7.4 Risk

Hall and Borgomeo (2013), in their study on risk-based principles for defining and managing WS, indicated that the concept of WS indicates a possible threat of potentially damaging conditions of coupled human-natural water systems. Srinivasan et al. (2017), in promoting their DFWS, posit that WS as a product of coupled human-natural system models reflects human adaptability to external drivers. Under these risk conditions, simulations can indicate how coupled human-water systems might evolve for a given governance, culture, and infrastructure.

Notwithstanding extensive usage in public policy, theories and practices of risk management have well-known limitations, predominantly in the context of uncertainties and contested values. In their deliberation on Cape Town's *Day Zero* crisis, Taing et al. (2019) reflected that early climate risk models demonstrated the possibility of significant drier and risky climate patterns in the Western Cape. This would translate into both serious droughts and floods (Cullis et al., 2019). The risk methodology used by the CCT was based on the City's WS/WDM programme. This strategy, as well as being dependent on a singular supply for most of its water, erroneously suggested that Cape Town would not be drastically affected until around 2025. Wolski et al. (2017) reported that current rainwater models demonstrated their inability to forecast the gravity, scheduling, or extent of the 2015-2018 Cape Town drought. Moreover, provincial and national government defended this failure, declaring that it was partially due to erratic and unforeseen climatic variance (Saal, 2018). Enqvist and Ziervogel (2019) asserted that the risk of depending exclusively on surface water were well-understood for a substantial period. Unfortunately, the City has restricted authority to employ alternative water sources. Moreover, in addition to its limited mandate, its WC/WDM was effectual and appeared to allow the delay of resource expansion. Demands for diversification were repeated by international experts and organisations alike after the insignificant rains of 2017 (Mariño, 2017; Pengelly et al., 2017).

2.7.5 Climate change

On studying climate resilience in urban WS, Grasham et al. (2019) found during an assessment of the susceptibility of the inner-city poor in sub-Saharan Africa that the negative effect of climate disturbances and unpredictability prejudicially affect the urban poor communities. Grasham et al. (2019) further contend that as the climate changes, the frequency and intensity of floods and droughts are broadly expected to increase across sub-Saharan Africa while urbanisation will put larger populations at risk. Grasham et al. (2019) report a considerable shortage of evidence for the impact of drought shocks on urban WS. The authors emphasise the need for exploring the crisis-driven nuances of water insecurity that challenge existing socioeconomic dynamics. These include disruptions or difficulties in accessing usual services, goods, capital or income-generating activities, impacted social capital, and changing decision-making processes. This has been corroborated by several authors (Visser, 2018; Tadross et al., 2009; Mukheibir & Ziervogel, 2006; Midgley et al., 2005) over the years, who concluded that Cape Town's water insecurity was compounded by climate change risks, as medium term predictions for the region included reduced average rainfall, higher temperatures, increased south-easterly winds, higher evapotranspiration rates, and an increased likeliness of general drier conditions. All these factors led to the compound risk of increased water consumption and reduced water supply.

Enqvist and Ziervogel (2019) in their overview of water governance and justice concur that climate variance is projected to have increased the probability for drought conditions. As reported by Otto et al. (2018), the future weather patterns are forecast to grow warmer and drier, and as such, climate transformation will be a progressively critical element in water management (Schiermeier, 2018; Jack et al., 2016).

2.7.6 Population

In the analysis to grasp the roots of Cape Town's water crisis, Muller (2017) identified the key component for the surge in Cape Town's water use as the continual population growth in the Metropolitan. Population growth combined with two seasons of warm, arid weather are touted as the major contributing factors. The World Wildlife Fund (2017) agreed in their report that the continuously growing demand for water from a variety of sectors, associated with unabated growth in population numbers, was the primary contributing factor towards water shortages in this region.

Visser (2018) concurs in his analysis of the implications of Cape Town's drought crisis that the vastly expanding population required more water and large numbers of people were competing for the accessible water from the same resource. This view is supported by Sinclair-Smith and Winter (2018).

According to Scott et al. (2018), water consumption is expected to increase due to the continuing rapid growth of the City and national urbanisation trends that have seen significant population relocation to urban areas of the Western Cape. The City's population grew by approximately 30% between 2001 and 2011 (Stats SA, 2012) and approximately 7,000 new formal customers are being connected to the water system each year (City of Cape Town, 2018b). Economic growth is projected to lead to a rise in water consumption in businesses and industry as well as an increase in domestic consumption as a result of increased household income (Scott et al., 2018). Toale and Molfetas (2019) report Cape Town's population as nearly doubling from 2.4 million in 1995 to over four million in 2018, with the City's dam storage increasing by only 15% via the Berg River Dam during the same period. In support of the aforementioned authors, the following statements were made by *inter alia* Enqvist and Ziervogel (2019):

i) WS, comprising safe water supply as well as safety from water-related calamities, faces a serious risk in cities. This is particularly valid in Southern Africa where a shift in weather patterns and urbanisation are estimated to ensue more rapidly than most other regions on the continent (Grasham et al., 2019; Nagendra et al., 2018).

ii) The inhabitants of Cape Town has increased (from 1.6 million in 1980 to over 4 million in 2018) versus the water availability per person which has significantly declined every year (from a high-level of more than 500,000 litres per individual in the early 1980s to about 200,000 litres per individual in 2016) (Koopman & De Buys, 2017). The population of Cape Town in 2018 was stated as 4,055,580; the population by 2040 is estimated to be 6 million (Toale and Molfetas, 2019).

iii) The CCT instituted wide-ranging WC/WDM in the 1990s, including the decoupling of water demand from population growth. However, this management strategy did not reduce Cape Town's susceptibility to water shortages due to the lack of diversity in the water supply system.

2.7.7 Economy

Dadson et al. (2017) in their seminal study on WS, risk, and economic growth found that by improving the efficiency of water availability and supply in various economic sectors, particularly water intensive ones such as agriculture and energy production, water-related investment is required to reduce risk and stimulate growth. Likewise, in instances where initial WS is low, primary investment in water-associated assets facilitates development by reducing critical and continuous effects of water-related risks. These water-related risks include floods, droughts and water-related diseases. Deprived of timeous investing, deficits due to water-associated risks wield an impediment to economic development and may well lead to a poverty trap. Dadson et al. (2017) further contend that exposure of productive water-related assets to water-related risk demonstrates the significance of accounting for environmental and personal health risks in economic models. This practice will present insights into the design of robust strategies for investing in water-related productive assets to manage risk in relation to climate variation.

Winter (2019) agrees that a sustainable water infrastructure system requires a consistent and dependable revenue stream. During 2017/18, no more than 70% of revenue from water users was collected (City of Cape Town, 2019a). Deprived of revenue, the system turned out to be unstable and ineffective. The City intends to improve its revenue collection by attaining a collection rate of 95% or more. It will do so by "reducing the number of estimated meter readings, improving billing accuracy, making bills easier to understand, making it easier for customers to pay, and resolving account queries speedily" (City of Cape Town, 2020:60).

Although Cape Town is the major urban water consumer in the region, regional water resources are shared with other urban areas such as the towns of Paarl and Stellenbosch in addition to a large agricultural sector, thereby forming a significant part of the regional economy and having strong economic links to other sectors such as tourism and agricultural processing (Sinclair-Smith & Winter, 2018).

As a result of the drought, a 5.5% decline in estate values was identified (Barnard 2018; Nel, 2018). Nonetheless, the residential water demand continued unchanged. Between January 2016 and December 2017, the quantity of newly sunk boreholes for private use registered by the CCT increased from 1,500 to 23,000 (De Kock 2018). Because of a radical reduction in water use as a consequence of the combined water-saving actions, income from water sales plunged drastically. The CCT's projected water budget shortfall inflated to R1.7 billion for the 2017-2018 fiscal period, founded on utilisation data for October 2017 (Visser, 2018).

Cape Town's water crisis led to pertinent negative economic and social impacts. Job losses in key industries such as tourism and agriculture were substantial. Tourism is reported to directly employ more than 217,500 people in the Western Cape and contributes more than R18.4 billion (USD 1.27 billion) to the economy. Findings of an informal survey show that income from tourism contracted significantly during the typically busy months of January and February 2018 (Toale & Molfetas, 2019).

Economically, Cape Town and several other South African cities subsidise poorer inhabitants' water requirements via 'block tariffs', where high-use homes are levied an increased per litre rate (Wilkinson, 2000). Around 146,000 households are estimated to be in informal settlements around Cape Town (Enqvist & Ziervogel, 2019). Approximately 1.5 million people, consisting of more than 30% of the overall populace in the City, are unable to afford to pay for water and are hence entitled to a free-of-charge allocation on a monthly basis. Moreover, more than 40% of homes in Cape Town are supplied with water at no cost (indigent plus informal family unit), and as such, the cross subsidisation of water is crucial (Ziervogel, 2019).

The drought put the City under enormous financial and operational stress, not only Metropolitan staff and resources, but also non-water related facilities, which had to operate with reduced finances (Enqvist & Ziervogel, 2019). Ordinary residents as well as the region's tourism trade, the agricultural sector, and regional ecosystems were negatively impacted (Ziervogel, 2019). Parks et al. (2019) concur that the water crisis had a widespread fiscal and societal impact, with loss to the tourist and agriculture industries, and conflicts among segments of the populace and government. Wolski (2018) maintains that the water shortages in the CCT were predominantly caused by a lower than average rainfall, aggravated by other considerations such as high consumption and lack of timely investment in increased water supply capacity.

These illustrations show that improved integration of cross-sectoral viewpoints in fiscal and district design is an essential element of efficient water governance. Moreover, water resources are seen as both a requirement for and clearly impacted by existing and potential economic actions (Pengelly et al., 2017).

2.7.7.1 Agriculture

The 2018 water restrictions that cut 60% of supply to agricultural irrigation translated into 37,000 job losses in the Western Cape agricultural and related downstream sectors. It is estimated that as much as 50,000 people have been pushed below the poverty line due to job losses, inflation and increases in the price of food since the crisis began. By February 2018, the agricultural sector had sustained R14 billion (USD 1.17 billion) in losses owing to water scarcities (Toale & Molfetas, 2019). During the drought, the agricultural sector was limited to hard quotas for irrigation water use. Preceding the drought, only 8% of the CCT’s effluent was purified to produce recycled water of acceptable quality suitable for irrigation and industrial purposes. This recycled water did not comply with potable water quality standards (Parks et al., 2019).

Assessments projected that yields of major crops were 20.4% less than average from 2016/2017 to 2017/2018, translating into a R5.9 billion ($415 million) loss to this sector. Moreover, the expectation of diminished crop led to less employment opportunities for seasonal manual workers, with job losses exceeding 30,000 as a direct result during the drought. The effects of diminished crop yields are projected to continue for up to 8-10 years. The demise of work opportunities further escalated social discontent and conflict in agricultural districts (Parks et al., 2019).

2.7.7.2 Industry and commerce

Cape Town single-handedly produces approximately 10% of South Africa’s GDP, and 79% of local enterprises depict prolonged water shortages as a risk to their operations (Toale & Molfetas, 2019). In December 2017, Level 6 water restrictions were promulgated in the Provincial Gazette, which compelled industries to decrease water use to 45% of pre-drought levels at a flat commercial rate (Parks et al., 2019).

Kretzmann and Joseph (2020) contend that domestic water users were in turn exposed to corrective stepped rates, accounting for a 556% rise at the lowermost ‘step’ of 0 Kℓ to 6 Kℓ, from R4.56 to R29.93 per kilolitre, and a 195% increase in price, from R17.75 to R52.44 per kilolitre for usage between 6 Kℓ and 10.5 Kℓ.

observed that the 2018 restrictions brought about considerable job losses – approximately 37,000 in the Western Cape (Toale & Molfetas, 2019). Small companies and the informal sector were ‘hit hard’ as a result of being subjected to the restrictions. Large companies on the other hand it appears, was shielded, while minor operations were left to fend for their own survival. According to Kretzmann and Joseph (2020), on November 2019 the CCT failed to deliver on a data request lodged under the Promotion of Access to Information Act (PAIA) on water use by big businesses.

2.7.8 Water conservation/water demand management

The Water Research Commission (WRC) warned that the CCT would encounter a significant water resource predicament by the year 2007 (Isaacs, 2018; Water Research Commission, 1990). Proposals for intervention involved construction of new dam capacity alongside establishing additional water preservation and management legislation. The warning by the WRC was established on populace growth predictions and existing freshwater resources. Consequently, the CCT effectively applied several programmes to decrease water demand. Nevertheless, the insufficient financing for funding additional water supplies from national government prohibited water expansion plans to be timeously implemented to prevent the 2015-2018 drought (Isaacs, 2018; Umraw, 2018).

Ziervogel (2019) in her commentary on unpacking the drought reports that the CCT, being mostly surface and therefore rainwater-dependent, receives more than 95% of its current water requirements from a scheme consisting of six rainfall-dependent surface water storage facilities of the WCWSS. The WCWSS also provides irrigation water to agriculture and several other towns. Irrigation water demand for agricultural food, fibre and fuel production use is high in summer but lower during winter seasons, whereas the CCT use represents about 58% of the total WCWSS accessible water capacity, agriculture irrigation requirements account for 26%, whereas minor municipalities account for approximately 6%. Roughly 10% is lost back to the atmosphere via evapotranspiration and other leaks from the bulk water scheme.

WC/WDM has played a fundamental role in the CCT's water administration since the early 2000s (Ziervogel 2019). In fact, the IWRM programmes initially accomplished a water demand flattening the face of rapid urbanisation and population growth of 30% between 2001 and 2011 (Stats SA, 2012). Additional preservation and demand administration policies included the repairing of leakages and introducing water flow control apparatuses (Beck et al., 2016). Prior to 2017 though, water flow control apparatuses were employed at low-income communities with high water consumption, largely owing to leakages (Mahlanza et al., 2016).

The WCWSS model supplied water at 98% point of confidence for Metropolitan consumers. Thus, on average, a 49 out of 50 likelihood would exist for adequate water resources without the threat of supply constraints for Metropolitan water consumers (City of Cape Town, 2019a). The degree of confidence for agriculture was 95%, which translates into a 19 out of 20 possibility of adequate raw water resources without the threat of supply constraints to agricultural water requirements (City of Cape Town, 2019b). Generally, projects that focused on WC/WDM more often than not produce speedier outcomes with less financing expenditure, compared to financing increased water supply from alternative augmentation sources such as ground water, water re-use and desalination (Table 3.6) (City of Cape Town, 2019b; Ziervogel, 2019).

The CCT's mean per person water consumption in 2012 was approximately 223.4 ℓ/consumer/d (Taing, et al., 2019; City of Cape Town, 2019c). The CCT succeeded in limiting the overall requirements to about 1999 quantities notwithstanding a populace increase of 50%, which was partly owing to cutting losses from leaks (Western Cape Government, 2012). This resulted in the CCT having among South Africa's lowest measurements (15%) of unquantified water loss or non-revenue water compared to the world average of 36.6% in terms of on average water losses owing to leaks, inaccurate metering and illegal connections (Toale & Molfetas, 2019).

The WC/WDM efforts of the CCT have undeniably enhanced water use efficacy. Nevertheless, the anthropogenic influence, akin to hydrology, is not easy to forecast. Evidence from other locales shows that decreases in water consumption are rarely maintained as soon as restrictive conditions end. In the case of Windhoek, Namibia, where during repeated droughts, consumption was drastically decreased for the duration of scarcity, merely to revert to similar quantities experienced prior to drought conditions once the drought ended (Muller, 2017).

Virtual water, which represents water consumed during the production of goods thereafter exported, has become apparent as a crucial element in water consumption calculations (Parks et al., 2019). South Africa, and the CCT in particular, with major neighbouring agricultural production and processing sectors, is a nett exporter of virtual water (World Wildlife Fund, 2016). The resultant increase in intensity in agricultural water consumption has similarly impacted on current water scarcities (Ziervogel, 2019; Muller, 2018).

2.7.9 Ecological reserve

According to Sinclair-Smith and Winter (2018), it is imperative that enough water remains in river systems to preserve the environmental wellbeing of the natural aquatic systems. This is described as the ecological reserve. Currently ecological reserve requirements are factored into the planning and management of all new dams and water supply schemes, required by the National Water Act, 36 of 1998 according to the Government Gazette of 1998 (RSA, 1998).

2.7.10 Augmentation to diversify water resources

In their research to secure the future water supplies of the CCT and reflecting on the *Day Zero* plight of the CCT, Taing et al. (2019) report that all sources of water must be considered to ensure an efficient Water Service Delivery (WSD) system. Therefore, the CCT’s planned water conservation strategies meaningfully propose guidelines aimed at establishing, stockpiling, and utilising non-municipal or alternate water sources such as greywater, rainwater, surface stored run-off, treated effluent or ground water (City of Cape Town, 2017b). Ziervogel (2019) concur that the CCT needs to diversify its water sources and move away from being mostly dependent on rain-fed surface water.

The CCT’s experience with stormwater collection and recharge of the Atlantis aquiver has thus far provided the following benefits: (i) decrease of floods in high volume run-off during storms; and (ii) regional environment wellbeing advantages by safeguarding ecological resources and biodiversity. As a result, recreational areas such as natural parks and marshlands have been improved (Fisher-Jeffes et al. 2017), consequently improving collective importance as recreational spaces when executed in natural parks or marshlands (Fisher-Jeffes et al., 2017).

Historical perspectives on water insecurity emphasise supply augmentation, including construction of new dams and other water supply infrastructure and short-term water restrictions enforced during times of drought (Sinclair-Smith & Winter, 2018). Currently, water in the CCT is supplied by 14 dams with a combined capability of approximately 900 million m^3, the majority of which is supplied by six big storage facilities: Theewaterskloof, Voëlvlei, Berg River, Wemmershoek and Steenbras Upper and Lower. Essentially, 98% of Cape Town's water is sourced from surface water. Current augmentation consists of ground water from the Atlantis Aquifer and the Albion Spring in Newlands. The CCT's water supply forms part of the Western Cape Water Supply System (WCWSS), consisting of an cohesive and jointly-managed scheme of the CCT and DWS-owned infrastructure, consisting of dams, pump stations, pipelines and tunnels, supplying raw water to various urban areas and major agricultural users in the Western Cape region (Sinclair-Smith & Winter, 2018).

The CCT finalised a viability analysis in 2014 for a 150,000 (upgradable to 450,000) m^3/day desalination plant on the West Cape Coast. Notwithstanding current enhancements in desalination technology, operating costs were estimated to be very high (R386 million per year for a 150,000 m^3 per day plant or R1.2 billion per year for a 450,000 m^3 per day plant), while the capital outlay for a 450,000 m^3 plant is estimated at R16.5 billion. An additional concern is that this technology is energy-intensive and will contribute to increased national electricity demand and related carbon-dioxide discharges (Sinclair-Smith & Winter, 2018).

The drought created a heightened awareness of the significance of underground water, especially the question of effective management of aquifers. Seeing that sub-surface water fell under the auspices of the national government's DWS, the CCT subsequently had inadequate assets and capability to oversee ground water management requirements (Sinclair-Smith & Winter, 2018). The current ground water exploration projects, envisaged as part of the augmentation of existing water supply, includes the extraction of ground water from the Table Mountain Group (TMG) aquiver. However, this remains the focus of an ongoing feasibility study. Nevertheless, a number of experimental boreholes have been drilled in Hottentots Holland and Wemmershoek areas to establish the sustainable delivery volume and the associated environmental impacts (Sinclair-Smith & Winter, 2018).

The current and long-term ecological impact of the escalation of increased abstraction from the water table and the subsequent ground water quality appears to be ambiguous due to a lack of data. The large aquifers that the City plans to employ will be thoroughly managed and usage data captured. However, the influence of the widely dispersed multiple of individual household boreholes remains undetermined. This concern highlights the significance of enhancing monitoring and statistical evaluation of ground water abstraction and re-charge (Sinclair-Smith & Winter, 2018). Enqvist and Ziervogel (2019) state that individual household boreholes were an effective alternative for locals and enterprises to mitigate the hazard of failed water services. Unfortunately, the proliferation of privately operated boreholes exist in an inadequately delineated legal space and their expanded existence presents a danger to the health of aquifers (Simpson et al., 2019; Ziervogel, 2019).

Before the drought, the CCT re-cycled approximately 8% of its wastewater for irrigation for agricultural and industrial purposes, but not for domestic use (Parks et al., 2019). Water reclamation and re-use currently requires the treatment of wastewater to standards suitable for release into natural rivers. By improving this capacity, it could increase the supply of drinking water to the City. Treated sewage is currently used only for non-potable purposes such as irrigation, industrial and construction. DWS completed a feasibility study which investigated re-use options, including an option that utilises the Cape Flats Aquifer for storage (Department of Water and Sanitation, 2019). The benefit of this methodology is that effluent recycling is less electricity-intensive and therefore less costly than seawater purification. From a total of 23 effluent treatment plants serving the City, 13 of the largest Waste Water Treatment Works (WWTWs) will be able to supply 161.8 Mℓ/d of recycled water for re-use (Department of Water Affairs, 2010).

At present, the CCT is investigating the upgrading of the recycling capacity at Faure treatment plant to provide 70 Mℓ/d of usable recycled water for irrigation and industrial consumers (City of Cape Town, 2018a). The widely distributed WWTWs over the Metropole ought to enable a new widespread recycle approach. Public participation and instruction on water reprocessing together with extremely meticulous water quality monitoring programmes will be required given the possible adverse view of recycled water in the public domain and the possible community health hazards (GreenCape, 2018). Similar programs may also enable synchronisation among community groups and private actors to encourage distinct devolved solutions such as reclaiming more treated effluent water for irrigation (Parks et al., 2019).

Water extraction from known aquifers in the region was calculated to be the most cost-effective and fastest scheme to bring online a variety of augmentation options (City of Cape Town, 2018a). Considering the relationships between time to implement, probable volume contribution and costs, ground water exploration came out on top, because the operational and investment costs are lesser than other schemes as it consumes less electricity than other alternatives (City of Cape Town, 2019a). The CCT's Water Resilience Profile (City of Cape Town, 2019c) recommended expansion of the City's water infrastructure to mitigate the effect of potential water deficiencies by incorporating the objective to generate a further 100 megalitres per day (Mℓ/d). This is expected to contribute additional capacity to the Metropolitan water supply system from three aquifers situated across the CCT. The proposed timeframe for implementation is 12 to 48 months (City of Cape Town, 2018a). Nevertheless, to be sustainable, aquifers require restoration by re-fill, which can be achieved by natural means such as rain water run-off seeping back into the ground or artificially by pumping recycled water into aquifers. This is paramount to the sustainable continuance abstraction of water and the prevention of significant negative subsequent environmental impacts (Parks et al., 2019).

2.7.11 Data

Data quality of the South African Weather Service (SAWS) rainfall network has continued to deteriorate over the last 20 years (Muller, 2017). Seasonal rainfall assessments indicate that the 2014/15 and 2015/16 periods were not significantly lower than average. It was only in the latter part of the 2016/17 rainfall period that volumes less than 75% of the normal were measured. Even though a large amount of the CCT's supply is accumulated from comparatively tiny catchments, they are very susceptible to regional dry periods. The cyclical assessments between 2010 and 2016 indicate that reduced precipitation was the singular facet of the conundrum.

Wolski (2018) reports that consensus has not been reached, with some arguing that the 2015 to 2018 drought was a moderate occurrence. The principle reason for the CCT's water crisis is touted as inadequate planning and maladministration by the Western Cape Water Supply System (WCWSS). This is in line with others arguing that even though the drought was extreme, negative human factors may have exacerbated the status quo (Muller, 2018).

Several weather stations record rainfall data in the locality of WCWSS catchments and storage facilities. Raw data are accessible from the DWS website (dwaf.gov.za/hydrology). Wolski (2018) states that the majority of stations in the data sets contain decent rainfall records. There are some with frequent data gaps or substantial data variability available between 1981 and 2017. In effect, just four stations are located in the vicinity of WCWSS dams without significant gaps or systematic errors.

The South African Weather Service (SAWS, 2017) monitors and records rainfall data, with data for certain SAWS locations in the Western Cape dating back to the late 1800s. There is regrettably no commonality between the DWS and SAWS rainfall measuring stations (Wolski, 2018). Surface water quality data are accumulated every month in numerous of the City’s watercourses, but the data are not freely accessible to the public (Winter, 2019).

Ziervogel (2019) states that even though there are operational challenges within the DWS, they also have strengths. The DWS are in possession of substantial data bases on numerous water-related topics. For instance, there is considerable information on the subject of water resources contained in aquifers. However, gaining access to this material is problematic due to reporting formats, units and time interval discrepancies requiring investment in better means of sharing information and expertise. One of the primary challenges is selecting suitable indicators for successfully managing water supply, which is totally dependent on the source and format of data in the public domain. During the early stages of the drought, volume data on water consumption and the day-to-day status of the water supply scheme were neither properly grasped nor shared, thus making it challenging to access and draw information collectively from a single source. Significant progress has been achieved since, which has made reports such as the CCT’s Water Outlook Report available in the public forum (City of Cape Town, 2019a).

Securing information in general was not easy, as information relative to the WCWSS was inadequate at the beginning of the water crisis. This suggested that system data models and related statistics were restricted or unavailable in the public domain. While the DWS and the CCT utilise similar information sets, they apply it in different ways, and this generates uncertainty. Management of the WCWSS is crucial to assuring 95+% of Cape Town’s current water supply. Rainfall data and associated run-off calculations and reporting from the WCWSS were unsatisfactory at the beginning of the water crisis in 2015/2016. The incorporation of data on climate change, rainfall impact, water availability, and sector-specific water consumption volumes was and has limited accessibility in the public domain. Ziervogel (2019) reports that there were no well-formed systems within the CCT that administrators could have gained access to in order collect information. Public administrators reported having to rely on online information searches to assess successful best practice options executed in other parts of the world. Ziervogel (2019) further contends that some of the experiences gained on information management and communication by the CCT during the water crisis can be summarised as: (i) understand that the local water system is paramount; (ii) dynamically pursue external know-how and skill; and (iii) actively share water information publicly to build trust.

2.7.12 Governance, management and politics

Cape Town as it is known today originally consisted of 25 separate municipalities that were merged into 6 municipal structures in 1997. The singular City of Cape Town Metropolitan Municipality was established in the year 2000 (Beck et al., 2016; Smith, 2004). The main purpose was to facilitate the reallocation of tax proceeds from the entire Metropolitan region for cohesive service delivery outcomes throughout the City. This included the surrounding suburbs, townships, and informal settlements (Mills et al., 2019).

The water crisis experienced by Capetonians from 2016 to 2018 can therefore not be classified as merely having too much or too little water. Crises often expose a governance or organisational calamity where the establishments have been unsuccessful in creating resilience to adapt to altering environments (OECD, 2018; Ziervogel et al., 2017). The difficulty in being pro-active is often due to established party-political, societal, fiscal, and governmental structures. These structures officially and unofficially influence decision making over water assets expansion and administration (Woodhouse & Muller, 2017; Batchelor, 2007).

Visser (2018) states that a key obstacle in mitigating the CCT drought rests inside the DWS dominated by the ANC government. The DWS appeared to have become dysfunctional and plunged into a shambles. Sinclair-Smith and Winter (2018) concur with this view and add that political preferences for more traditional supply-side measures might also have hindered the implementation of WDM programmes. WDM initiatives in developed countries are generally oriented towards improving efficiency. WDM projects in developing countries focus more on reducing extremely high water leakage rates. This is to extend limited water resources to inadequately served and rapidly growing populations (Sharma & Vairavamoorthy, 2009).

Taing et al. (2019) contend that contributing factors were largely related to local government mismanagement and ignorance of the implications, such as the CCT's obliviousness of nationwide projections and generally ineffective medium- to long-term planning (Muller, 2018; Rodina & Findlater, 2018; Poplak, 2018; Newkirk II, 2018). The over-confident understanding of positive results and singular focus of the CCT's WC/WDM operations created a false sense of WS (Ziervogel, 2019; Muller, 2017).

Enqvist and Ziervogel (2019) state that good governance requires accounting for advancement of water sources, in particular to the benefit of all users. Moreover, good water governance requires harmonisation across sectors and scales, and also that water governance needs to be inclusive. Ziervogel (2019) supports this view, proposing that experience gained during the water crises can be successfully implemented via a systems approach of WC/WDM practices, namely: (i) dynamic management and incorporation of diverse portions of the water supply system; (ii) formation of a robust networked water supply system: and (iii) identifying and eliminating the restrictions of the existing water-related economic model. Ziervogel (2019) continues by proposing the development of adaptive capability to be organised and equipped in the event of severe incidents, whether these be climate-induced or otherwise responsible for negative service delivery impacts. Incidents that negatively affect the whole Metropole induce a variety of contagion effects to consumers, the financial system, the natural environment, and political affairs. Improving adaptive governance and capacity creation will improve preparation for identified threats, necessitating substantial re-visioning, resources, and time. The successful application of this methodology in cities across the world has demonstrated multiple benefits (Ziervogel, 2019).

2.7.13 Cape Town's Water Strategy

The early success of the WC/WDM interventions implementation by the CCT in reducing water losses and non-revenue water since 2011 created a false sense of WS. Moreover, the planned augmentation of Cape Town's water supply was not implemented because of high costs (Visser, 2018; Muller, 2017).

Failure by the CCT and the DWS to implement the planned Voëlvlei Phase 1, water re-use and desalination interventions to increase the capacity of the Western Cape Water Supply System (WCWSS) as well as the subsequent unforeseen increase in water demand resulted in the CCT experiencing an unprecedented water crisis (City of Cape Town, 2018a; Muller, 2017). The strategy to mitigate the drought depended on the following key performance areas:

i) Collaborate with the DWS to manage and monitor dam behaviour, increase surface water capacity in the Berg River and Voëlvlei dams. and clear alien vegetation in the surface water catchment areas through the *Working for Water* programme.
ii) Manage water demand initiatives and develop the CCT Water Strategy to formalise the financial and governance aspects around the level of assurance. Optimise of Augment projects regarding volume and timing.

The CCT during 2018 employed several parallel courses of action as part of its Water Conservation and Demand Management Strategy, namely:

i) Water restrictions: The consumption target set by the DWS for 2018 was decreased to 450 Mℓ/d. Individual consumption was reduced to 50 ℓ/person/ day at Level 6 water tariffs. This equated to 4 million citizens at 50 ℓ/person/ day = 200 Mℓ/d. 150 Mℓ/d was to be utilised by business, government etc., thus coming to a 100 Mℓ/d under daily target volume of 450 Mℓ/d.

ii) Public information drives: All inhabitants had to be made aware of the crisis. The CCT introduced several frequent press releases to aid citizens in lowering consumption (e.g. leak finding and fixing), how to maximise the use of 50ℓ daily, and maintaining the use of all mass media to connect with all residents, rallying everyone to decrease consumption to 450 Mℓ/d in alignment with level 6B limitations.

iii) Supply pressure decrease: The decrease of water supply pressure was first applied more than 10 years ago, then speeded up via automation in districts throughout the City to enhance the scheme and lower the demand – in particular the influence of leakages. Pressure reduction brings down volumes by restricting zones to limited allocation if required by high user demand. Savings of 55 Mℓ/d have been achieved.

iv) Domestic flow regulators: This represents the installation of water management devices to manage the debt of consumers in arrears and to limit homes who have not reduced consumption in cooperation with restrictions by limiting daily household usage and protecting against water loss due to leakage.

v) Corrective tariffs: Stepped block tariffs were applied in conjunction with water restrictions to levy higher rates for increased water use. Gradually higher punitive tariffs were applied in rising blocks tariffs, which resulted in a large volume users progressively being charged higher rates.

vi) Transformation: The CCT consulted with big and smaller enterprises to encourage and incentivise decreased water use. The overall impact of private boreholes on the system are still to be assessed.

vii) Consumer behaviour adjustment: The Star rating tool was introduced for marking and visually representing individual household consumption data on the CCT website to motivate all consumers to maintain usage limits.

A further component of the WC/WDM is augmentation of supply, i.e. bringing online alternative water sources. Augmentation projects (ground water, water re-use, and desalination of seawater) committed to and in progress cannot sustainably contribute adequate water to maintain the scheme in the short term, but it is critical for future supply (Department of Water and Sanitation, 2010; City of Cape Town, 2018a). The CCT is unable to contemplate total independence from the WCWSS as it requires >90% of its total supply from surface water sources from this system (City of Cape Town, 2018a).

Cape Town's Water Strategy was officially accepted by the City Council on 30 May 2019 after a period of public comment. There were approximately 200 formal responses from the public (Winter 2019; City of Cape Town, 2019b). The strategy resolved to provide a formal guide in support of the vision to become a more drought resilient and water sensitive City by 2040. The aims are to: (i) ensure safe access to water and sanitation; (ii) prudent use of existing water resources; (iii) sufficient development of reliable diverse sources; (iv) access and collective supply from regional resources outside the geographical area; and (v) a water sensitive City by 2040 (Winter 2019; City of Cape Town, 2019a).

South Africa's omission to learn from former water crises and a lack of a broad, interdisciplinary perspective is part of what has pushed it to *Day Zero* (Vogel & Olivier, 2019) The final strategy paper has not been published yet as officials are working on a more accessible and user friendly format and design. This will be a useful document that can be used to monitor the progress of attaining the five key performance indicators of the strategy (Muller, 2019). In tracing key performance indicators, three obvious indicators can be derived from the current strategy documentation available in the public domain, namely: (i) diversification of water supplies; (ii) management of water restriction levels; and (iii) improved revenue collection (City of Cape Town, 2019c).

The CCT committed to investing in alternative water sources, such as expansion of existing surface supply, ground water, desalination, and water re-use to augment existing supplies. The addition of 300 Mm^3 litres per day of augmentation supplies will cost approximately 5.4 billion in today's Rand value. This will by 2040 reduce the CCT's dependency on the WCWSS by 25% (City of Cape Town, 2018a; Muller, 2019). The determination of restriction levels will in future be based on volume of water available in the WCWSS at the beginning of the hydrological year, commencing on 1 November rather than the current revenue driven system (Muller, 2019). The implementation of a improved water revenue collection system will support the sustainability of the water infrastructure system. This will be achieved by improving the collection rate from 70% in 2017/2018 to 95% by lowering the amount of estimated readings and increasing invoicing correctness and accounts administration (City of Cape Town, 2019a).

All non-surface supplied and storage water systems have a cost premium over rain-fed water storage facilities. Despite extremely low rainfall circumstances as faced in 2017, the total volume of surface water run-off accumulated in surface storage facilities and dams was the approximate equivalent of ~720 Mℓ. For all intents and purposes, the CCT will continue to be dependent on surface water storage facilities replenished by rainfall (City of Cape Town, 2018a).

Dependability (high assurance of supply) of the scheme has been boosted by the addition of ground water, re-use of treated effluent and seawater desalination as alternative sources. The rates of these augmentation sources are tabulated in Table 2.3 and Table 2.4 in comparison to the rates of surface water from reservoirs at R5.20/Kℓ to enable worthwhile comparison and safeguard fiscal sustainability.

What is not evident from the strategy document is the lack of measurable indicators for social impact, safe access to water and sanitation and becoming a water sensitive City. Water quality and biodiversity in the rivers and wetlands as part of the progress to becoming a water sensitive city are also not specified. Surface water quality data are collected on a regular basis from all the CCT rivers, waterways and marine outfalls, but information is not accessible in the public domain (Muller, 2019). The CCT Water Strategy offers inadequate information on how equitable, reliable water supply will be achieved with agriculture and the regional towns dependent on the WCWSS (Muller, 2019).

Table 2.3: Water cost comparison of augmentation projects (City of Cape Town, 2018a:11)

Augmentation Project	Volume Yield	Cost per Kilolitre (1000ℓ)
Surface Water	60 Mℓ/d	R5.20
Ground Water	20-48 Mℓ/d	R12
Water Re-Use	10-70 Mℓ/d	R15
Desalination	12-150 Mℓ/d	R24-36

The water supplementation project has expanded considerably ever since initiation of the Water Resilience Programme in May 2017. The augmentation program is essential to delivering assurance in circumstances of minimal precipitation or reduced water accessibility. Cycles of minimal precipitation may turn out to be more recurrent and more acute as a consequence of climate variability. It is probable that supplementary, more costly sources of water such as re-use and desalination will be inactive during water sufficient periods. Development of these additional supplies will not have been wasteful expenditure as the cost of very severe restrictions on the economy exceed the investment in alternative water supply resources to ensure WS (City of Cape Town, 2019a).

In short, to assure drought resilience, the CCT requires differentiated water supply sources. The specifics of application and budget allotment are yet to be determined but it is concurred that resilience necessitates diversification of water supplies. (Department of Water and Sanitation, 2018; City of Cape Town, 2018a).

The Water Resilience Programme of May 2017, the CCT New Water Augmentation Programme of 2018, and the CCT Water Strategy proposal of 2019 identified the following alternative water sources to augment the WCWSS:

i) Ground water extraction from the Cape Flats Aquifer (CFA) and Table Mountain Group (TMG) Aquifer: Both these aquifers have substantial storage capacity. Ground water is also impacted by drought, but with a considerable time lag. The abstraction license obliges recharge of ground water aquifers from re-cycled effluent to refill the aquifer and to manage the improvement of water quality.

ii) Permanent seawater purification at the best possible scale: Assess and implement long-term desalination at a plant size or in modules of 120 to 150 Mℓ/d. Salt removal offers the single ‘new’ supply of water, and besides technological and fiscal limitations, it has an infinite augmentation capability and is not rain-dependent (City of Cape Town, 2018a).

iii) Large scale effluent re-cycling and re-use: With the cost per kilolitre of desalination and to a smaller degree ground water being considerably more than surface water, the most logical next water sources is to treat and re-use waste water to increase the advantage. The Faure Water Treatment Plant has been identified to initiate a recycling project with a capacity of 70 Mℓ/d (City of Cape Town, 2018a).

iv) Additional surface water storage facilities: The Bergriver/Voëlvlei Phase 1 Augmentation Scheme (BRVAS). which is expected to add 23 Mm^3 (60 Mℓ/d) into the WCWSS in 2021, will be implemented by the national DWS.

The sequence of events indicates that the consistency of average and timeous rainfall lulled the decision makers accountable for planning, developing and operating the WCWSS into a false sense of WS for Cape Town. This allowed the wrongful conclusion that the WC/WDM efforts alone were successful long-term solutions to ensure WS for the CCT and that planned augmentation projects could be postponed (Muller, 2017).

Human behaviour, very much like the hydrological cycle, is difficult to predict and to date, the majority of academic research into WS has been relatively poorly integrated with the needs of water practitioners and policy makers (Bogardi et al., 2016; Cook & Bakker, 2016; Meissner et al., 2018a; Sinclair-Smith & Winter, 2018).

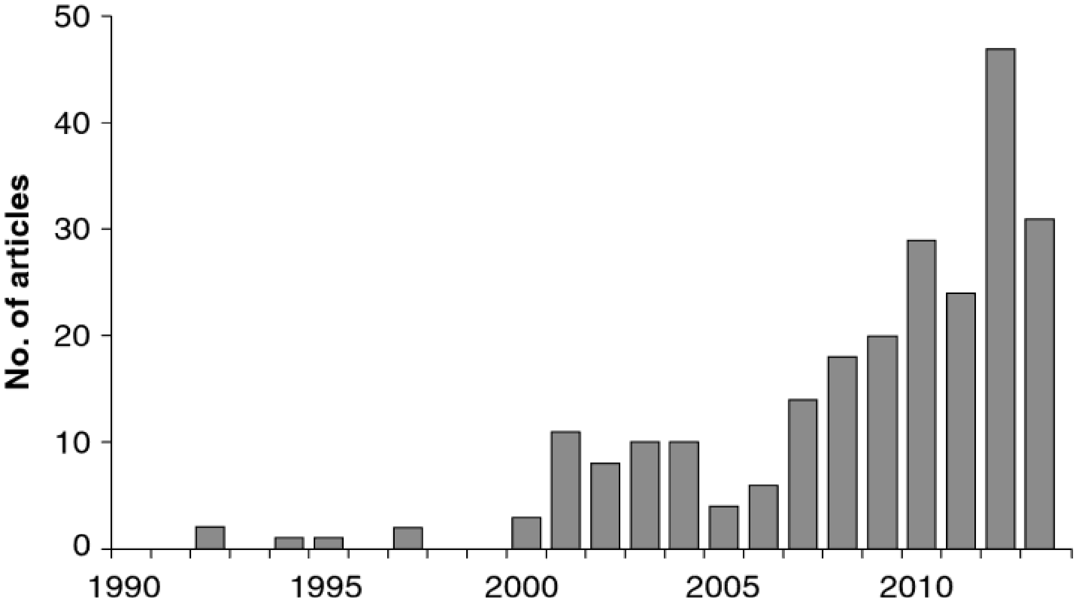


Figure 2.1: WS related articles in academic literature (1990-2013) (Cook & Bakker, 2016:20)

During the last 20 years. numerous peer-reviewed publications on WS have appeared across the social, natural, medical and engineering sciences world-wide (Cook & Bakker, 2016).

Schimpf and Cude (2020) report in their literature review that more than 25 different definitions of WS were quoted since 1998 (UN-Water, 2016; Jepson et al., 2017). The Jepson et al. (2017) domestic water insecurity assessment categorises these different descriptions into four interdisciplinary subjects:

- Human development needs
- Environmental sustainability
- Geopolitics
- Exposure, adaptation and risk to climate change

The assessment additionally differentiates by spatial domain level (e.g., individual, household, community, country, global) and WS framework (e.g., humanitarian, vulnerability, ecosystem sustainability, geopolitics) (Jepson et al., 2017).

Schimpf and Cude (2020) report the availability of 400+ peer reviewed WS publications across the social, natural, and medical sciences disciplines, with more than 50% appearing over the last 5 years (Cook & Bakker, 2016). The Cook and Bakker (2016) WS literature review showed 95 findings employing the search phrase ‘WS’ in the Web of Science database. Within the 95 commentaries, the bulk were focused on three major disciplines namely, water resources, environmental studies, and engineering, whilst less than 10 articles concentrated on public health. The review did not deliver results in terms of identifying the quantity of quoted classifications for water insecurity (Schimpf & Cude, 2020).

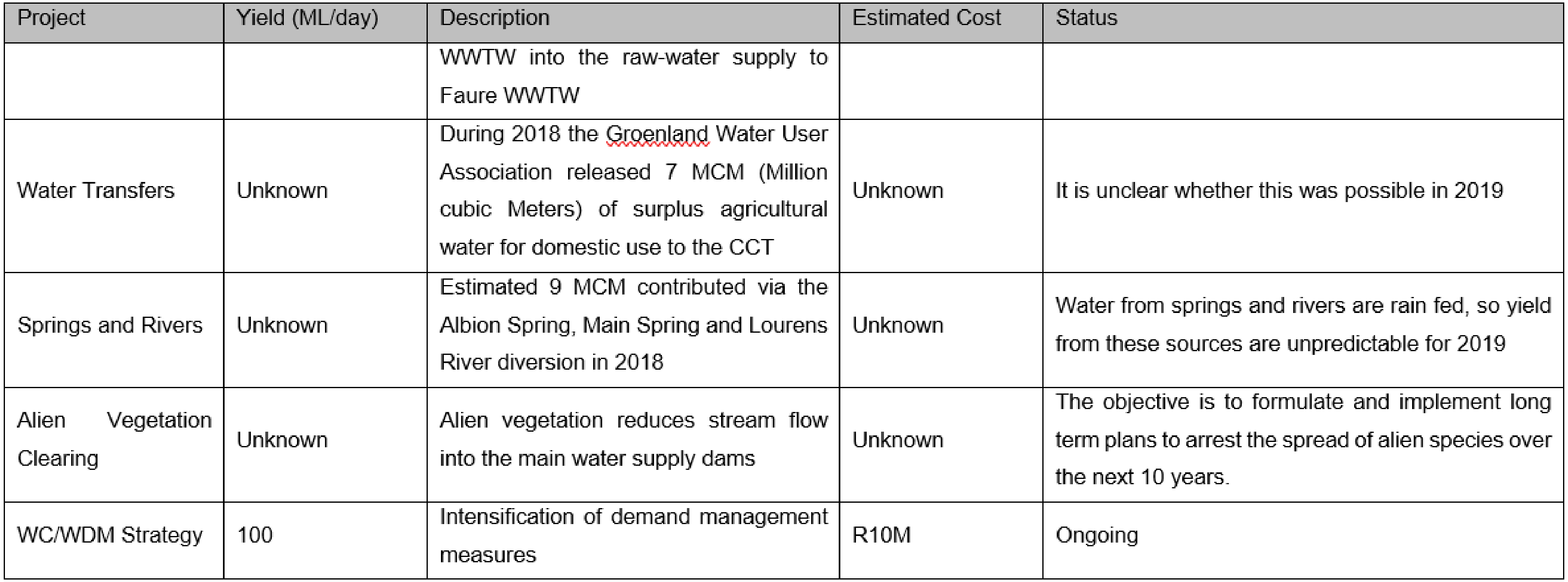
The crucial role that WS plays in supporting life in all its definitions as well as the lessons learned from the three-year drought brought on by increased climate uncertainty exposed a wicked problem with WS in the CCT (Muller 2017; Visser, 2018; City of Cape Town, 2019a). This research is based on the premise that water-related threats to economic growth and human livelihood, ecosystem services and increased hydrological variability enforce the need for robust WS research, incorporating and extending key aspects of Integrated Water Resource Management (IWRM) (Hering & Ingold, 2012).

This research contributes to crossing the current barriers between policy makers, practitioners and researchers (Bakker, 2012), by:

- Firstly, testing the WS of the CCT, using the Dynamic Frame work for WS as described by Srinivasan et al. (2017) (section 2.6.1)
- Secondly, expanding the framework to include the augmentation projects proposed by the City of Cape town (2020)
- Thirdly, testing the augmentation projects for their risk profile through Regional-Scale Risk Assessment using the Relative Risk Model (RRM) (O’Brien et al., 2018)

Table 2.4: Cape Town's water augmentation projects (revised from Flower, 2017; City of Cape Town, 2018a)

Project	Yield (ML/day)	Description	Estimated Cost	Status
Additional Surface Water	60	Augmentation of Voelvlei Dam capacity Phase 1	R300M	Planned for completion at end of 2021
TMG Aquifer	10	Development of well fields into deep aquifer at Steenbras, Wemmershoek and Theewaterskloof Dams	R85M	In progress, yield contribution to CCT water supply insignificant. Progress strained due to unknown environmental impact (CCT, 2018)
Cape Flats Aquifer	20-48	The CFA stretches over nearly 400 km2, from False Bay in the south to Tygerberg Hills in the north-east and Milnerton in the north-west.	Unknown	As per the water strategy, the target yield for the CFA over the next 10 years is 20MLD starting in 2019 up to 48MLD by July 2020
Atlantis Aquifer	5-12	Artificial recharge of the Atlantis aquifer began in 1979, the naturally recharged groundwater yield of the aquifer was insufficient to meet the area's long-term need	Unknown	By Apr 2018, 33 boreholes were in production with a cumulative yield capacity of 20 MLD with available boreholes pumping 24/7. Thus far, local demand has been sufficiently met with 14- 16 MLD
Temporary Small-Scale Desalination	10-20	Strandfontein Monwabisi V&A Waterfront	R250M	Limited success, major negative impacts on system delivery experienced during 2018 operational (CCT, 2018)
Permanent Desalination at Scale	100-150	The Site Selection Investigations were initiated in September 2018. (CCT, 2018)	Unknown	Feasibility studies still being conducted
Wastewater Re-use for drinking water	70-100	Faure New Water Scheme project is being designed to provide 70 expandable to 100MLD of re-use water from Zandvliet and potentially Macassar	R250M	Not in production, Target Yield for the scheme is 70MLD by January 2023 (CCT, 2018)



Project	Yield (ML/day)	Description	Estimated Cost	Status
		WWTW into the raw-water supply to Faure WWTW		
Water Transfers	Unknown	During 2018 the Groenland Water User Association released 7 MCM (Million cubic Meters) of surplus agricultural water for domestic use to the CCT	Unknown	It is unclear whether this was possible in 2019
Springs and Rivers	Unknown	Estimated 9 MCM contributed via the Albion Spring, Main Spring and Lourens River diversion in 2018	Unknown	Water from springs and rivers are rain fed, so yield from these sources are unpredictable for 2019
Alien Vegetation Clearing	Unknown	Alien vegetation reduces stream flow into the main water supply dams	Unknown	The objective is to formulate and implement long term plans to arrest the spread of alien species over the next 10 years.
WC/WDM Strategy	100	Intensification of demand management measures	R10M	Ongoing

Note: The above assessment by the CCT providing in the region of 350 Mℓ/d needs to be considered as provisional and is likely to change (City of Cape Town, 2018a).

2.8 Indices and indicators for WS

The inter-connectedness of freshwater availability, water use, and human well-being has in the past decade seen a significant increase in writings from various paradigms and disciplines. It is generally accepted that adequate clean water is a fundamental requirement for human health, ecological sustainability, and the production of food, goods and services as well as the generation of electricity (Gleick et al., 2002). With the evolution of knowledge of the underlying relationships between these water-related variables, so too has the need to measure, evaluate and report on the various implications been growing. Correspondingly, the use of water-related indicators and indices to measure, track and predict water-related phenomena, gained momentum (Gleick et al., 2002).

Indicators (*indicare* – to show, point out) are instruments that offer evidence about phenomena (Fiege, 2019; Mitchell, 1996). These instruments convey or advise on the advancement of a procedure in the direction of an objective, such as sustainable development. It can similarly signify a tendency about a happening and a development in management performance (Hammond et al., 2015). Indices to measure various aspects of water resources have been used (i) in France since the 1880s to determine the qualitative measure of biota on the river Seine, and (ii) in England during the 1900s for the development of Chemical Oxygen Demand (COD) analysis to measure biological pollution focusing on public health and sanitation. In the 1960s, the focus moved to indices affecting the environment, where recently the paradigm shifted to water resource development and WS, with the focus on increasing pressure on water resources from urbanisation and climate change (Global Water Partnership, 2000).

The development and application of indices are highly influenced, open to bias, and distortion by role-players dependent on political and financial incentives. The use of multi-dimensional indices attempting the inclusion of various variables in combination with mathematical functions and weightings assigned by experts may result in an ‘information Iceberg’, where the value of the fundamental data and how it is accumulated is mostly kept concealed from the view of the end-user (Molle & Mollinga, 2003). A problem inherent to the creation/selection and using of indicators for WS is the mixing of inputs, outputs and states of the variables used to define the index and the failure of many indicators to identify their ultimate goal and purpose. This emphasises the necessity of the unbiased utilisation of the indicator to be targeted towards a defined controlling or evaluation action (assessing WS with appropriate indicators) (Global Water Partnership, 2000).

The definition of an objective performance indicator requires a set of measurable raw values tabulated into framework systems for summarising into Key Performance Indicators (KPIs). KPIs for WS can be categorised as follows (Chaves, 2014:85; Liu et al., 2017:553):

- Quantitative – indicators represented by numbers
- Qualitative – indicators not represented by numbers
- Primary – indicators that can forecast the outcome of a method
- Trailing – indicators presenting the success or failure of a process *post hoc*
- Input – indicators measuring the assets expended, producing the conclusion
- Process – indicators representing the efficacy of the method
- Output – indicators reflecting the outcome or findings of a method
- Practical – indicators interfacing with prevailing established methods
- Directional – indicators reflecting whether an organisation is advancing or not
- Actionable – indicators adequately controllable to affect change
- Financial – indicators employed in performance evaluation from an operating index perspective

The primary objective for the indicators chosen is to provide practical and strategic results that will maximise value to the user. KPIs are tools to periodically assess the performance of institutions, businesses, sectors and individual stakeholders against understandable, meaningful and measurable parameters (Chaves, 2014). Molle and Mollinga (2003) supports the paradigm that indicators are indispensable pre-requisites for the evidence-based decision-making process to facilitate (i) advising and aligning policy, (ii) evaluating, and (iii) assessing situations and implementation. Indicators and indices should aggregate and simplify relevant information, displaying and communicating trends to end-users and decision makers (Gallopin, 1997). Original raw data should remain accessible, understandable, plausible, applicable and commonplace (Habitat Conservation Trust Fund, 2003).

Variable numbers used to calculate meaningful indicators should be applicably large enough to envelop the complexity of the problem/process to be assessed, but also small enough to be obtainable by interested and affected parties. Indices such as the Environmental Sustainability Index (ESI) (Esty et al., 2005) consisting of in excess of 20 sub-indicators and variables, are applicable only in data-rich environments (Chaves & Alipaz, 2007). This makes applying the ESI only viable in first world countries where appropriate HISs are maintained. Chaves (2014) argues that WS indices need to be adequately integrated with several related resources because of its interrelated dependency on resources such as land (Falkenmark &

Lundqvist, 1998), population (Sullivan, 2002), natural vegetation (Chaves & Alipaz, 2007) and climate (WWAP, 2014).

A tabulation of several mainstream water indicators, indices and frameworks in use internationally are presented in Table 2.5 with reference to their data requirements and applications in short. This is by no means an exhaustive list. A short discussion of some of these indicators/indices follows in the sub-sections below.

Table 2.5: Water resources indicators, applicable scales and data requirements (adapted from the European Commission, 2005; Liu et al., 2016)

#	Indicator/ Index	Reference	Spatial Scale	Required Data
1	Falkenmark Water Stress Indicator	Falkenmark (1989)	Country	Total annual renewable water resources versus population
2	Vulnerability of Water Systems	Gleick (1990)	Watershed	Storage volume (of dams) Total renewable water resources Consumptive use Proportion of hydroelectricity to total electricity Ground water withdrawals Ground water resources Time-series of surface run-off
3	Basic Human Needs Index	Gleick (1990)	Country	Domestic water used per capita
4	Water Resources Vulnerability Index (WRVI)	Raskin (1997)	Country	Annual water withdrawals Total renewable water resources GDP per capita National reservoir storage volume Time-series of precipitation Percentage of external water resources
5	Water Scarcity Indicator	Heaps et al. (1998)	Country, Region	Annual freshwater abstractions Desalinated water resources Internal renewable water resources External renewable water resources Ratio of usable water
6	Relative Water Scarcity Indicator	Seckler et al. (1998)	Country	Water withdrawals in 1990 Water withdrawals in 2025
7	Water Availability Index (WAI)	Meigh et al. (1999)	Region	Time-series of surface run-off (monthly) Time-series of ground water resources (monthly) Water demands of domestic, agricultural and industrial sector
8	Dry Season River Basin Flow Indicator	WRI (2000)	River Basin	Time-series of surface run-off (monthly data) Population
9	Access to drinking water and sanitation services	WHO/UNICEF (2000)	Country	Percentage of population with access to drinking water Percentage of population with access to sanitation services

#	Indicator/ Index	Reference	Spatial Scale	Required Data
11	Index of Watershed Indicators (IWI)	USEPA (2002)	Watershed	15 condition and vulnerability indicators
12	Water Poverty Index (WPI)	Sullivan (2002); Sullivan et al. (2003)	Country, Region	Internal renewable water resources External renewable water resources Access to safe water, access to sanitation Irrigated land, total arable land, total area GDP per capita Under-5 mortality rate UNDP education index Gini coefficient Domestic water use per capita GDP per sector Water quality variables, use of pesticides Environmental data (ESI)
13	Green-Blue Water Scarcity	Rockström et al. (2009); Gerten et al. (2011)	Country, Region	Requirement versus availability of green-blue water resources
14	Water Footprint based assessment	Hoekstra and Mekonnen (2011)	Country, Region	The ratio of water footprint to water availability
15	Quantity-quality environmental flow (QQE) indicator)	Zeng et al. (2013); Liu et al. (2016)	Country, Region	Incorporating water quantity, quality and Environmental Flow Requirements (EFR)
16	Urban Water security Indicator	Jensen and Wu (2018)	City, Region	Resources, Access, Risks and Governance

2.8.1 Falkenmark Water Stress indicator (Resources to Population Index)

When illustrating water accessibility in a nation, the Falkenmark Water Stress Indicator, which has been created by the Swedish water professional Falkenmark (1989), is one of the most frequently employed gauges.

The indicator is founded on the view that a 1,000 Mℓ can sustain 2,000 individuals in a highly developed society. Making use of Israel as reference, the total annual renewable water resources per person can be assessed. It is then considered that water availability in excess of 1.7 Mℓ/person/annum is described as the upper limit beyond which water scarcity happens only occasionally or locally. Beneath this volume, water shortage occurs in various degrees of severity. Below 1.7 Mℓ/person/annum water scarcity occurs on a regular basis, whereas less than 1.0 Mℓ/person/annum water scarcity becomes a constraint to commercial growth, health and general well-being. Any area with less than 500 Mℓ/person/annum water availability presents a possible restriction to survival and life.

In spite of wide application and acceptance, this indicator presents several limitations according to Chaves (2014). Primarily, only renewable surface and ground water flows in an area are studied. Additionally, the water accessibility per individual is determined as an average with respect to both the temporal and the spatial scale, thereby disregarding water scarcities during arid periods or in specific areas inside a country (European Commission, 2005). It also does not consider water quality, nor does it provide evidence concerning a country's capacity to make use of the resources. Even though a country may have adequate water as a result of the Falkenmark indicator, it might not be possible to utilise because of pollution or limited physical access (Chaves, 2014).

2.8.2 Vulnerability of Water Systems indicator

This index was created by Gleick in 1990 to be applied to watersheds in the United States as an element of possible climate change impact on water supplies and water schemes. The Vulnerability index explains the susceptibility of water supply systems founded on the five benchmarks and related limits (thresholds) listed below. The gauges are not grouped into an encapsulating index but offer several solutions to every area. This methodology accentuates the segments of watersheds that are put at risk (Gleick, 1990; Gleick, 2018:8869):

i) Storage capacity comparative to total renewable water supplies: Watershed is classified as exposed if the storage capability is lower than 60% of the overall renewable water supplies.
ii) Consumption Water (CW) use comparative to total renewable water supplies: Upper limit for susceptibility is a ratio of 0.2.
iii) Ratio of hydroelectricity comparative to total electricity: If the contribution of hydroelectricity exceeds 25%, the territory is deemed susceptible.
iv) Ground water overdraft comparative to total ground water abstraction: Areas with a ratio exceeding 0.25 are classified as at risk.
v) Inconsistency of flow: This is computed by dividing the surface run-off by the quantity contained in storage. A low ratio <3 implies a low variability of run-off and therefore a low risk of floods or droughts equally. A variability value >3 indicates vulnerability in this aspect.

2.8.3 Basic Human Needs Index

This methodology is founded on the utilisation as an alternative to the availability of water. The UN-Water (2016) computed the volume of water required per individual to fulfil basic water requirements (BWR). This BWR consists of needs such as drinking, food preparation, washing, sanitation and hygiene, as 50 ℓ/person/day. By following this index, assessments of the number of countries are considered where the median household water use is lower than this level. This methodology of this index is exclusively applied at a country level. District water scarcity is not represented and water quality is not incorporated into the model. Moreover, country-wide figures on household water usage have been found to be lacking and untrustworthy. The demands of additional water consumers, including commerce, agronomy or the environment, are not considered by this index approach.

2.8.4 Water Scarcity indicator

The Water Scarcity indicator considers data on water abstractions and water accessibility to indicate water scarcity. Its initial description was devised by Falkenmark (1989). Subsequent evolvement included various adaptations to facilitate a variety or requirements and data sets, including the intensity of water consumption of resources, for example, the bulk freshwater consumption as proportion of the complete renewable water supplies or as ratio of domestic water supplies (Liu et al., 2017). Heaps et al. (1998) supplemented the variable of desalinated water supplies to the Water Scarcity indicator. The portion of desalinated water utilisation is inconsequential on the international scale, but it is critical in several counties, for example in the United Arab Emirates. In the UAE, desalinated water represents 18% of the yearly consumption. As with the case of the Basic Human Needs Index in section 2.8.3, and the Water Scarcity Index in section 2.8.4, this indicator ignores temporal and spatial differences along with water quality information.

2.8.5 Water Availability Index

Meigh et al. (1999) considered the temporal inconsistency for water accessibility in their application of their GWAVA model. This specific indicator incorporates surface water and ground water supplies in contrast with the overall volume requirements of each sector, such as household, business and agricultural requirements. The period displaying the highest shortfall or lowest excess correspondingly is significant. The indicator is standardised to the range –1 to +1. While the indicator is nil, accessibility and requirements are balanced. The surface water accessibility is determined as 90% of the dependable run-off. The ground water accessibility is projected as either the probable recharge determined from the monthly surface water balance, or as the potential aquifer yield. The smaller number is reflected in the computation. This index does not consider desalination or the virtual water footprint as described by Hoekstra (2008). Neither does it account for the human-water heterogeneity as has been incorporated into the DFWS as one of the indicators, similar to the Production Water and Consumption Water (PW/CW) footprint (Srinivasan et al., 2017).

2.8.6 Dry Season River Basin Flow indicator

This indicator was established by the World Resources Institute (WRI) as part of the Pilot Analysis of Global Ecosystems (PAGE) (WRI, 2000) for the determination of water status on the spatial level of a river basin. It only contemplates freshwater resources and not water re-use or desalination. This indicator reflects on the temporal unpredictability of water accessibility crucial for instance in localities with distinct rainy and dry seasons. Water catchments with a dry period are considered where less than 2% of the water run-off is usable in the four driest months of the year. The indicator is computed by dividing the run-off volume throughout the dry period, that is, the four successive calendar months with the smallest collective run-off, by the populace. Founded on the Falkenmark definition, a catchment is considered water stressed if less than 1.7 Mℓ/person/year is accessible, and quantities between 1.7 Mℓ/person/year and 4.0 Mℓ/person/year imply sufficient quantity of water. The spatial application is not appropriate for use in this research as this study is considering WS across several water catchments or basins. However, it is still being used to determine dry season river basin flows in major rivers (Yuan et al., 2019; Marques et al., 2019; Liersch et al., 2019). An additional drawback is that this indicator does not embody a complete image of the water supply circumstances as it represents merely the water accessibility. However, as it does incorporate temporal unpredictability of water supplies into consideration, it may operate as a component of a more complicated framework.

2.8.7 World Health Organisation (Access to drinking water and sanitation services)

One of the truly vital achievements has been the acknowledgment in July 2010 by the United Nations General Assembly of the Human Right to Water and Sanitation (Office of the High Commissioner of Human Rights, 2000). This paradigm is still driven by the World Health Organisation (WHO) and the United Nations Children's Fund (UNISEF) Joint Monitoring Programme (IMP) for water today (WHO/UNICEF, 2019). The WHO/UNICEF JMP for Water Supply, Sanitation and Hygiene internationally generates relevant assessments of progress on drinking water, sanitation and hygiene (WASH). They are also responsible for world-wide monitoring of the Sustainable Development Goal (SDG) objectives associated with WASH. Their report offers informed national, regional and global assessments for WASH in homes for the period 2000-2017. The 2030 Agenda for Sustainable Development obligates UN members to take courageous and transformative strides to shift the world onto a sustainable and resilient water path, inclusive of the recognition of basic human rights for all, the end of poverty in all its forms, and to ensure no one will be left behind. The UN General Assembly conducted its initial four-yearly assessment of advancement in September 2019. Their statement evaluates progress in lowering disparities in everyday WASH services and pinpoints the peoples most at risk of being “left behind” (WHO/ UNICEF, 2019:6). The Assembly acknowledges every human-being’s right of access to adequate water for private and household use (50 to 100 ℓ/person/day). The water must be harmless to drink, adequate and reasonably priced (water costs ought not exceed 3% of total household take-home pay). Water should be materially available (within 1,000 metres of the house and collection time should not exceed 30 minutes).

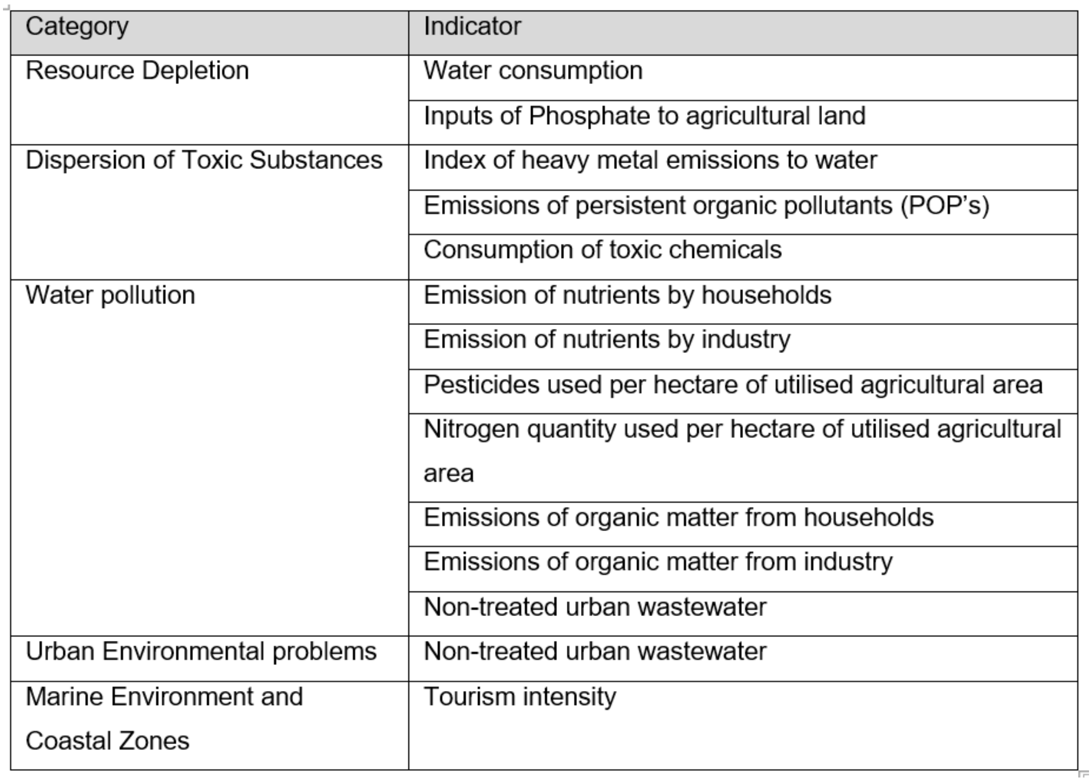
Water and the Sustainable Development Goals SDG 6 is to “ensure availability and sustainable management of water and sanitation for all” (United Nations Global Compact, 2020:1). These targets include the complete aspects of the hydrological cycle and sanitation systems. The accomplishment is devised to add to improvement among a variety of additional SDGs, for the most part focused on wellbeing, schooling, finances and the natural environment. The UN has for a significant period addressed international calamities created by inadequate water allocation to meet fundamental human requirements. These are inclusive of increasing pressure on the world’s water supplies to meet domestic, commercial and agricultural needs (UNESCO, 2014; WHO/UNICEF, 2019):

i) In total, 2.1 billion individuals do not have access to securely administered potable water supply (WHO/UNICEF, 2019).
ii) In total, 4.5 billion individuals do not have access to adequate sanitation services (WHO/UNICEF, 2017).
iii) In total, 340,000 children younger than five perish annually from waterborne diseases (WHO/UNICEF, 2015, 2019).
iv) Water insufficiency even now affect 4 out of every 10 people (WHO/UNICEF, 2019).
v) Ninety per cent (90%) of all natural catastrophes are water-related (UNISDR, 2017).
vi) Eighty per cent (80%) of effluent flows back into the ecosystem without treatment or re-use (UNESCO, 2014).
vii) Approximately 60% of the world’s transboundary watercourses operate without a cooperative management framework (Stockholm International Water Institute, 2020).
viii) Agriculture accounts for 70% of global water use (FAO, 2020).
ix) Seventy-five per cent (75%) of the total industrial water abstraction is for energy production (UNESCO, 2014; WHO/UNICEF, 2019)

2.8.8 Water Poverty Index

The Water Poverty Index (WPI) (Sullivan, 2002; Lawrence et al., 2002), was created by the Centre for Ecology and Hydrology (CEH) in Wallingford. This index aims to demonstrate the correlation between water shortage concerns and socio-economic facets. It classifies nations along the lines of the provisioning of water, blending five elements as follows: Resources, Access, Usage, Capacity and Environment (Shalamzari & Zang, 2018; El-Gafy, 2018; Wurtz, et al., 2019). These elements are drawn from two to five indicators, which are standardised to a range from 0 to 1. In the instance of equivalent weighting, the sub-index and element values are assessed as a straightforward average of the related indicators. This value is multiplied by 20. The overall index is produced as a sum total of the element values to obtain a value between 0 and 100. A value of 100 is only feasible if a nation ranks the highest in each of the five elements. These indicators are easy to employ and comprehend but it lacks explaining the true nature or influencers of WS. The more complicated indicators are not extensively utilised because of the complexity of data required that are absent in developing countries. The Environmental Sustainability Index (Table 2.6), which ranks 97 markets, represented 89.1% of the world's population and 97.2% of global GDP in 2018, thereby highlighting country-specific risks and opportunities in the sustainability space (Research and Markets Report, 2019).

Table 2.6: Environmental Sustainability Index (Research and Markets Report. 2019:2)



Category	Indicator
Resource Depletion	Water consumption
	Inputs of Phosphate to agricultural land
Dispersion of Toxic Substances	Index of heavy metal emissions to water
	Emissions of persistent organic pollutants (POP's)
	Consumption of toxic chemicals
Water pollution	Emission of nutrients by households
	Emission of nutrients by industry
	Pesticides used per hectare of utilised agricultural area
	Nitrogen quantity used per hectare of utilised agricultural area
	Emissions of organic matter from households
	Emissions of organic matter from industry
	Non-treated urban wastewater
Urban Environmental problems	Non-treated urban wastewater
Marine Environment and Coastal Zones	Tourism intensity

To counter criticism of stationary indicators and incorporate both the interconnectedness among human and water systems and the considerable amount of routes by which these systems develop, Srinivasan et al. (2017:14) suggest framing WS as a consequence of linked human-water structures. The authors propose this dynamic methodology to WS in three stages:

i) Use a combination of indicators that convey human-water usage to water accessibility.
ii) Frame how these indicators chart to distinct categories of water insecurity.
iii) Present a set of contributing elements that pushes both human-water usage and water accessibility, and then model these indicators in the context of connected human-water structures.

2.9 Frameworks

A framework can be depicted as a comprehensive synopsis or outline of interconnected elements, which endorses a specific methodology to a detailed purpose. This framework operates as a guide that can be amended as necessary by inserting or removing items (Flynn, 2016). The term ‘framework’ can also be seen as a supportive structure around which something can be built or as a system of rules, ideas, or beliefs that is used to plan or decide something (Srinivasan et al., 2017).

A number of frameworks have been proposed to assist WS evaluations and policy making at various levels, from regional watersheds to a nationwide and world-wide scale (Grey & Sadoff, 2007; Norman et al., 2013; Van Beek & Arriens, 2014). Frameworks may share parallels with wide-ranging water governance assessments in one perspective (OECD, 2018), while on the other hand emphasise measurable risk and resistance evaluation methods that are applicable to water accessibility, weakness and sustainability indicators (Vollmer et al., 2016; Pires et al., 2017). The latter allows graphical evaluations and trend assessments with relatively minimal effort but have been found to overly simplify complicated and every so often disputed water matters, thus abandoning their societal and governmental components (Zeitoun et al., 2016). Therefore, WS as a model can be equally widened and deepened and its functional applicability enhanced by blending quantitative and qualitative assessments, thus studying WS via a variety of complementary facets and elements while participating with a variety of interested and affected parties.

This research covers two critical elements to achieving WS, which, according to accessible information, have not been addressed to date. The significance of studying the relationships among diverse water uses and users, freshwater systems, and other sectors is progressively more emphasised (World Economic Forum, 2011; Hoff, 2011; Vollmer et al., 2018).

A significant quantity of frameworks and indicators have been created to evaluate the sustainability of water administration from a local to a global scale – see the reviews of 95 indicators by Vollmer et al. (2016) and 170 indicators by Pires et al. (2017). These indices facilitate in-basin assessments over various timescales or through states and comparative assessments throughout water catchments or states. Vollmer et al. (2016) established a Freshwater Health indicator and employed it in an Asian water course, while Jensen and Wu (2018) created urban WS indicators (UWSI) and piloted them in Hong Kong and Singapore. In supplement to surveys with distinct spatial dimensions, there is research that concentrates on a particular sector, such as agricultural water usage (Allain et al., 2018). In most of the previous WS and sustainability evaluations, the target area was situated either in Africa or Asia, with recent research primarily centred on China (Vollmer et al., 2016; Sun et al., 2016a, 2016b; Jensen & Wu, 2018; Li et al., 2019).

The scope in the established frameworks and indices differs to a great extent. Chaves and Alipaz (2007) presented the Watershed Sustainability Index (WSI), which includes hydrology, ecosystem, natural life, and policy, all containing the factors of stress, government, and reaction. Gain et al. (2016) performed a spatial multi-criteria evaluation to consider WS in terms of availability and accessibility to services, safety and quality, and management (Marttunen et al., 2019). Sun et al. (2016a, 2016b) apportioned elements influencing sustainable water consumption into five sub-categories, including their vital variables: economy, population, water supply and demand. This apportionment of elements coupled with distinctive sub-variables for water supply and demand, accounted for water pollution and management capability in relation to waste water treatment capacity (Marttunen et al., 2019).

Frameworks, indices and indicators can play a significant role in numerous aims, for instance:

i) To be employed as diagnosing instruments to detect risks to WS (Vörösmarty et al., 2010).
ii) To be employed as management instruments to provide guidance to executive policy, the allotment of assets, and to assess the efficacy of interventions (Jensen & Wu, 2018; Lawrence et al., 2002).
iii) To stimulate policy actions (Jensen & Wu, 2018).

iv) To enhance prospects for producing assessments on the efficacy of administration policy (Lawrence et al., 2002).
v) To offer assessment assistance for improved design of district water resources development (Li et al., 2019).
vi) To be effective instruments for interested party engagement and communication, and to enable policy makers to communicate policy achievements to the public (Jensen & Wu, 2018).
vii) To be essential instruments for the activation of integrated water resources management (Vollmer et al., 2018) and sustainable development goals (United Nations, 2015a; Srinivasan et al., 2017).

Notwithstanding the fact that numerous suitable indicators and indices have been created to evaluate the sustainability of water administration, their usefulness in policymaking is not commonplace (Lehtonen, 2015; Howlett & Cuenca, 2017). Several challenges are contained in the application of indicators and indices that may clarify their restricted use. Operational challenges correlate to the selection, banding and combination of indicators, and deliberation of interested party (stakeholder) involvement (Sun et al., 2016a, 2016b). The sizeable variety of perspectives have developed into a large number of indicators and indices, which renders the selection of those that are applicable, analytically sensible and quantifiable, as problematic.

Numerous literature evaluations were published throughout the last couple of years, addressing hypotheses and practices associated with the Water-Energy-Food nexus (Keskinen et al., 2016, Endo et al., 2017; Mannan et al., 2018; Galaitsi et al., 2016; Simpson & Jewitt, 2019). It is noted with interest that these reviews are in agreement that the effectiveness of WEF nexus techniques to methodically assess water, energy and food interlinkages has been constrained (Albrecht et al., 2018). A practical WEF nexus investigation has yet to substantiate claims that nexus methodologies can develop resource management and governance outcomes (Galaitsi et al., 2016).

In terms of this research, the recommended framework supports these definitions by operating as a comprehensive, rational, stepwise model that establishes the links among a variety of interconnected models. This is achieved at the same time as describing applicable information or segments essential to accomplishing specified outcomes. The framework ought to have the following characteristics, according to Chaves (2014):

i) Universal and adjustable: the framework ought to be relevant to a variety of settings in distinct establishments (within capital-intensive industries) and should not be limited to a particular location only.
ii) All-inclusive and thorough: the framework ought to be a multi-discipline, cohesive, universal methodology that considers the whole, or at minimum the bulk, of the applicable characteristics involved in the conundrum researched.
iii) Objective- or outcome-oriented: the structure and the actions within ought to be defined in such a manner that conclusions or objectives are the aim and are plainly declared.
iv) Practical: the structure ought to be relevant to industrial practice.
v) Structured: the framework ought to be rational, orderly and progressive.

2.9.1 Water security: DFWS

The indicators, indices and framework selected for this research are derived from a seminal paper by Srinivasan et al. (2017). Their DFWS addresses criticism of stagnant indicators and verifies both the interconnectedness among human-water systems and the infinite amount of paths by which these schemes co-develop (Srinivasan et al., 2017). The authors frame WS as the product of connected human-water structures and submit their dynamic framework methodology to WS in three steps (Srinivasan et al., 2017):

i) A combination of indicators that correlate human-water use to water availability; then
ii) how these indicators can be graphically plotted to present different types of water insecurity; then
iii) a combination of contributory elements that drive both human-water use and water availability in order to enable these indicators to be modelled in the perspective of coupled human-water systems.

The benefits of this framework include the following (Srinivasan et al., 2017);

i) Outcomes will represent coupled human-WS.
ii) It will be able to anticipate WS trajectories under anthropogenic influence.
iii) It will be able to forecast and predict water in/security.
iv) It will be able to can inform appropriate action.
v) It will be able to map physical resource availability, infrastructure and economic choices.

The DFWC applied for this research represents the four major determinants that indicate WS across all definitions, namely: environmental constraint, predominant cultural and economic activities, infrastructure investment, and governance of water source usage. This Dynamic Framework for Water Security was used in this research to: (i) determine the CCT WS between 2008 and 2018; and (ii) then expanded to include the influence of WS for the CCT by incorporating the planned water augmentation projects contained in the CCT Water Strategy of 2019-2026. The water augmentation project indicators have been subjected to a Regional-Scale Risk Assessment using the Relative Risk Model (RRM).

2.9.2 Regional-Scale Risk Assessment using the Relative Risk Model

In the late nineties, Landis and Wiegers (1997) established a modified Environmental Risk Assessment (ERA) methodology, namely the Regional-Scale Risk Assessment that requires utilisation of the Relative Risk Model (RRM) (Landis et al., 2017; O'Brien et al., 2018; Teng et al., 2019). The RRA may be employed across various spatial scales, as this enables assessment of a variety of sources of different stressors affecting several endpoints. The methodology also involves the ecosystem dynamics and attributes of the environment that may possibly impinge on the threat assessment (Landis & Wiegers, 1997). Subsequent to the early expansion, the RRM has been developed into the operating procedure which has been applied and verified in several ERA methodologies all over the globe (Landis & Wiegers, 1997; Wiegers et al., 1998; Murray & Claassen 1999; Landis et al., 2000; Walker et al., 2001; Claassen et al., 2001; Moraes et al., 2002; Obery & Landis, 2002; Hayes & Landis, 2004; Chen & Landis, 2005; Colnar & Landis, 2007; Landis & Thomas, 2009; Landis et al., 2007; O'Brien et al., 2018; USEPA, 2019; Teng et al., 2019).

From a CCT point of view, the significance of the RRM rests in its capability to be tailored to focus on the hazards of numerous sources from a variety of stressors on regional habitats and endpoints, and in this manner, aiding to the aims of Integrated Water Resource Management (IWRM) in South Africa (O'Brien & Wepener, 2012; Claassen, 2013). This RRM approach enables the evaluation of numerous stressors in distinctive habitats on a chosen spatial magnitude whilst allowing the consideration of ecosystem composition and functional dynamics. It can provide direction towards the administration of regional surface ecosystems in South Africa. The RRM approach is fundamentally uncomplicated and involves limited assumptions. It is not limited to the obligation for controls or reference sites, or states or theories about population dynamics, incidental consequences or the linearity of responses (Landis & Wiegers, 1997). As a further contribution, the model allows for the use of stressors for which not much evidence is accessible. The RRM enables the contemplation of potential future decision making, which is established through the ranking processes (O’Brien & Wepener, 2012).

This research used the RRM approach, as refined by O’Brien and Wepener (2012), to evaluate and rank the relative risk of the CCT Water Strategy’s water augmentation indicators and indices as defined by the DFWS for the CCT (Srinivasan et al., 2017).

A summary of some of the existing frameworks in use are represented in Table 2.7, which differentiates and compares the hydraulic information functions of water risk aspects. This includes spatial application, underlying data challenges, mitigation responses and user friendliness offered by these frameworks. Jacobs et al. (2018) state that actual or perceived uncertainties in the hydraulic knowledge base significantly affect the reaction of stakeholders to water resources information and development options. This, in turn, negatively affects the willingness to make difficult water-resource management decisions.

The high cost of significant capacity building to develop a common knowledge base required for meaningful public participation and stakeholder engagement excluded this aspect from the study. This research in contrast derived a cost saving benefit from utilising open-access HISs in the application of the DFWS and the RRM to determine the WS risks for the CCT in lieu of public participation and stakeholder engagement. The research contributes to an effective knowledge system that supports sustainable water-resources management through integrated and adaptive management, thereby linking knowledge systems to decision processes in a transparent manner. It further supports short- and long-term decisions, accurate monitoring, analysis and archiving of information, easily duplicated and applicable over a variety of spatial and temporal scenarios (Jacobs et al., 2018).

Table 2.7: Risk framework comparison (adapted from McCraine et al., 2019:35-39)

Frameworks	Description	Risk analysis	Framework covering all water risk aspects	Geographical Coverage	Underlying water data challenges	Mitigation Responses	User friendliness	Supporting disclosure of water information	Source
CDP Water Disclosure	Questionnaire sent to companies asking disclosure of water use information	No risk analysis Companies are asked to disclose whether risk assessment has been performed	Structured questionnaire on relevant elements of water use and impact	Not relevant in this tool	Not supported by water data	No	Long questionnaire with open questions	Tool focusses on disclosure	CDP Global.2018 *Global Water Report.* https://www.cdp.net/en/research/global-reports/global-water-report-2018 [8 October 2019]
CERES Aqua Gauge	Scorecard to grade water management activities on detailed definitions of leading practice	No risk analysis, rough indication of risk levels possible	Questionnaire based on performance and management of water issues	Not relevant in this tool	Not supported by water data	Provide examples of activities and actions that may improve management of water risk	Easy to use – Excel based and Free	Links actions to several disclosure platforms	CERES. 2019.*Ceres Aqua Gauge.* www.ceres.org/issuess/water/aqua-gauge/aqua-gauge [7 October 2019]
Dynamic Framework for WS	Define, Classify, Quantify and Model WS over different time scales	No direct risk quantification	Framework indication water use indices in a coupled human-water system	Adaptable	Highly dependent on specific water data availability, usage	Highlight critical areas for further research. Can be used to anticipate future watershed trajectories, predict water insecurity and inform appropriate action	Easy to use Excel based and free	Focusses on availability of data and data gaps	Srinivasan et al. (2017)
GEMI Local Water Tool (specific LWT for Oil &Gas)	Online tool to assess local water risk of a specific site	Quantifying water risk via a system of weighted risk indicators, provides template for management plan and raw data for disclosure	Analysis of physical, supply, regulatory, social competition and climate viability risks	Global	Assessment of local user input. Scarcity based on withdrawal data, not on consumption	No	Download required. Excel based Prepared answers available	Yes, clear connection to GRI, Dow Jones, CDP and Bloomberg Provide raw data for specific disclosure	Global Environmental Management Initiative. n.d. GMI Local Water Tool. www.gemi.org/water/ [8 October 2019]

Frameworks	Description	Risk analysis	Framework covering all water risk aspects	Geographical Coverage	Underlying water data challenges	Mitigation Responses	User friendliness	Supporting disclosure of water information	Source
GEMI Connecting the Drops	Online tool for business to better understand emerging water issues given their unique operations, needs and circumstances	Not water matrix or mapping tool Descriptive steps for better understanding companies water situation Instructions on performing a risk assessment	Very structured Covers most relevant elements 5 module analytical assessment on water use and impacts, Risk, strategy etc..	Not relevant in the tool	Not supported by water data	Yes, case studies and water matrix to address measures for continuous operational improvement	Manual and base data essential to complete 5 modules of assessment Serious time commitment	No	Global Environmental Management Initiative. n.d. Connecting the drops. www.gemi.org/water/ [16 August 2019]
Regional Scale Relative Risk Assessment	10 -step risk assessment process with application to address the treats of various stressors from various sources to local habitats and endpoints	Risk sources, stressors and indicators with adjustable weightings	De-composed Probabilistic assessment of sub-systems with detailed risk assessment using BNN probability to compute posterior probability from prior probability with utilising new data	Detailed, scalable, diverse habitats	Adaptable to consider related Sources, Risk Regions, Stressors. Can support all water related data New data can be used to compute mitigation responses	Yes, clearly identifiable mitigation endpoints	Excel based easily computable and replicated	Not yet	O'Brien, (2012); Wepener et al., (2015); O'Brien et al., (2018)
RepRisk	Daily tracking of project's environmental and social risk exposure by monitoring independent 3rd party sources	Reputational risk score based on negative reports of company/project activity. Not focussed on water, only one of the indicators measured	Focussed entirely on reputational risk, water only one of the elements	Global	No water data support	No	Easy-to-use, as RepRisk can report on daily basis without further action from user. RepRisk is not free	No	RepRisk. n.d. *Benchmarking Report* www.reprisk.com [3 March 2018]
The Water Risk Filter	Water risk assessment tool includes mapping, mitigation responses, case studies and country profiles	Quantifying water risks through system of weighted risk indicators. Highly automated based on GPS location and input	Covering all water related risk aspects with distinction between performance and location	Global	Regulatory risk based on qualitative research, direct link with WFN database for scarcity data and maps.	Yes, responses structured along risk types and stewardship steps, >80 case studies	Intuitive and visual online tool designed for non-expert user	Yes, provides CDP report adapting the Water Risk Filter	World Wildlife Fund. 2018. *Water Risk Filter 5.0*. https://waterriskfilter.panda.org/ [8 October 2019]

Frameworks	Description	Risk analysis	Framework covering all water risk aspects	Geographical Coverage	Underlying water data challenges	Mitigation Responses	User friendliness	Supporting disclosure of water information	Source
					Based on consumption, pollution and biodiversity threat data				
Water footprint Assessment Tool (under development)	Creates WF assessment based on geographic and agricultural commodity information	Not a risk analysis but mapping function serves as a basics "hot spot" risk tool	WF mapping and WFN datasets. Focus on water quality data, very few other indices	Global, very detailed	Strong WFN footprint and scarcity data based on consumption, different overlays monthly hydrographs	No, WF response framework under development	Under development with focus on sharing all available scientific data	No	Water Footprint Network. 2019. *Water Footprint assessment.* www.waterfootprint.org [13 September 2018]
WBCSD Global Water Tool	Excel based tool water use and discharge. Mapping tool with	No risk analysis	Basin and country level datapoints, based on water user input. Concentrate on water withdrawal data and maps. No unique indicators	Global	Scarcity based on annual withdrawal data, not consumption	No	User friendly, Excel-based data presentation populated automatically. Raw data need to be interpreted by user	Yes, certain water reporting indicators (GRI, CDP, Bloomberg, Dow Jones, Sustainability index. Inventories, risk and performance metrics	WBCSD. 2007. *Global Water Tool.* www.wbcd.org/web/watertool.htm [16 August 2018]
WRI Aquaduct	Online based water risk mapping and measuring tool River basin coverage under development	Various risk indicators which weightings can be adjusted individually not company or performance-based risks	Clear framework of risk indicators grouped in three categories. Focus on location bound risks,	Global coverage for scarcity and climate change risk, very detailed scarcity and pollution information.	Scarcity based on annual withdrawal not consumption, little data available for global level.	No	Online interface with attractive mapping. Results are difficult to interpret	Not yet	World Resources Institute. 2019. *Aqueduct Water Risk Atlas.* https://www.wri.org/aqueduct [13 September 2019]

2.10 Chapter summary

The CCT is currently experiencing a water crisis with severe implications. The unforeseen drought, increase in demand, and the delayed interventions contributed to the current water crisis. More than 90% of Cape Town's supply is sourced from comparatively small catchments that are susceptible to regional dry periods. The seasonal assessments from 2010-2016 show that reduced precipitation are but one component of the conundrum. Increased water consumption is just as crucial.

The slowdown and ensuing decrease in expansion of water demand between 2011 and 2014 was, in principle, due to the implementation of successful water demand management actions, and it was anticipated that these decreases could be sustained. Alternative supply interventions were not implemented as planned due to costs, while water demand increased because of urbanisation. Two dry winters later CCT found itself in a water crisis.

Although several interventions, ranging from new and increased surface water storage and ground-water sources to water re-use and desalination, are currently in play to mitigate the present situation, they are mostly reactive. As such, South Africa continues to experience water scarcity that necessitates crucial administration, mitigation and interventions.

WS presents one of the major challenges of the 21st century. As populaces increase, civilization confronts the probability of uncertain future water deliveries being equally due to climate change and ever-increasing water requirements. The fundamental idea underpinning WS is the necessity to maintain equilibrium between human and environmental water demands. The United Nations Sustainable Development Goals for water (SDG 6) explicitly address this balance and set targets for each goal. There is no single working definition of WS, and the interpretations vary between broad and narrow, academic and applied. This makes WS a dynamic and constantly developing concept.

The evolution of WS terminology between its inception in the 1990s and currently varies across academic literature, water policy development, governance, and adaptive risk management in both the natural and social sciences, showing a distinct and at times incomparable standard of measurement, methods and scales of analysis. WS is direct nexus linkage to the supply of several other material requirements such as food, electricity and economic production.

Most of the earlier WS indices focused on physical water scarcity and the expansion of water supplies to satisfy human demand, and in the process, threatening essential environment services and biodiversity. Despite the evolution to incorporate human and environmental needs, it still did not account for cross-scale feedback and interactions between people and diverse water sources. Most WS indices and frameworks are limited in their spatial-temporal application.

The DFWS accounts for these limitations by specifically addressing cross-range reactions and trade-offs between human-water systems, ever-increasing spatial specialisation in the contemporary world, and offering historical reference and predictive insight. The specific indicators for this framework are water resources utilisation intensity, the capability of populaces to spend on water storage, treatment and reticulation, and spatial disconnect in the production and consumption of water footprints. The sum of the cross-dependencies between human-natural systems as applied in the DFWS often leads to emergent patterns of form, function and dynamics, thereby resulting in outcomes that could not have been predicted from the knowledge of the behaviour of the individual elements.

Regional-scale risk evaluations of various stressors to social and ecological endpoints, addressing ecosystem vitality, have been concluded globally since the mid-1990s at various spatial scales through applying the RRM. Development of this RRM for application in South Africa has been successfully executed to evaluate a range of natural and anthropogenic stressors, including water pollution, diseases, alien species and a range of altered environmental states, which made it ideal to incorporate into the DFWS to address the aims and objectives of this research.

The combination of the DFWS and the RRM in a WS risk assessment using open-access hydrological information has not been found in literature. There is no or little research available that applies to the interrelatedness of human-natural influences in the determination of WS, with specific reference to Cape Town. Successful determination of WS for the CCT through incorporating these dynamic indices and utilising the available human-natural hydrological information will support quality short and medium-term decisions regarding WS.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

The previous chapter comprised a literature review on the work of some prominent contributors and researchers in the water field. The definition of WS as well as the WS measurements, indices, frameworks and relevant water-related academic work have been discussed in alignment with the focus of the RQs and the objectives of this research.

In Chapter 3, the research process is presented. Information is supplied on the method adopted to undertake the research and a justification for this adoption is provided. Also described in this chapter are the processes and sequence of the various stages of the research design, including the data collection process, data collection timeline, and the data analysis method. The chapter also contains a discussion on the validity and reliability of the data, and how these requirements were met. The chapter concludes with highlights of the key features of the methodology and a look ahead to the next chapter.

3.2 Background

The research area (in terms of geographic boundaries) is the CCT, the oldest urban area in South Africa, situated on the southern coast, with its highest elevation at 1,590.4m, on the coordinates 33°55'31"S 18°25'26"E. The CCT is governed by a metropolitan type of municipality covering an area of 40,026 km^2, and is home to 64% of the population of the Western Cape province (City of Cape Town, 2019c; Climate-Data.org, 2019).

The aim of this research was to explore the WS status and related risk factors of the CCT within the spatial boundaries of water produced and consumed. The CCT has since 2015 been experiencing its worse recorded drought in 100 years (Muller, 2017; Visser 2018). Cameron and Katzschner (2016) as well as Fisher-Jeffes et al. (2017) concur that unforeseen drought, demand increases, and delayed interventions contributed to the current water crisis.

The CCT is dependent on >90% of its water supply from outside its city boundaries, supplied by the Western Cape Water Supply System (WCWSS). The WCWSS is a complex water supply system in the Western Cape region of South Africa, comprising an inter-linked system of six main dams, pipelines, tunnels and distribution networks. This includes a number of minor dams, some owned and operated by the Department of Water and Sanitation and some by the CCT (Brandt, 2018; Pitt, 2018; City of Cape Town, 2019c).

Water, in itself, is a complex resource – liquid, solid, vapour, flowing, falling, static, transporter, depositor and solvent – all in one. This coupled with society's needs and aspirations, which is equally complex with highly diverse values. Combined, it presents a set of problems that appears uncontrollable and not susceptible to simple or conventional solutions (Hay & McCabe, 2010).

Water can at any one place and time exist in three completely different states, namely vapour (gas), liquid and solid, or even as a combination of the three. Water are also contained in these different states in all organic and inorganic matter on earth. Only 2.5% of all water on earth is freshwater and 96% of all freshwater can be found underground; therefore, water and its influencers are varied, complex and interrelated (World Wildlife Fund, 2016).

Because of this complexity and interrelatedness, information on water can be found across all disciplines and in various formats. Usually, the purpose for which water-related data is captured determines its format and measurement in time scale, position and unit. For this research, open-access hydrological records from government, local authorities, statutory organisations, tertiary institutions and electronic libraries were remotely accessed. These sources were investigated for water and water-related data applicable to answering the RQs and fulfilling the objectives.

According to Denzin and Lincoln (2005), a research methodology or strategy is determined by the nature of the RQs and the subject being investigated. Thus, the research format used in an investigation should be seen as an instrument employed to answer the RQs. Archival data collection was employed as the data collection instrument. For the data analysis, the DFWS was used as tool to determine the WS of the CCT, and the Relative Risk Model was applied to determine the relative risk rankings of WS indicators for Cape Town.

The aim of this research was to explore the current WS status of the CCT by processing open-access hydrological data available in the public domain using a DFWS. A further aim was to augment the framework by including the indices related to the CCT's new water augmentation projects, and then to explore the related risk factors of WS for the CCT.

This research was guided by the following RQs:

RQ1: What is the current WS status of the CCT versus the WS impact of the proposed augmentation options as proposed by the New Water Programme?

RQ2: What are the risk elements associated with the WS status of the CCT's augmentation options as proposed by the New Water Programme?

A quantitative research approach was selected as the most suitable methodology as it aligned with the requirements of the DFWS and the Relative risk Method, the availability of open-access current and historical water information sources, and the short time frame available to complete the research. A further motivation was the low cost of this approach and its suitability to explore a known phenomenon by applying the DFWS to the CCT.

3.3 Research philosophy

The research philosophy represents a system of beliefs and assumptions about the development of knowledge. It represents a method in which information about an event is collected, examined and utilised (Saunders et al., 2019). The phrase 'epistemology (what is known to be true)' as opposed to 'doxology (what is believed to be true)' incorporates the different beliefs of a research approach. The objective of science, then, is the procedure of proving or disproving beliefs. Two of the key research philosophies in the sciences, according to Gallier (1991), is a positivist philosophy, occasionally termed scientific, and a interpretivist philosophy, also known as anti-positivist.

The positivist believes that objective facts offer the best scientific evidence, and more often than not, it results in the selection of quantitative research procedures. Inside this paradigm, the ensuing research results are expected to be considered objective and generally applicable. This research followed a quantitative, systematic empirical investigation, within a positivist paradigm, into WS risk assessment of the Water Management Area of the CCT, using data from open-access Hydrological Information Systems (HISs) (Göktürk, 2009). Vose (2008) states that quantitative research may be considered a methodical practical review of visible events through statistical, calculated, or computational procedures. The intent of a quantitative investigation is to build and make use of mathematical methodology, concepts, and suppositions relating to the events under investigation.

The process of measurement is a key aspect of quantitative research as it supports the underlying relationship between empirical observation and numerical articulation of quantitative affiliations. The methodology was applied as an outcome-based or solution-oriented business information technology research method. As such, exploratory research was conducted. The recommendations at the conclusion of this research were more final than tentative with the delivery of an improved and current spatial WS framework specific to Cape Town.

3.3.1 Ontology

Ontology denotes assumptions about the nature of reality. In business and management these objects span individuals, organisations, events and artefacts. For this research, the nature of reality was considered as being real by the researcher, and the choice of what to research was based on thereupon. The world was considered as external and isolated to the observer, with one true universal reality. The organisations from which data were sampled, were viewed as granular and orderly. An objective philosophical perspective was followed, believing that the reality of WS exists. The WS status of the WMA/WCWSS of the CCT is discoverable and comprehensible. The WS reality exists objectively and externally (Table 3.1) (Saunders et al., 2019; Al-Saadi, 2014).

Table 3.1: Ontological positions and assumptions (adapted from: Al-Saadi, 2014:6)

Position	Assumptions
Objectivism	• Reality exists in-dependently of our beliefs or understanding • Reality can be observed directly and accurately • Personal belief about the world is distinct from the way the world is. • Only the material or physical world is real • Social phenomena and their meanings cannot change • Events have causes determined by other circumstances • Causal links between events and their causes is discoverable by science • Life is defined in measurable terms rather than inner experiences
Positivism	• World is independent and unaffected by the researcher • Facts and values are distinct • Objective and value-free inquiry is possible • Disputes are resolved through observations • Knowledge is seen as hard, tangible and objective • Knowledge is arrived at through gathering of facts • Social world is interpreted through the explanation of human behaviour

3.3.2 Epistemology

The positivist paradigm states that reality is constant and that it can be witnessed and explained from an impartial point of view (Kleinberg-Levin, 1988); that is, with no impeding of the events being investigated.

Positivists assert that events should be separated and that studies should be repeatable. This methodology every so often includes the exploitation of reality with differences in only a singular independent variable, with the purpose of identifying regularities and relationships among certain of the component parts of the social realm. Projections can be presented based on earlier noted and described truths and their inter-relations.

“Positivism has a long and rich historical tradition. It is so embedded in our society that knowledge claims not grounded in positivist thought are simply dismissed as unscientific and therefore invalid” (Hirschheim, 1985:33). In their review of 902 Management Information System research articles, Alavi and Carlson (1992) observed that most, if not every one of the empirical studies reviewed were positivist in method. The positivist paradigm has also had a remarkably effective relationship with the physical and natural sciences.

Snape and Spencer (2003) describe positivism as an epistemological position that concentrates on the significance of impartiality and proof in the pursuit for truth. This must all be achieved in a domain that is unchanged by the investigator. Furthermore, in the positivist perspective, facts and values are extremely distinctive, hence making objective and value-free investigation feasible. The positivist research paradigm was deemed suitable for this research based on the assumption that knowledge is valid if based on observations of the external reality and that these observations are independent of social actors (Gabriel et al., 2013; Al-Saadi, 2014). As such, the positivism paradigm was selected for this research because of it is suitability in approach as it relies on facts and quantitative data.

The positivist paradigm is measurable, objective, value free, generalisable, replicable (Al-Saadi, 2014; Wellington, 2015) and applicable to the measurement of WS. Using the positivist approach, measurable parameters were sought and applied in this study to frame WS in order to inform and improve water conservation/water demand management. The researcher was independent of the subject and could objectively measure WS without affecting it. Hence, the subsequent research findings are likely to be considered objective and generalisable as reported by Saunders et al. (2012).

3.4 Research approach

The research approach consists of the steps from broad assumptions to the detailed method of data collection, analysis and interpretation. It is therefore based on the nature of the research problem being addressed. There are three types of research approaches: inductive, abductive and deductive. With an inductive inference, known premises are used to generate conclusions, generalising from the specific to the general. Data collection is used to explore a phenomenon, identify themes and patterns, and create a conceptual framework to generate and build a theory. The inductive approach does not involve formulation of hypotheses. It starts with RQs, aims and objectives that need to be achieved during the research process (Dudovskiy, 2019; Bell et al., 2018).

In this study, the inductive research approach was selected and followed because of the availability of open-access information sources, both current and historical, the short time frame available to complete the research, and because it is suitable to explore a known phenomenon and test the WS theory in the Water Management Area of Cape Town.

3.5 Research strategy

The research strategy selected for this research project was an archival document analysis of databases containing open-access hydrological information. Exact water and water-related indicators combined with secondary research data from published works and online data were used to measure WS within the spatial domain and geographic boundaries of the CCT (Table 3.2; Table 3.3).

Research actions included the identification of variable indicators and indices to assess the real water situation in terms of WS, and consequently, processing these indicators and indices through the DFWS as proposed by Srinivasan et al. (2017). Numerical data on observable factors affecting WS were presented graphically to enable relevance and objective comparisons over the measuring period. The data were abstracted at an annual interval to represent changes over time. Water-related parameters were expressed in units of volume, and infrastructure investment in units of currency, while results were expressed as ratios. The expression of results in ratio rather than difference enabled reporting to be scale in-dependent; this was motivated by the internal and external water model of Hoekstra and Mekonnen (2011).

3.6 Role of the researcher

In reflection over the process of the research, the researcher viewed himself as an informed observer in relation to the subject. The positivist paradigm views observers as independent and objective of the subject, and no mitigation was deemed necessary. However, interactive peer-review during the research process would have added value.

3.7 Research design

Research design describes an outline of approaches and procedures selected by a scholar to bring together a variety of elements of research in a relatively rational approach to facilitate efficient and effective processing of the research problem. The research design further offers an understanding of the best possible application of a chosen methodology to the particular research problem. It further involves three key elements, namely data gathering, measurement and assessment of event indicators.

Suitable and fit for purpose research design generates minimum bias in data and validates confidence in the assembled and evaluated research material. The vital fundamentals of research design are represented by:

- A precise purpose statement of the research design
- Procedures to be employed for collected elements for research
- Procedure employed for examining accumulated elements
- Typology of research methodology
- Possible objections to the research
- Spatial parameters of the research
- Timeline
- Measurement of analysis

The four characteristics of research design are: neutrality, reliability, validity and generalisation. The results projected in the research design should be free from bias and neutral, thus, research should be reliable in its repeatability. Instrumentation employed in the research should deliver results according to the objectives of the research and the outcome should be applicable to the general population and not restricted. From the two types of research design – qualitative and quantitative – a quantitative design was selected for this research because the outcomes required statistical conclusions to collect actionable insights. Numbers provide better insight to make important business decisions (Bhat, 2019).

Descriptive research design was used to describe the WS of the CCT. It is a theory-based design created by gathering, analysing and presenting collected data. The results of descriptive research design can provide insights into the ‘why’ and ‘how’ of the subject (Bhat, 2019).

This research followed an online, non-random, purposive sampling process. Purposive sampling is a non-probability sampling process that was selected based on the characteristics of the population and the objectives of the research. It is a sampling technique that relies on the subjective judgement of the researcher. Purposive sampling is also known as judgmental, selective, or subjective sampling (Crossman, 2019; Cole, 2019). Advantages include low cost, lack of geographical limitations, lack of time constraints, and flexibility in data collection. The research was non-participant driven.

3.8 Instrumentation

The instrument adopted for data gathering in this research is archival data collection, which can be defined as a process of reviewing already collected (secondary) data. This data collection method is a rigid, well-laid out procedure and focuses on quantitative research resources available in the public domain. For this research, the focus was on a secondary data collection process from institutional archive repositories, libraries and online resources by examining data and records of environmental data, physical resource data as well as infrastructure and economic records in the public domain.

Parameters explored with open-sourced hydrological data include population census data, financial data, infrastructure data, and water volumes associated with precipitation, infrastructure, agriculture, non-agriculture, outflow, water used by natural ecosystems, production water footprint, direct human-beneficial abstraction, and consumptive water use footprint. A longitudinal time horizon was determined once data were tested over a variety of timeframes, and data gaps were identified.

A composite view of WS requires consideration of the main components presented by water resource utilisation, human demand or consumption development, and ecological sustainability. As such, applicable current and historical data available in the public domain were identified and mined. Annual cumulative data were collected for the period from 2008 to 2018. This timeframe was identified from the literature review as a critical period for water management decisions for the CCT by both the South African National Biodiversity Institute in 2005 and the 2010 DWA analysis of the Integrated Water Resource Planning for South Africa (Department of Water and Sanitation, 2018; City of Cape Town, 2019c).

3.9 Data collection

Water-related data were collected primarily from secondary sources. Hydrological records from CCT, DWS and statutory organisations reflect long-term primary data on stream flow, rainfall, water quality and climate records available for the last 80 years. Historical water-related data go as far back as 1972 for the CCT, whereas data for agricultural use, the West Coast, Swartland and Stellenbosch only date back as far back 1996.

Peer-reviewed water-related literature sourced from journals and books was extensively used for verification and interpretation, as were grey data and water-related articles in the popular press. Annual cumulative data were collected for the period 2006-2026. This timeframe was identified from the literature review in Chapter 2 as a critical period for water management decisions for the CCT. This was emphasised by the South African National Diversity Institute, and the 2010 DWA analysis of the Integrated Resource Planning for South Africa (City of Cape Town, 2019c) These management decisions directly impacted on the drought experienced from 2015-2018 (Visser, 2018).

This research followed a quantitative systematic empirical investigation within a positivist paradigm into WS of the Water Management Area of the CCT. Göktürk (2009:2) defines a paradigm as “a set of assumptions, concepts, values and practices that constitutes a shared communal way of viewing reality”. The data collection for this research was conducted in isolation from any official relationships or participation with data resources and solely focused on data available in the public domain. Therefore, there is no conflict of interest to declare. A deductive approach was employed because of the variability in availability of both current and historical open-access hydrological information sources, the short time frame to complete the research, and its suitability to explore known phenomena. A quantitative investigation of primary databases of hydrological and statistical information was employed as the research strategy, and the research design was an online, non-random process.

3.9.1 Hydrological information

Data were collected from various diverse and independent sources with one common denominator being water-related, in an attempt to stimulate discourse and contribute knowledge to a complex, messy and wicked business (Hay et al., 2014).

Data were collected from open-sourced, publicly available, HISs such as HPS-WINS, SASSCAL, SANCIAHS-MAIS, MODIS, WHYCOS, academic institutions, national and local government, and published work. The data source is relatively large and was objectively selected to enable the generalisation of findings. Table 3.2 represents the major hydrological information sources accessed for secondary data.

Table 3.2: Hydrological information sources

Source	Data Type	Availability
African Centre for Water (ACW)	Grey	www.acwr.co.za
Centre for Municipal Research and Advice (CMRA)	Grey	www.cmra.org.za
CCT	Secondary Grey	www.capetown.gov.za
Climate Systems Analysis Group (CSAG)	Secondary Peer Reviewed	www.csag.uct.ac.za
Community Supply and Sanitation Unit (CSSU)	Secondary Peer Reviewed	www.cput.ac.za
Council for Scientific and Industrial Research (CSIR)	Secondary Peer Reviewed	www.csir.co.za
Department of Water and Sanitation (DWS) Resource Quality Information Services Data and Reports (RQIS)	Secondary	www.dwa.gov.iwqs/report.aspx
Future Water UCT (FW)	Secondary Peer Reviewed	www.futurewater.uct.ac.za
Green Cape (GC)	Grey	www.greencape.co.za
HydroNet (South African Weather Service)	Secondary	www.hydronet.co.za
Institute of Water Studies (IWS)	Secondary Peer Reviewed	www.uwc.ac.za
Journal of Hydrology	Secondary Peer Reviewed	www.journals.elsevier.com
National Integrated Water Information System (NIWIS)	Secondary	www.dws.gov.za/niwis2/
Monash South Africa (MSA)	Secondary Peer Reviewed	www.msa.ac.za
South African Weather Service (SAWS)	Secondary	www.saws.org.za
Stellenbosch University Water Institute (SUWI)	Secondary Peer Reviewed	www.sun.ac.za
Water Institute of Southern Africa (WISA)	Grey	www.wisa.org.za
Water Research Commission (WRC)	Secondary Peer reviewed	www.wrc.org.za
Western Cape Government (WCG)	Secondary Grey	www.westerncape.gov.za
World Hydrological Cycle Observing Systems (WHYCOS)	Secondary Grey	www.whycos.org
World Wildlife Fund (WWF)	Secondary Grey	www.wwf.org.za

3.9.2 Official data

Historical and official water and water-related data from Department of Water and Sanitation (DWS), South African Weather Service (SAWS), CCT, and the Department of Environmental Affairs and Development Planning (DEADP) are not readily available. Even though proclaimed as in the public domain, rainfall data for the station at Cape Town International Airport from 2002-2007 will cost R7,590.00 (SAWS, 2017).

The WRC was established in 1971 in terms of the Water Research Act 34 of 1971, following a period of serious water shortages in South Africa. The mandate of the WRC was to invest in knowledge creation, transfer and dissemination contained in five Key Strategic Areas of South Africa’s water-sector R&D needs. The WRC focuses on supplying integrated solutions to invariably complex inter-disciplinary problems. In 2015, the DWS, then the DWAF, created the National Integrated Water Information System (NIWIS), which is an open-access HIS accessible to commercial water users, researchers and the general public.

3.9.3 Primary data

No field work or primary data gathering was employed for this research. Open-access hydrological information was collected from government departments, NGO’s, business publications, tertiary institutions, scientific and academic publications, and public documents.

3.9.4 Secondary data

Secondary data were sourced from published and peer-reviewed articles in credible journals and books as well as studies commissioned by the Water Research Commission (WRC). Table 3.4 delineates the data indicators/indices required by the DFWS, whereas Table 3.5 denotes the data requirements to expand the DFWS framework through the augmentation projects for the CCT (City of Cape Town, 2019c).

3.10 Grey literature and popular press

Grey literature that was published outside commercial or academic publishing and distribution channels, such as annual reports, technical literature, working and white papers, and technical evaluations were consulted to cover as wide a base of open-access, publicly available water data available as possible. To minimise the effect of information bias and political, social agendas, the information obtained from grey literature was cross-checked and verified against secondary literature sources. The researcher collected data from various diverse and independent sources with one common denominator, water, in an attempt to stimulate discourse and contribute knowledge to a complex, messy and wicked business (Hay et al., 2014). The sampling universe consists of all open-sourced hydrological, environmental and census data applicable to WS of the CCT.

The samples collected cover annual totals of the WS parameters for the period 2006-2017, which will consist of 11 parameters measured over 12 years. The purpose for accumulating data over this period was to obtain a suitable baseline from 2006-2015 preceding the three-year drought period, the effect of the drought from 2015-2018, and the impact of the planned augmentation projects during its implementation phase from 2019-2026.

3.10.1 Validity and reliability

Validity and reliability of the instrument for data collection is high as data sources are specific and consistent. Data consist of tabulated measurements over a consistent time frame kept by government and/or statutory institutions. To ensure reliability and validity, data were collected as close to the stewarding depository source as possible. Secondary and grey data sources were triangulated with recognised data repositories and peer-reviewed literature.

3.11 Data selection

Archival data collection, defined as a process of reviewing existing secondary data, was used as the data collection instrument. The Dynamic Framework indices dictated the specific data required, which were sourced from hydrological and statistical records, academic institutions, scientific publications and grey data sources. The time span for data collection ranged from 2006-2026. The rationale for this choice was, firstly, to obtain 10 years of historical data for the WS indices, and secondly, a 10-year forward look to include the effects of the augmentation projects contained in the New Water Programme, the latter of which is the permanent desalination planned to come online in 2026.

The research was limited to the spatial system boundaries of the CCT Metropolitan Municipality Water Management Area inclusive of all local and non-local water receipts. All through 2017, information on Cape Town’s administration of the drought was restricted, which produced considerable scepticism, mistrust and misinformation in the public realm (City of Cape Town, 2018a). Data assembled for the research were limited to open-sourced publicly available hydrological information available from literature, government, local authorities, tertiary institutions, public entities and business.

Official water-related data – although proclaimed by official powers as transparent and widely available – were found to be difficult to access during the preliminary research phase. Koopman and de Buys (2017) contend that long-term rainfall records represent general trends in our catchments and that statements on the severity of climate change impact, such as droughts, appear to be unsubstantiated if viewed against historical data. This led them the authors to state that if CCT did experience several previous droughts of similar magnitude, the reason for such a dire unexpected impact of this drought is mostly related to water demand and not rainfall.

The data collection method was a rigid, well-laid out procedure that focused on quantitative resources available in the public domain. The procedure focused on secondary data collection processes from institutional archive repositories, libraries and online resources. This was done by examining data and records of environmental data, physical resource data as well as infrastructure and economic records.

Parameters explored in the open-sourced hydrological data included population census, financial and infrastructure data as well as water volumes associated with precipitation, infrastructure, agriculture, non-agriculture, outflows, water re-use, water used by natural ecosystems, production water footprint, direct human-beneficial abstraction, and the consumptive water use footprint.

Schiermeier (2018) emphasises the urgent need to examine and comprehend what occurred, and to identify and isolate the key experiences of the CCT drought for the benefit of local authorities in general, as the threat of drought to urban centres appears to be more widely experienced than previously thought. Adapting and managing the climate variability is not simple or straightforward, especially not in the water utility management segment that requires a high assurance of supply (Ziervogel, 2019).

Although significantly influenced by climate variability and assurance of supply, WS is also affected by many other factors such as complexity of governance, high levels of inequality, and informality. The creation of a water-sensitive city requires a holistic perspective, the incorporation of a multi-disciplinary system approach, and an adaptive ability at a variety of scales and range (Ziervogel, 2019). This reflection on the drought experienced in the CCT during the last few years will provide opportunities to examine how, when and what is required to better manage a slowly evolving climate event in the future.

This research was conducted during 2018 and 2019 on a longitudinal time horizon span and included data from the 2006-2026. The timescale was determined after the data were tested over a variety of time frames, and data gaps were identified. The reasons for this 20-year period were to:

i) Have a substantial historical data trail to identify patterns, if any.
ii) Take into consideration the time sensitive nature of the data, namely that low rainfall in one time period only affects supply in a knock-on effect in later time periods.
iii) To identify the timing, impact and sustainability of the planned water augmentation projects of Cape Town’s New Water Programme on the water potential, augmentation resources and WS of Cape Town.
iv) Identify the risks associated with the various sources, stressors, habitats and effects on the management goals identified as endpoints.

The data collection method was chosen because of:

i) the accessibility of open-access data in the public domain versus cost and administrative complications of accessing official data; and
ii) the availability of the variety of sources and the non/limited ethical implications related to open access data sources available in the public domain.
iii) And, since the onset of the current drought, data from official sources have been reported in more detail and frequency than ever before.

Data sources utilised are listed in detail in Table 3.2. No community participation or outside consultation was utilised during the data gathering process of this research, therefore data could not be skewed by public perception or interpretation. Data, according to the parameters specified in Table 3.3 for the first deliverable and Table 3.5 for the second deliverable, were accumulated mostly via electronic means from various hydrological information sources, reports and publications as presented in Table 3.2.

The data gathered consisted of the following indices, as required by the both the DFWS and the RRM:

3.11.1 Precipitation (rainfall)

Rainfall levels and dates for the CCT International airport were freely available from 1960-2002; thereafter, the SA Weather Service (SAWS) requested payment for access to precipitation readings and rainfall station statistics, thus limiting the free distribution of the available data. The applicability of this data was also limited as it was measured at a point far removed from any major dam. Considering that the variability of rainfall across the WCWSS from 400 mm over the Western Coastal region to more than 2000 mm in the Hugh Water Yield Areas (HWYA) of the Boland mountains. Rainfall data were acquired free of charge via the National Department of Water & Sanitation internet site, where the hydrological services data date back up 1974 and earlier.

DWS have 36 years of records of rainfall in the WCWSS area, from 1981 to current, but there are frequent gaps and accessibility of the records varies. Furthermore, only four rainfall measuring stations are located near WCWSS dams, and records run according to the hydrological year (October to September). The hydrological year is a term commonly used in hydrology to describe a continuous time period of 12 months spanning from the start to the end of seasonal rainfall period, which, for South Africa, is from 1 October of one year to 30 September the following year. This is the period for which hydrological information on events and variability is recorded and analysed (DWA Groundwater Dictionary, 2019).

SAWS records extend as far back as the 1800s, but with no intersect between DWS and SAWS with 96 stations. Only 13 stations have data going as far back as the 1930s and of these, only three were suitably situated to affect WCWSS dams.

3.11.2 Dam levels and storage capacity

Dam level and capacity data were acquired from the CCT website, which provides dam capacity data in percentage of capacity, complete historical information public accessible, as well as historic dam, rainfall and consumption. Data were not available in the public domain despite the assurance from CCT that data will be made available upon request. Various other sources were investigated, and snippets of data were acquired from academic and business publications.

3.11.3 Water consumption

Isolated views of Cape Town’s water use is available on the City’s open-access data portal. It has limited use for critical analysis in that it only records data from 2013 onwards and the statistics have been released at different periods. More basic water consumption, water re-use, population, GDP, and infrastructure capacity data were accessed through the CCT Water Outlook Reports and data sets available on the City’s open data portal (City of Cape Town, 2019c).

3.11.4 Statistics on gross domestic product (GDP) and population

Statistics required by the indices for the Dynamic Framework (Appendix A; Appendix B) relating to population, population growth, gross domestic product (GDP), water-use dynamics, augmentation resources, New Water Programme, and projects were accessed on the internet utilising the resources reported in Table 3.2.

Open-access hydrological and water-related information from 2006-2026 was utilised for this research. The time frame is elaborated on as follows: using 2016 as the pivot point of the drought, looking back to the previous decade and its influences on the WS indices through to influences on the current WS status, then looking forward to the impact on WS for the CCT considering the augmentation projects planned for the New Water Programme at their various stages of implementation, which will conclude with the impact of permanent desalination in 2026.

3.11.5 Production Water (PW) and Consumption Water (CW) footprint

The PW and CW indicators are the product of water used for producing goods and services versus water consumed via goods and service per capita, respectively. The average PW/CW footprint is based on data obtained considering the green, blue and grey water use by country as presented in research conducted by Hoekstra and Mekonnen (2011) on the water footprint of humanity.

3.11.6 Published peer-reviewed academic work

The drought activated an increase in academic publications which contributed towards a wide spectrum of paradigms and knowledge. These publications were accessed and used in this study to test and verify the data, methodology and results.

3.11.7 Water quality and ecological integrity

The National Water Act, Act 36 of 1998, specifies water quality and ecological integrity and determines that no ownership of water shall exist and that the only right to water will be for basic human need and the environment; all other use will be subject to authorisation (Republic of South Africa, 1998). According to the Act, ecological integrity will be maintained by the ecological reserve (ER) or environmental water requirements (EWRs) to ensure that the long-term survivability of aquatic and related ecosystems is not neglected. As such, it recognises the complete ecosystem, and not only water as an essential support system to all life. The *resource* is well-defined to incorporate the watercourse as a whole, inclusive of surface waters, river mouths or aquifers. This consideration embraces the view that a waterway consist of rivers and springs, networks in which water flows frequently or from time to time, marshlands, lakes and dams into or from which water flows, and the riverbeds and riverbanks of a water system.

The quality of the water source is likewise considered generally to incorporate variations in the flow as well as in the physical, chemical, and biological characteristics of the water. This also includes the nature and condition of the in-stream and riparian habitat, its composition, condition and the diversity of any aquatic biota. The source is thus viewed by the Water Act in a holistic sense, which embraces the water, the ecosystem in which it is contained and through which it flows, while continuously impacting on the quality and quantity of water and the ecological processes that constitute the resource. The ER was consequently established to accomplish a dynamic ecological state of the resource that provides a range of benefits to society through the provision of aquatic goods and services (Van Wyk et al., 2006). The determination of this ER is catchment specific and not part of this research. The basic human needs reserve (BHNR) has been quantified as 25ℓ of portable water available within a 200m radius of the user's domicile (Du Toit et al., 2010).

Despite the variety and availability of basic water-related data accessible in the public domain through periodic communication, official reports, and open data portals, much more can be done by all three tiers of government and their departments, including DWS, SAWS, academics and institutions to provide verified and actionable historical and current water-related data.

Table 3.3: Water use volumes for the CCT (Sinclair-Smith, 2018:2)

Indicator	% of WCWSS	% of the CCT	Volume Mℓ/annum	Description
WCWSS	100	99.23	898 221	Total water available at full capacity
Minor Dams	63	0.77	4 377	Capacity of minor dams in the CCT
CCT			565 879	Capacity supplied to the CCT from WCWSS
Formal Housing		64.5	364 992	Total domestic consumption
Informal Settlements		3.6	20 372	
Industry and Commerce		13.9	78 660	Total industrial and commercial consumption
Non-Revenue Water		18	102 646	Water not earning revenue (leaks, wastage and other)
Agriculture	32		287 430	Total agricultural consumption
Other Towns	5		44 911	Water supplied to other towns by WCWSS

3.12 Data analysis

Data analysis for this research consisted of three parts to answer the RQs:

i) Apply the DFWS of Srinivasan et al. (2017) to determine the Water Security (WS) of the CCT from 2006-2018 to include the period leading up to the drought (2015-2018) for primary deliverable RQ1.

i) Then, for the secondary deliverable of RQ1, include the proposed impact by water augmentation planned by the CCT in their New Water Programme (2019-2026) (City of Cape Town, 2018b).

ii) Conduct a Regional-Scale Risk Assessment by employing the Relative Risk Model (RRM) to process primary deliverable RQ2 (Landis & Wiegers, 2007; O’Brien & Wepener, 2012; O’Brien et al., 2018).

3.12.1 Dynamic Framework for Water Security (DFWS) for Cape Town

The DFWS of Srinivasan et al. (2017) was employed to process the raw data for the outcomes indicated in section 3.12. This framework was selected after a comprehensive comparison of water indicators as presented in Table 3.4 and a framework comparison in Table 2.5. Srinivasan et al. (2017) and Padowski et al. (2015) concur that previous meta-analyses have found that WS is defined by four sets of parameters, namely: (i) culture, representing specific societal water requirements; (ii) resource availability, depicting the volume of water available; (iii) economic capacity and financial ability to invest in water resource creations; and (iv) governance, representing the rules and controls water utilisation.

In their application, the authors highlight three major shortcomings of earlier definitions and quantifications of WS, which their Dynamic Framework claims to address. Srinivasan et al. (2017) posit that whereas most framings of WS focus on particular spatial dimensions, thus largely ignoring cross-scale responses transecting population, ground water and surface water utilisation, their DFWS addresses this issue by framing WS as an consequence of linked human-water systems. According to Srinivasan et al., this was achieved by firstly presenting a group of markers that correlate human-water consumption to the volume of water available; secondly presenting these indicators in graphical format to map different kinds of WS/Insecurity; and finally, presenting a group of casual elements that influence human-water usage against the volume of water available, and then displaying these indicators in the context of linked human-water systems.

The influence of different water utilisation patterns results in the variation of different types of WSs. Since a larger volume of water is usually allocated to more productive water users, inevitable competition between human and ecosystem requirements will arise during water scarce years (Srinivasan et al., 2017). A composite view of WS as proposed by Srinivasan et al. (2017) requires the consideration of three major components of WS: water resource utilisation, human demand and/or consumption, and human development.

Although there is evidence from literature that the WCWSS can supply the CCT's current CW and PW demand within an acceptable range, there are areas of clear concern. One of these concerns is the effect of climate unpredictability and the anthropogenic influence on the system (Muller, 2017; Wolski, 2018; Ziervogel, 2019). The complexity and interconnectedness of the coupled human-water system (Srinivasan et al., 2017) is widely discussed and quantified in a paper by Hoekstra and Mekonnen (2011) in terms of water use inclusive of blue, green and grey water use, which was included in this research to determine WS.

3.12.2 Water Resources Utilisation Intensity represented by PW/(P+I)

Water used for the production of food, goods and services, is represented by Production Water (PW) as a fraction of available water resources Precipitation + Water Imports (P+I), both presented in volumetric format and thus as the ratio of PW/(P+I), which has no unit. This represents the fraction of water utilised for direct human consumption or Water Resources Utilisation Intensity (WRUI).

3.12.3 Trade and Technology investment represented by TT

GDP/Capita is used to represent the economic ability and capacity of a population to invest in water storage, reticulation and processing infrastructure as well as the trade for commodities from outside the WCWSS.

3.12.4 Production Water and Consumption Water use represented by PW/CW

The uneven distribution in the water produced versus water consumed are represented by the ratio produced by the Production Water (PW) and Consumption Water (CW) footprints. The water footprint concept was inspired by Hoekstra and Mekonnen (2011), who described and quantified water represented in products and consumption activities. According to Srinivasan et al. (2017), the PW and CW, both stated in volume, are represented by a ratio, which is expected to be directly related and very much dependent on the dominant economic activity of the region studied.

It is proposed that plotting these three variables against each other, WS can be displayed/described in graphical format. A watershed with a high CW, low economic production capacity and therefore low GDP, is likely to threaten WS. Water stress, represented by PW/(P+I), may be relieved by decreasing abstraction or increasing imported water (I). As economic well-being, represented by GDP, increases, societies use more water, either by increased abstraction which may be to the detriment of the environment, or through virtual water imports (food, goods, service and utilities) from outside the watershed.

Once the water utilisation drivers of human–natural systems are known, WS can be modelled and its occurrence predicted for a given watershed. This is supported by empirical meta-analysis of previous surveys performed by Padowski et al. (2015) and Srinivasan et al. (2017), who identified four major factors influencing WS, namely: Water use determined by culture/economy; water resources availability; GDP, considered in this research; and governance, excluded from this research.

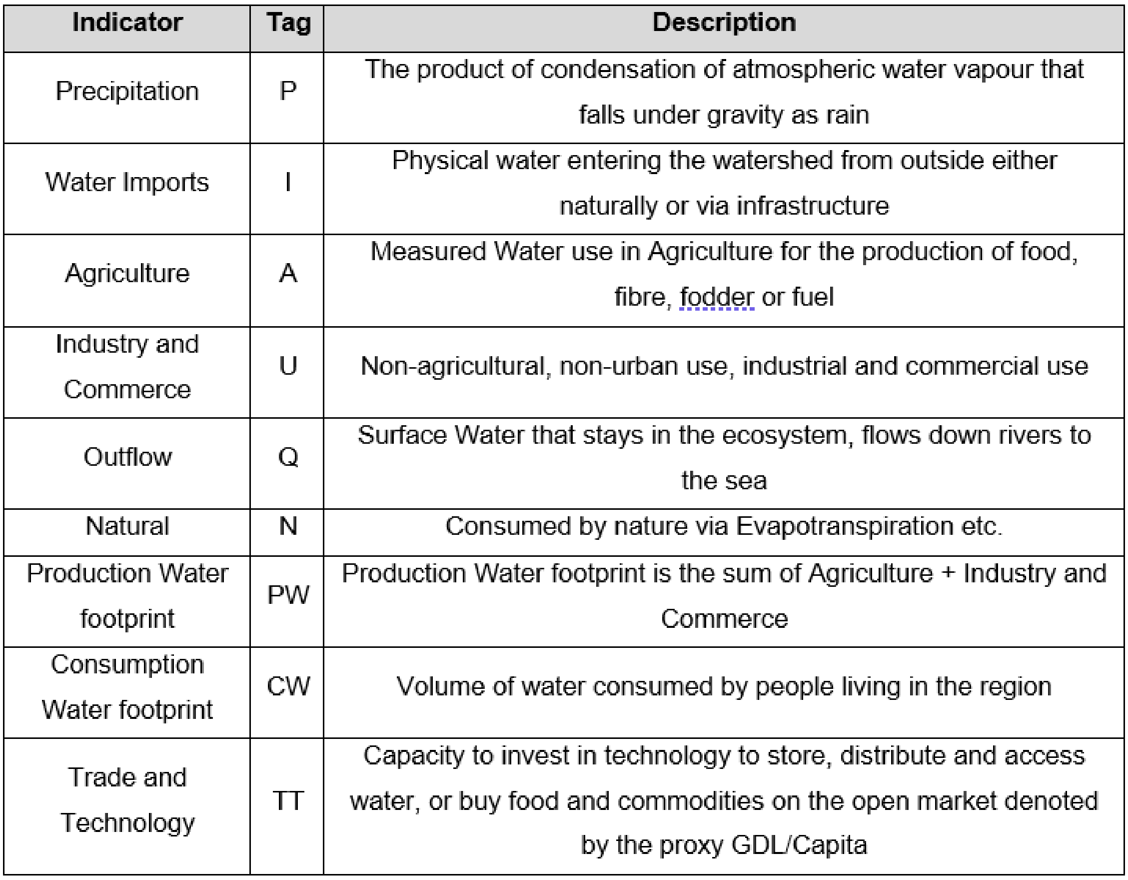
Srinivasan et al. (2017) present an outline to explain, categorise, measure and model WS over distinct timescales. Water security or insecurity may present itself in various shapes or forms in different societies; consequently, it will not be feasible to quantify WS by a single index. WS ought to be viewed as a *safe operating subspace* contained in a three-dimensional area represented by delineating the actual resource capacity, infrastructure capacity, and economic capacity of the system investigated (Rockström et al., 2009).

Linked human-water system frameworks can then be applied to predict future watershed trajectories, forecast water insecurity, and advise on suitable mitigation. The indicators and indices employed in the analysis of the current status of WS for the CCT and the influence of the proposed augmentation projects as contained in the New Water Programme for the CCT are presented in Table 3.4, Table 3.5, and Table 3.6.

This research utilised the DFWS of Srinivasan et al. (2017) to determine the status of WS for the CCT and then expanded the Dynamic Framework by including the proposed CCT water augmentation projects and determining its impact on the CCT's WS. The perspectives and definitions of WS presented in the previous chapter highlighted the strain between consistency in the selection of quantitative WS descriptions on the one side and spatial variation of complexity, space and timespan on the other (Srinivasan et al., 2017). WS in a singular spatial and temporal unit has the benefit of being uncomplicated and adaptable to various spatial and temporal scales but does not calculate the effect of anthropogenic water influence and does not inform mitigation. It also does not have any predictive or explanatory capabilities and solely represents the state of the scheme over a shorter timespan (Srinivasan et al., 2017).

Viewed as an outcome of a linked anthropogenic-water approach, WS considers human flexibility to outside drivers such as the evolvement of a human-water system under the influence of governance, culture and infrastructure. Frameworks that hold human values fixed against variable hydrological information can provide predictions about WS in the short- to medium-term, which is considered the typical temporal planning horizon for water authorities (Sivapalan & Blöschl, 2015; Srinivasan et al., 2017).

Table 3.4: DFWS indicators and indices for 2006-2018



Indicator	Tag	Description
Precipitation	P	The product of condensation of atmospheric water vapour that falls under gravity as rain
Water Imports	I	Physical water entering the watershed from outside either naturally or via infrastructure
Agriculture	A	Measured Water use in Agriculture for the production of food, fibre, fodder or fuel
Industry and Commerce	U	Non-agricultural, non-urban use, industrial and commercial use
Outflow	Q	Surface Water that stays in the ecosystem, flows down rivers to the sea
Natural	N	Consumed by nature via Evapotranspiration etc.
Production Water footprint	PW	Production Water footprint is the sum of Agriculture + Industry and Commerce
Consumption Water footprint	CW	Volume of water consumed by people living in the region
Trade and Technology	TT	Capacity to invest in technology to store, distribute and access water, or buy food and commodities on the open market denoted by the proxy GDL/Capita

The analysis of the evolution of WS in the literature review in Chapter 2 presents the theoretical footings to identify, categorise, quantify, frame and forecast the status of WS for the CCT and the effect on the WS of the water augmentation plan for Cape Town. A composite view of WS as proposed by Srinivasan et al. (2017) requires the consideration of three major components of WS, namely: water resource utilisation, human demand and/or consumption, and human development. The Dynamic Framework maps WS as a water secure functional subspace contained by a three-dimensional area represented by the physical resource capacity, infrastructure capability, and economic status (Rockström et al., 2009).

The first deliverable processed gathered data through the DFWS for the Water Management Area of the CCT as described by Srinivasan et al. (2017):

i) Volumetric water-related data were assessed to calculate the fraction (ratio) of total volume of water abstracted for human benefit to the total available water resources on an annual basis (Sullivan, 2002; FAO, 2020).

ii) Secondly, the water-related financial investment capacity in trade, technology and goods was determined. GDP/Capita data were used as a representation to depict this capacity of societies (Stats SA, 2017).

iii) Thirdly, production and consumption information for the CCT was calculated as a proportion of the PW and the CW footprints of the population. This relationship is motivated by the internal and external water hypothesis offered by Hoekstra and Mekonnen (2011).

When three of these variables (ratios), namely:

i) Total Water Potential (TWP=PW/(P+I)), Total Trade and Technology (TT) investment;

ii) Production Water (PW); and

iii) Consumption Water (CW) and Total Water Consumed (TWC=PW/CW),

are plotted (Srinivasan et al., 2017), WS for a spatial unit, in this case the CCT, can be graphically projected.

The secondary deliverable of RQ1 was obtained through the expansion of the WS status quo by adding or including the CCT augmentation projects indicators as reflected in the CCT Water Strategy (City of Cape Town, 2019c). The CCT have been developing a City Water Strategy; this stratagem consisted of the conclusion of experience gained throughout the 2015-2018 drought period and included the augmentation, comprehensive investigation, scenario planning and pressure testing of a built agenda to deliver novel, alternate and varied water sources to complement the existing rain-fed surface water sources (City of Cape Town, 2018b).

Table 3.5: Expanded DFWS for the CCT – indicators and indices of augmentation projects of the New Water Programme for 2019-2026 (Source: Author)

Indicator	Tag	Description
Water Re-Use	WR	Volume/percentage of water re-use
Ground Water	GW	Volume of ground water abstracted
Desalination	DS	Volume of water gained by desalination of sea water
Surface Water Augmentation	SW	Construction of new and increase of surface water resources
Total Augmentation Supply	AS	Sum of WR + GW + DS +SW

Table 3.6: Advantages and disadvantages of the augmentation projects of New Water Programme (Source: Author)

Resource	Advantage	Disadvantage
Surface Water	• Relative low costs	• Timespan to develop • Rainwater-dependent
Water Transfers	• Low cost to operate existing infrastructure	• Timespan to develop new infrastructure • Rainwater-dependent
Water Re-Use	• Availability, currently only 8% recycled for non-potable use • Quick to implement • Non-rainwater-dependent	• Cost • Perception of quality • Quality control • Water use dependent
Ground Water	• Relative costs • Quick to implement	• Unknown quality • Unknown quantity • Unknown sustainability • Rainwater-dependent
Desalination	• Non-rainwater-dependent	• Expensive • Pollution to and from plant • Timespan to develop

3.12.5 Regional-Scale Relative Risk Assessment Methodology for Cape Town

The third deliverable explored the associated risk elements of the WS indicators by further processing the results using a probability risk assessment process as described by the Regional-Scale Risk Assessment Methodology. Data obtained from the DFWS were further analysed using the Relative Risk Model (RRM) assessment tool in order to rank the risk factors contributing to the WS status of the CCT (Appendix A).

The WS Regional-Scale Risk Assessment for the CCT, which employed the RRM in this research, was derived from seminal work done by various authors since 1993 on establishing the Environmental Risk Assessment (ERA) (USEPA, 1992; Suter, 1993) to the adaption and expansion of the ERA, to a Regional-Scale Relative Risk Assessment Model by Landis and Wiegers in 1997. The RRM has been effectively demonstrated in the application of different scenarios and at various regional-scales (Landis & Wiegers, 2007).

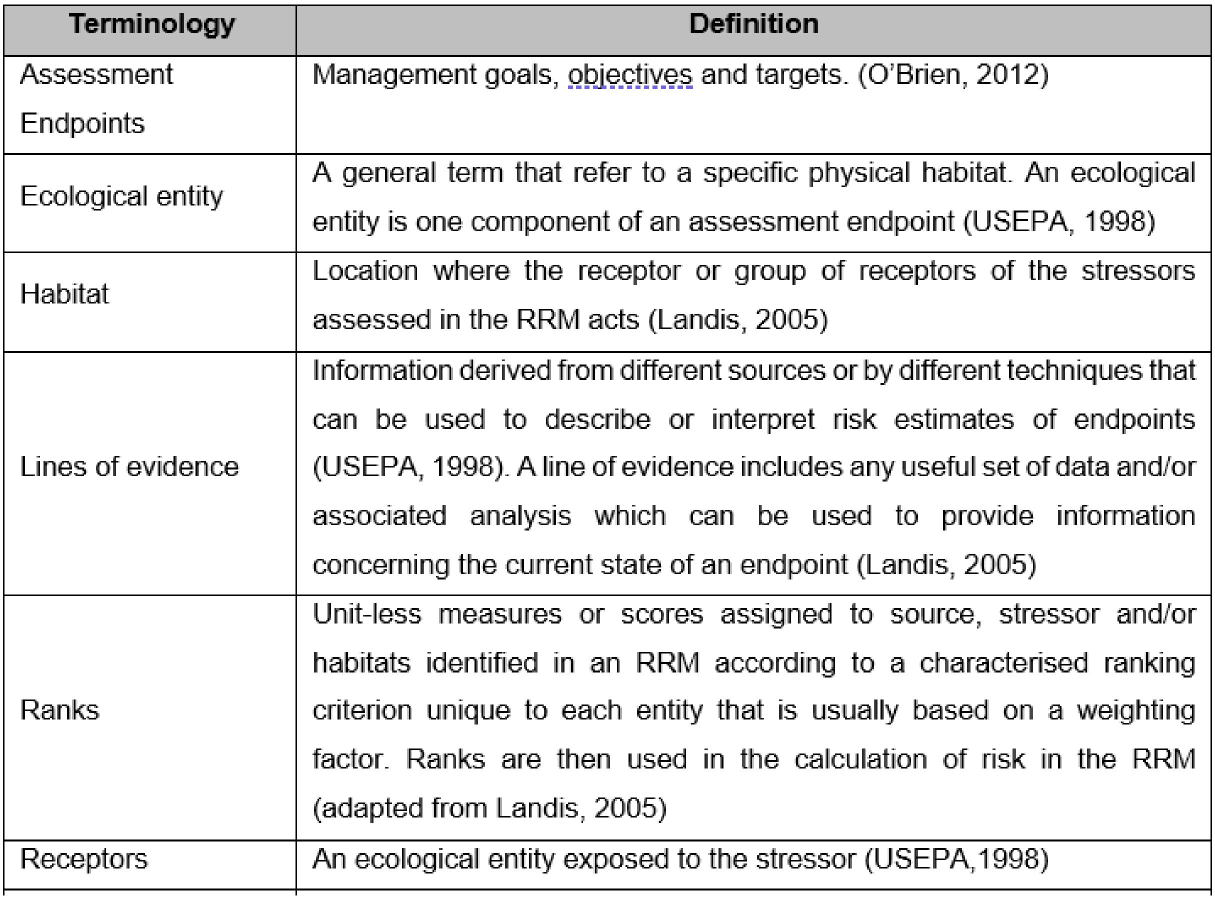
A Regional-Scale Risk Assessment using the RRM is a form of ecological risk assessment that is carried out on a spatial scale where considerations of various sources of various stressors affecting various endpoints or objectives are allowed (Landis & Thomas, 2009; O’Brien & Wepener, 2012). This transparent, adaptable, scientifically validated approach is being continually developed both locally and internationally and has been used extensively as a robust and reliable technique that importantly allows for uncertainty associated with the outcomes to be carefully evaluated (Landis & Thomas, 2009; Ayre & Landis, 2012; O'Brien & Wepener, 2012).

The RRM has been shown to advance the management of aquatic ecologies in South Africa to accomplish a equilibrium in the safeguarding of biodiversity, while allowing for the social and economic needs of society (O'Brien & Wepener, 2012). Regional-scale assessments using the RRM have been carried out on scales from 62 km^2 to 33,570 km^2 and included diverse habitats, various stressors with unique receptors, and corresponding endpoints.

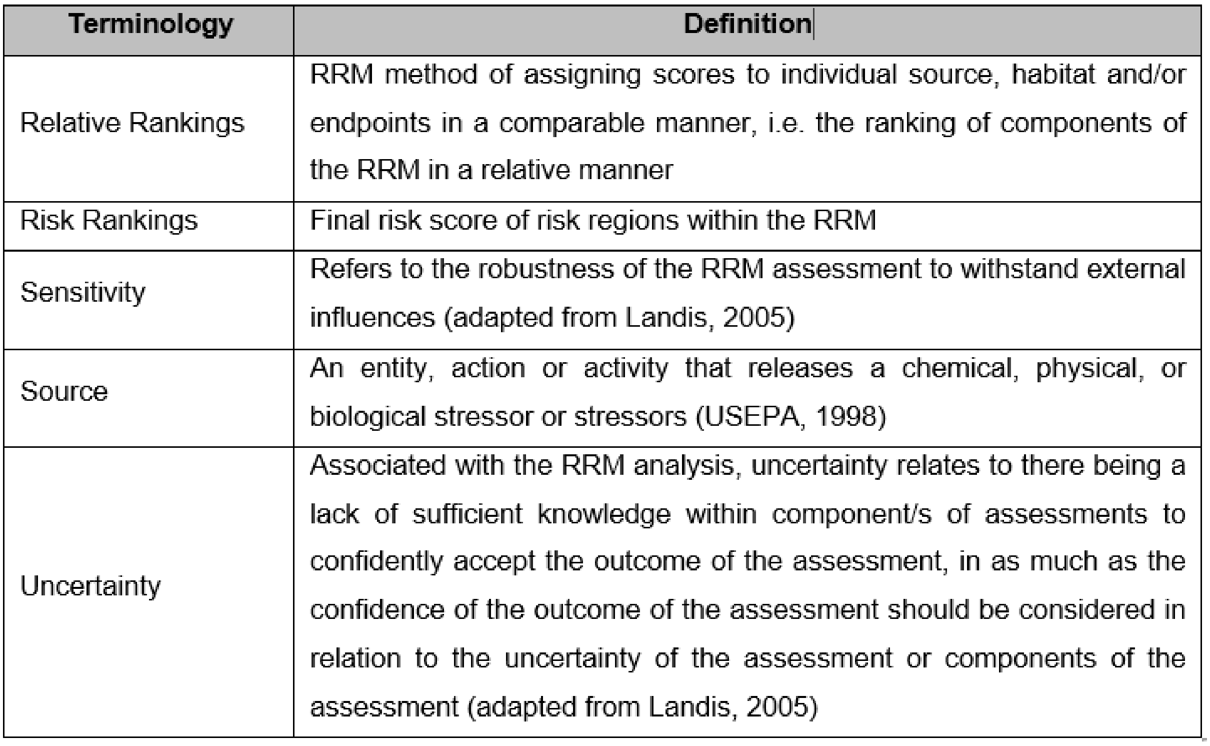
This research demonstrated the use of the latest regional-scale RRM approach to contribute to the implementation of a WS risk assessment for the Western Cape Water Supply System (WCWSS) servicing the CCT.

Table 3.7 below defines the terminology for the Regional-Scale Relative Risk Assessment Model.

Table 3.7: Defining Regional-Scale Relative Risk Assessment terminology (O'Brien & Wepener, 2012:155)



Terminology	Definition
Assessment Endpoints	Management goals, objectives and targets. (O'Brien, 2012)
Ecological entity	A general term that refer to a specific physical habitat. An ecological entity is one component of an assessment endpoint (USEPA, 1998)
Habitat	Location where the receptor or group of receptors of the stressors assessed in the RRM acts (Landis, 2005)
Lines of evidence	Information derived from different sources or by different techniques that can be used to describe or interpret risk estimates of endpoints (USEPA, 1998). A line of evidence includes any useful set of data and/or associated analysis which can be used to provide information concerning the current state of an endpoint (Landis, 2005)
Ranks	Unit-less measures or scores assigned to source, stressor and/or habitats identified in an RRM according to a characterised ranking criterion unique to each entity that is usually based on a weighting factor. Ranks are then used in the calculation of risk in the RRM (adapted from Landis, 2005)
Receptors	An ecological entity exposed to the stressor (USEPA,1998)



Terminology	Definition
Relative Rankings	RRM method of assigning scores to individual source, habitat and/or endpoints in a comparable manner, i.e. the ranking of components of the RRM in a relative manner
Risk Rankings	Final risk score of risk regions within the RRM
Sensitivity	Refers to the robustness of the RRM assessment to withstand external influences (adapted from Landis, 2005)
Source	An entity, action or activity that releases a chemical, physical, or biological stressor or stressors (USEPA, 1998)
Uncertainty	Associated with the RRM analysis, uncertainty relates to there being a lack of sufficient knowledge within component/s of assessments to confidently accept the outcome of the assessment, in as much as the confidence of the outcome of the assessment should be considered in relation to the uncertainty of the assessment or components of the assessment (adapted from Landis, 2005)

3.13 The 10 steps framing the RRM

The Regional-scale RRM implemented in this research on the WS risk assessment for the CCT is based on the ten procedural steps of the RRM, contextualised within the IWRM framework for the CCT (O'Brien et al., 2018:154).

Step 1: Listing of management goals as endpoints for the CCT

The relevance and effectiveness of the RMM can be greatly enhanced by informing the decision-making needs of all the interested and affected parties concerned with the research (Landis & Thomas, 2009). Although focused on WCWSS and its information requirements, the RRM can contribute towards the National Water Resource Strategy (Department of Water and Sanitation, 2012; Department of Water Affairs, 2012), and cater to particular stakeholder needs.

This step in the process usually requires a range of stakeholder workshops to facilitate inclusion and fulfil information requirements to enable the establishment of appropriate endpoints for the research. This process was replaced with an in-depth literature review on indices and indicators available via open-access HISs, published peer-reviewed literature and grey literature. Padowski et al. (2015) and Srinivasan et al. (2017) found that patterns observed in real world case studies of WS could be explained by four sets of factors, namely: the prevalent culture and economy, the resource potential of water supply, the wealth of the society, and the governance of the water resource in the region.

Therefore, the endpoints considered for this research included:

i) Sustainable Water Potential, TWP=PW/(P+I), described as Water Resources Utilisation Intensity (Srinivasan, et al., 2017).
ii) Sustainable augmentation of the New Water Programme project planned by the CCT (City of Cape Town, 2018a).
iii) Sustainable WS, Spatial Heterogeneity (PW/CW) in water production and consumption footprint.

Step 2: Establish a diagram indicating prospective sources and habitats pertinent to the determined management objectives for the CCT

The detailed diagram is required at this step to help with the detection and classification of prospective stressors and sources of stressors present within the boundaries of the research area, which is aligned with the management goals. All possible variables, stressors, receptors, habitats and endpoints, spatial distribution and relationships between components and important topographical features can be referenced to this map (Figure 3.1). The conversion of management goals to endpoints set in Step 1 for this RRM research consist of the formation of a viable risk management plan for the system.

The objectives of this research included:

i) The identification and contribution of risk impact knowledge for further research.
ii) A benchmark/basis for system users to manage usage and activity impact.
iii) Informing interested and affected parties.

Step 3: Delineate of the diagram into Risk Regions established on a sequence of sources, stressors, habitats and endpoints

The combinations of source information, habitat and management objectives as endpoints were translated to formulate risk regions for relative analysis. The risk scores calculated throughout the RRM assessment were established on these risk regions (O’Brien & Wepener, 2012).

As shown in Figure 3.1 below, risk region boundaries are established after considering the habitat segments, the sources of stressors, and exposure of the stressor pathways. This ensures the inclusion of suitable sources, stressors and habitats into the risk regions (Landis & Wiegers, 2005).

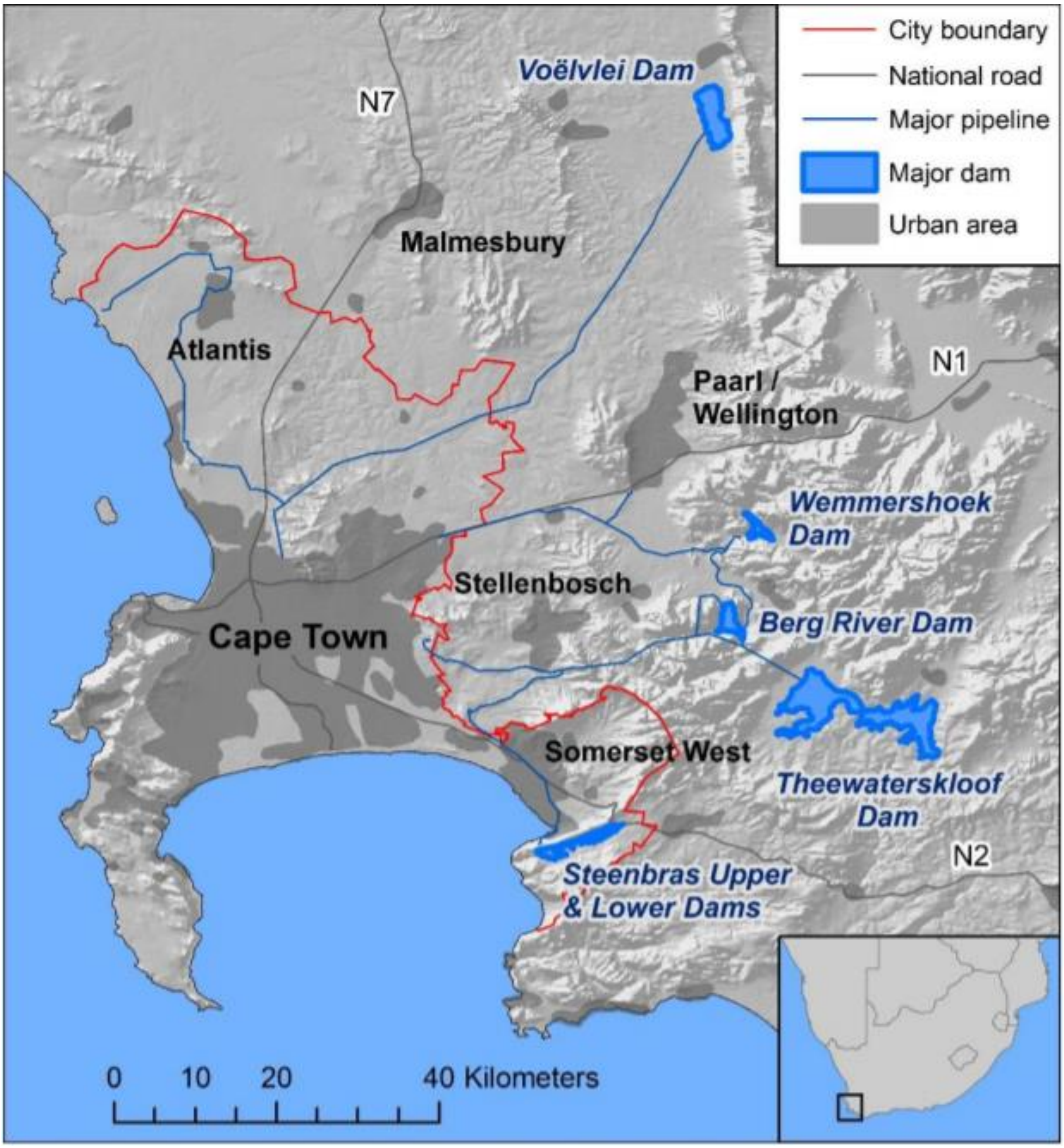


Figure 3.1: WCWSS water management boundary (adapted from City of Cape Town, 2018a:4)

Step 4: Create a conceptual model that connects the sources of stressors to receptors and to the assessment endpoints

The conceptual model (Figure 3.2) outlines the probable interactions between sources, stressors, habitats and endpoints to be assessed for each risk region (Landis & Wiegers, 2005). The conceptual model had to be appropriately structured and instructive to perform as augmentation of the fundamental RRM structure. The conceptual model was constructed and populated through the creation of resource-use scenarios using information gathered from various databases, peer-reviewed and grey literature.

The more detailed a conceptual model, the better, as it allows for the exclusion of some stressors because of absence of exposure pathways and the addition of different factors initially not considered as part of the initial range of the assessment (Landis & Wiegers, 2005). Complicated theoretical interactions among stressors and sources identified by the conceptual framework were tested within the assessments as it was categorised as falling outside the purpose of this research. The conceptual model was pivotal to the assessment; it was employed in several of the subsequent stages, especially in the assessment of uncertainty and sensitivity in Step 7.

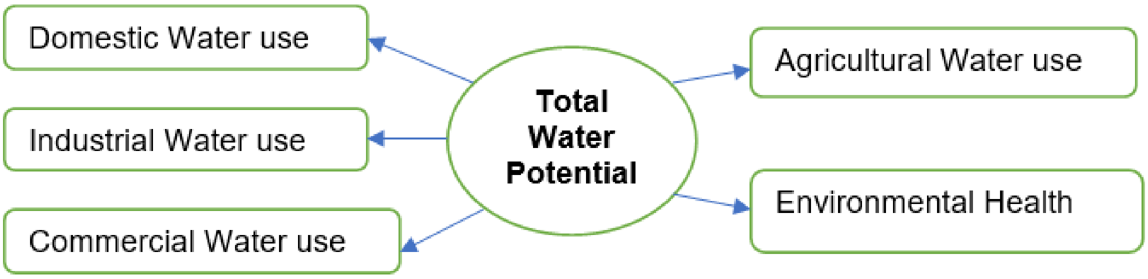


Figure 3.2: Conceptual model of the Risk Regions (RR) considered for Cape Town (Source: Author)

The conceptual model for the study was developed to represent associations among known sources, established stressors, chosen habitats and assessment endpoints for the risk regions considered for Cape Town (Figure 3.2). The relationships in the conceptual model are based on the pathways of potential exposure of stressors to habitats and predicted effects of stressors to endpoints.

Figure 3.3 presents the conceptual model for the study, where initial relationships between five (5) identified source groups (Figure 3.2) were made with stressors of the study that were categorised into four (4) types of stressors: rain-dependent water supplies, water restrictions, water costs, and water demand management impact (Figure 3.2; Figure 3.3; Figure 3.4). Source stressor relationships were then presented according to the habitats of interest in the study, which included: water resources utilisation intensity (PW/(P+I)), Trade and Technology (TT) investment, and Spatial Heterogeneity (PW/CW) in water production and consumption footprint (Figure 3.4). After these source-stressor-habitat relationships were established, they could be compared to established endpoints of the study (Figure 3.4) to present strong, weak and no pathways of exposure from sources to endpoints. These relationships were applied to set up the RRM model for the study (Figure 3.2; Figure 3.3; Figure 3.4).

Figure 3.3: Theoretical representation of the Relative Risk Model (RMM) (Source: O'Brien & Wepener, 2012:158)

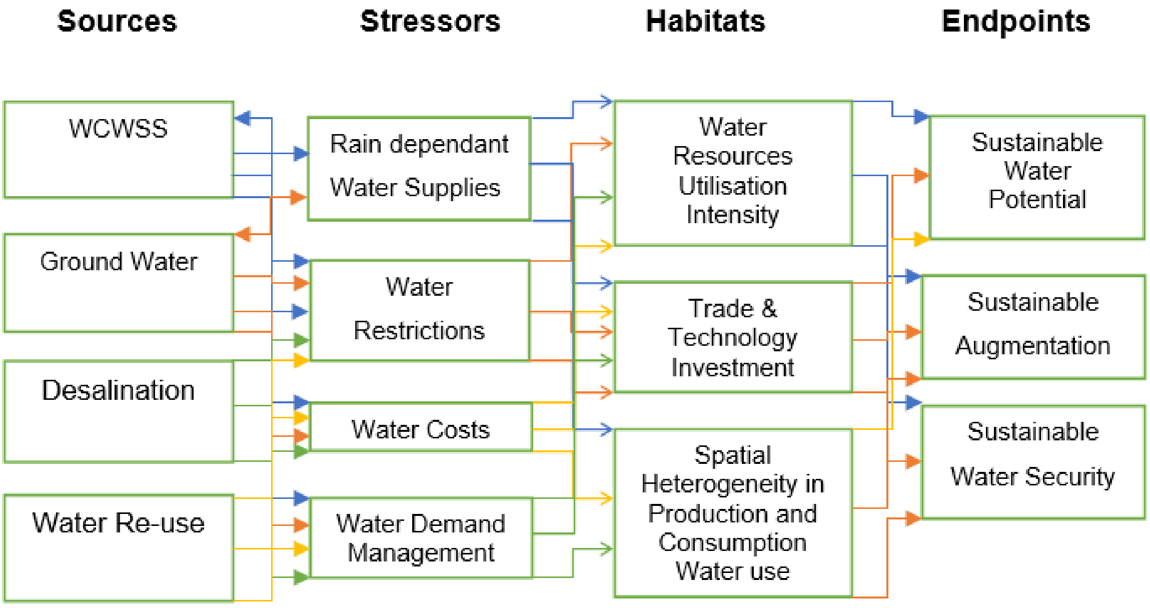


Figure 3.4: Conceptual representation of the Relative Risk Model (RRM) used in this research (Source: O'Brien & Wepener, 2012:158)

3.13.1 Exposure evaluation

3.13.1.1 Source and related stressor identification

The sources and the related stressor interactions with these sources identified in the study area were determined based on the singular current water supply to the CCT, namely the Western Cape Water Supply System (WCWSS) and the proposed alternative augmentation sources, namely ground water, desalination and water re-use contained in the New Water Plan and Cape Town's Water Strategy (City of Cape Town, 2018a; City of Cape Town, 2019c).

Surface water, water imports and ground water are rainwater-dependent, therefore precipitation will play a pivotal short-, medium- and long-term role in the water potential of these resources, whereas desalination and water re-use are rainfall-independent and precipitation will not have a direct influence on these resources.

Precipitation will have a direct material impact on water restrictions, water costs, and water demand management.

Ground water abstraction by private individuals, agriculture and industry is very difficult to control as record keeping is dependent on feedback from the user. Water restrictions, water costs, and water demand management will only be effective in controlling ground water abstraction if it can be measured accurately.

Water costs are directly related to its resource and range from the least expensive which is surface water at R5/cubic meter costs. water imports, water re-use, and ground water to desalination are the most expensive at R36 per cubic meter respectively. The higher the assurance of water supply, the higher the costs (City of Cape Town, 2019c).

3.13.2 Habitat identification

Three habitats associated with the CCT's water sources were identified from the New Water Plan and Water Strategy (City of Cape Town, 2018a; City of Cape Town, 2019c), namely: Water Resources Utilisation Intensity (PW/(P+I)), Trade and Technology (TT) investment, and Spatial Heterogeneity (PW/CW) in water production and consumption footprint.

Step 5: Identify a ranking system to determine the relative risk to the assessment endpoints

3.13.3 Effects assessment

Based on the Regional-Scale Risk Assessment Methodology (Obery & Landis, 2002; O'Brien, 2012; O'Brien et al., 2018), the effects assessment provides the criteria to rank sources and habitats based on their ability to impact established assessment endpoints. This step requires the formation of a ranking system for every source, stressor and habitat that will translate in turn to setting up the assessment end points (Landis & Wiegers, 2007; O'Brien et al., 2018).

Following the RRM approach (Landis & Wiegers, 2005; O'Brien et al., 2018) ranks were assigned to sources and habitats on a two-point incremental scale with ranks of 0 indicating no impact, 2 representing a low impact, 4 as a medium impact and 6 as a high impact. Ranking criteria applied to sources and habitats for the WS risk assessment for the CCT utilising the RRM are presented in Table 4.1 and Table 4.2. According to O'Brien and Wepener (2012) and Landis and Wiegers (2005), measurement data are translated into non-dimensional rankings to measure and compare the effects of stressors on endpoints (O'Brien & Wepener, 2012; Landis &

Wiegers, 2005). The ranking system of high, moderate or low are applied to sources, stressors and habitat variables according to the circumstances prevalent in the research region. Ranks are assigned according to site specific criteria and are based on size, frequency of sources, and presence of habitat. The non-dimensional rating system criteria ought to be applied in regard of the accessible data. The states represent the range of conditions in the research area, the levels of impact, and the management ideals as follows:

i) **Zero:** This state represents a stable state with zero effect of risk, equivalent to a pre-anthropogenic state and used as benchmark.
ii) **Low:** Depicts a mostly natural state with minimal effect or risk, the ideal and most desired state.
iii) **Moderate:** Represents a moderately used or altered state with modest impact or risk representing the threshold of potential concern or alert.
iv) **High:** Represents a substantially modified or compromised state with comparable high effect or risk.

The resources used for determining impact are the Water Outlook Reports published periodically by the CCT (City of Cape Town, 2018b). This research followed the weight-of-evidence approach as recommended by O'Brien and Wepener (2012) and O'Brien et al. (2018) in reference to Burton et al. (2002).

The ranking schedule for source and habitat variables at each risk region of the RRM assessment for the CCT is shown Table 4.1. The ranks are assigned to sources with the stressor association established on the existence of the source inside the risk region and probable impact denoted by its position and consequent downstream effects in Table 4.1 and Table 4.2.

The larger the number of stressors associated with a source, the higher its source rank, and the closer to the activity the higher the impact and therefore also the source ranking. The further downstream the activity is the lower the source ranking, which incrementally lessens with an increase in distance from the stressor. The habitat regions for the identical risk region are established on the significance and sensitivity of every single habitat relative to its status as a system indicator function or endangered habitat. Risk regions considered in this research include:

i) A = Domestic Water Use (DWU), which is directly influenced by P, WR, WC and WDM.
ii) B = Industrial/Commercial Water Use (I&CWU), directly influenced by P, WR, WC and WDM and greatly affect Trade and Technology (TT) investment.

iii) C = Agricultural Water Use (AWU), the single largest water user after DWU and the first to be limited in case of drought, thereby directly affecting food production, employment and therefore GDP (T&TI).

iv) D = Environmental Health (EH), impacted by P, mining of aquifers (over abstraction of more water than replaced by re-charge) of GW, WI between catchments, ecological reserve usually represents the last 10% of water left in dams which concentrate pollution factors and thus having a negative environmental impact.

Here, filters are applied to evaluate possible links among risk elements, inclusive of source, habitat and effects to assessment endpoints. The filter is a numerical weight factor (0 or 1) that indicates either a no, low (0) or high (1) possibility that a risk association exists (Landis & Wiegers, 2005; O'Brien et al., 2018). In RRM assessments, two types of filters are proposed by Landis and Wiegers (2005), namely an exposure filter and an effect filter. The exposure filters act as a screen for source and habitat types so as to identify combinations that most likely cause exposures, where the effect filter screens the source and habitat permutations for those that are mostly liable to affect the assessment endpoint of a research objective (O'Brien et al., 2018).

Exposure filters are determined by deducing which of the stressors are generated by the sources (Landis & Wiegers, 2005, cited by O'Brien et al., 2018; O'Brien & Wepener, 2012). Two sequence specific questions regarding every stressor relative to a specific source-habitat combination is investigated:

i) Is the source releasing or causing a stressor? (Landis & Wiegers, 2005).

ii) Will the stressor then happen and continue in the habitat? (O'Brien et al., 2018; O'Brien & Wepener, 2012).

A positive response to either of the questions will assign a value of 1 to the source-habitat combination filter, while a negative answer will produce a 0 value to the filter. Indirect relationships will result in a 0.5-value assigned to the filter.

Effect filters are assigned in a similar way but have a separate filter for each assessment endpoint. An important consideration at this point is the re-evaluation of the management goals of the assessment to ensure the variables of the endpoints produce the desired conservation, maintenance, and mitigation outcomes (O'Brien et al., 2018). Effect filters can be developed at this point to ensure management outcomes are addressed.

The answers to the following questions will aid in the development of effect filters:

1. i) Will the endpoint be affected by the release of the stressors identified?
2. ii) Are the endpoint receptors susceptible to the stressor in the habitat?

A positive response to both questions will assign a value of 1 to the source-habitat and endpoint combination, while a negative response to both questions will result in a value of 0. An indirect or unclear potential relationship can be scored with a value of 0.5. Beneficial source-habitat-endpoint relationships can be given a negative (-) filter value, which will indicate a positive contribution to the endpoint.

Step 6: Calculate the relative risks

This stage represents the construction of exposure and effect filters for the RRM and the incorporation of the ranks and filters to allow for the calculation of relative risks in Appendix C, Table 4.3 and Figure 4.3 (O'Brien et al., 2018; O'Brien & Wepener, 2012).

$$RS = Sij \times Hik \times Wjk \quad (1)$$

Where:

i = RRs or sub-area (Region A, B, C, etc.)

J = Source series (Surface Water..., Water Re-Use)

k = Habitat series (Total Water Potential)

Sij = Ranks for sources (WI) between sub-areas (j)

Hik = Ranks for Habitats between sub-areas

Wjk = Weighting factor determined by exposure or effect filter

Equation 1: Calculating the Final Risk Score for individual Risk Regions by multiplying the ranks by the appropriate weighing factor (O'Brien & Wepener, 2012:8)

The results represent a matrix of risk scores associated with the relative exposure or effect related to the source and habitat in every risk region. The probable relative risk stemming from a source (Equation 2), taking place within a related habitat (Equation 3), can be condensed by the sum of all the related scores. This step also combines ranks and weighting factors through multiplication, with the result producing a relative risk estimate in each risk region.

The final risk scores (RS) are the product of the ranks and associated weighting factors for each risk region as produced by the following equations:

$$RS_{source} = \sum (Sij \times Hik \times Wjk) \text{ for } j=1 \text{ to } n \text{ source} \quad (2)$$

Equation 2: Calculating the potential risk from a specific source (O' Brien & Wepener, 2012:8)

$$RS_{habitat} = \sum (Sij \times Hik \times Wjk) \text{ for } k=1 \text{ to } n \text{ habitat} \quad (3)$$

Equation 3: Calculating the potential risk resulting from a specific source and occurring in a specific habitat (O'Brien & Wepener, 2012:8)

Step 7: Evaluate the uncertainty and sensitivity of the relevant risk rankings

The RRM applied in this research allows for several quantitative methodologies such as the Monte Carlo Permutation (MCP) process to simulate uncertainties by conducting a number of iterations and producing a range of numbers (Landis & Wiegers, 2005). The MCP presents a probabilistic methodology that computes the change in the model yields or risk scores as a function of model inputs or ranks and filters (Colnar & Landis, 2007).

Each filter component was assigned a high, medium, or low ranking based on the confidence obtained from available information. The ranks and filters were then assigned discrete statistical allocations to denote uncertainty. A MCP simulation was run at 10,000 iterations using an Excel add-on called *Risk Assessment software @Risk*™ to account for uncertainty in the model as displayed graphically in Figure 4.6 and Figure 4.7 (Colnar & Landis, 2007).

Model sensitivity analysis testing was then done with the @Risk™ software to examine the influence of augmentation projects on the WS for Cape Town. Evaluation correlation coefficients were produced to rank model factors corresponding to their impact to the projection of uncertainty as displayed graphically in Figure 4.10 and Figure 4.12 (O'Brien et al., 2018).

Step 8: Produce a testable hypothesis for future field and laboratory investigation

To confirm the risk ranking results produced by the RRM and further reduce uncertainties with primary data, this step requires establishing a suitable hypothesis for field and laboratory testing. Fieldwork and laboratory testing were not within the scope of this research.

Step 9: Test the hypothesis that were generated in Step 8

This step forms part of the hypothesis generated in the previous step; it did not fall within the scope of this research and was therefore excluded, but it may be considered for future research.

Step 10: Communicate the results to effectively portray the relative risk and uncertainty in a response to management goals

Local application of the RRM requires rigorous peer review to ensure its scientific validity and improvement depend on its availability, ease of use, and the ability to produce reliable results. This stipulation for communication will be fulfilled by submitting this research for publication in a suitable scientific journal.

3.14 Unit of analysis

The unit of analysis for Water Security, which is represented by WS indicators in ratio scale, facilitates the scale-independent graphical presentation of the results. The ratio scale was inspired by Hoekstra and Mekonnen (2011). The RRM generated Relative Risk Scores (RS) measurement as units of analysis, which, plotted together in graphical format, facilitate a visual comparison of the results.

3.15 Research limitations

The research is delineated by the following limitations:

i) Only open-access hydrological and water-related data were used.
ii) Water-related indicators specified by the DFWS of the CCT were considered.
iii) Water allocations to agriculture were excluded in the DFWS.
iv) Water contributed by alien vegetation removal (Working for Water Programme) was excluded from the DFWS.
v) The generation of a hypothesis and the testing thereof was excluded from the RRM.
vi) The research is primarily based on secondary and grey literature.
vii) The free version of Palisade @Risk Monte Carlo Simulation Software offered only limited access and functionality.

Historical water consumption data were limited through the CCT open data portal because records only extended back to 2013 and statistics varied over inconsistent time periods. The CCT only provided information on megalitres of raw water treated and not historical consumption data; the correlation between water treated and consumed is unclear (Winter, 2017). Not addressed in this research is the effect of regime shifts and political influences affecting changes in governance and culture as societies evolve. Such regimes shifts cannot be facilitated through conventional hydrological predictions of WS but anticipation of the impact of governance shifts can provide predictive insight (Srinivasan et al., 2017).

To confirm the risk ranking results produced by the RRM and to further reduce uncertainties with primary data, establishing a suitable hypothesis for field and laboratory testing is required (Step 8 in section 3.13.3). This step was not included in the research, but may be considered for future research.

3.16 Assumptions

It was assumed that the outcome of applying the DFWS and RRM in this research would prove to be sensitive enough to provide insight into anthropogenic influences on the status of Cape Town’s WS. It was further assumed that the first deliverable would produce results indicating the status of WS from 2006-2018, where after the timeframe would be expanded from 2019-2026 to include the proposed impact of the augmentation projects contained in the New Water Programme on the WS as the second deliverable and:

i) forecast water in/security;
ii) inform appropriate mitigation actions to support WS; and
iii) map physical resource availability, infrastructure capacity and cultural/ economic water use impact to inform Integrated Water Resource Management (IWRM).

The RRM application for this research was expected to provide results which would contribute to:

i) Producing a graphical account of the relative risk scores found per risk region in the research area, ranked between high, moderate, and low relative risk to WS for Cape Town.
ii) A graphical interpretation of the total risk regions for all the sources contemplated in this research.
iii) The total risk presented to each habitat per risk region measured in this research.
iv) The augmentation projects ranked by effect on the average water potential for Cape Town.
v) A graphical ranking of the effects of individual indicators on the WS of Cape Town.

3.17 Ethics

This research followed the steps in the Ethics in Research Handbook of the Faculty of Commerce from the University of Cape Town to ensure ethical compliance (University of Cape Town, 2019). The research has no significant ethical implications because of the following reasons:

i) No human participants were used as a data source for this research.
ii) The possibility that this research can be harmful to any person or third party is negligible.

iii) This research did not involve any community participation.

iv) No service to a community is provided by this research.

v) This research is not sponsored, therefore no conflict of interest is declared.

vi) This research does not involve the field of health nor has any association with it.

This research was not participant driven, and all data were accessed and used ethically. The data accessed were freely available in the public domain. No proprietary artefact has been produced as a result of this research, therefore no significant ethical implications exist.

No financial support has been received or implied for this research by any actor, interested and affected party or organisation, therefore no conflict of interest has been declared.

3.18 Chapter summary

This chapter described the data collection and analysis methodology employed in this research from the perspective of the quantitative research philosophy, research approach, strategy, design and instrument selected to investigate the solutions to the posed RQs. The DFWS and the RRM approach selected for data analysis in this research has been described in detail. The research design, instrumentation and data collection process were explained and presented as background to describe how data sources were identified, accessed and investigated.

The data collection method included the collation of supplementary bio-physical data with all related data available from grey and published peer-reviewed literature. The analysis methodology presented in the chapter describes the analysis process as first applying and then expanding the DFWS to produce the primary and secondary deliverables for RQ1. The WS status determined in the first deliverable was expanded to include and analyse the impact of the water augmentation projects proposed by the CCT in their New Water Programme on WS to produce the result for the secondary deliverable. These WS indices were then processed using a risk assessment methodology to determine the risks and impact as deliverable for RQ2 (Ayre & Landis, 2012; O'Brien & Wepener, 2012). The data were calculated and expressed as ratios rather than differences to make results scale-independent. The results of the indices, ratios and rankings were then be presented in graphical format.

The next chapter provides a detailed description of the data analysis, results and findings of the research.

CHAPTER 4: ANALYSIS, RESULTS AND FINDINGS

4.1 Introduction

Chapter 3 presented a discussion on the methodology employed in the process of data collection, the data collection timeline, the analysis framework utilised, as well as a detailed discussion of the validity and reliability of the data. The chapter also presented the quantitative research design and methodology on how the requirements of the aims and objectives of the RQs of this research have been met.

This chapter comprises three parts: (i) analysis; (ii) key results; and (iii) findings of the research. This has been done within the context and perspective of the historical and current WS status of the years 2006-2018 leading up to and during the 2015-2018 drought period. The WS impact of the water augmentation projects planned by the City in its New Water Programme for the years 2019-2026 and an analysis of the its risks is also presented.

These results contribute to IWRM knowledge and information as well as support the building of adaptive capacity with the understanding of the risks posed by sources, the stressors and effects on the management goals as endpoints. Significantly, this will enable water managers to focus on probable risk in the WC/WDM processes and contributes knowledge to the CCT Water Strategy.

4.2 Background

The CCT has been experiencing a worsening water crisis with severe implications for future predictive reliability during the last few years – unforeseen drought, demand increases mainly due to population growth and delayed interventions contributed to the 2017-2018 water crisis experienced in the Western Cape and more specifically in the greater CCT Metropolitan region (Cameron & Katzschner, 2016; Fisher-Jeffes et al., 2017; Ziervogel, 2019).

Cape Town’s 2018 drought strategy consisted of WC/WDM practices, incorporating the following: management of dam levels by restricting outflows to agriculture, environmental reserve and downstream users; water demand management by progressive water restrictions; communication campaigns to educate and inform the public by *inter alia* the publication of a Water Map to acknowledge households that used less than 6 Kℓ; pressure reduction via household flow regulators for uncooperative users; and punitive tariffs for exceeding water use limits.

To supplement and diversify current surface water resources exclusively dependent on rainfall, the CCT proposed augmentation projects that are contained in the NWP, which became part of and accepted by the City Council in 2019 as the draft Water Strategy for Cape Town. The NWP consists of exploring and the bringing online of water supply from springs and rivers, water transfers from outside catchment areas, ground water exploration of various aquifers, short term temporary desalination, long-term optimal desalination, water re-use, and the creation of additional surface water capacity.

The primary aim of RQ1 was to determine the WS status of the CCT leading up to and during the drought by sourcing data from 2006-2018, and then as a secondary part of RQ1, to explore the planned water augmentation projects as proposed for implementation from 2019-2026 in the New Water Programme for Cape Town.

The objective of the first RQ was to examine the WS indicators available from relevant data in the public domain. This included the latest literature, both academic and popular press and their applicability to the Water Management Area (WMA) servicing the CCT. The WS indicators were examined in terms of the DFWS available from the latest literature and their applicability to the Water Management Area (WMA) of Cape Town. Subsequently, the influence of these indicators was framed and calculated through applying the DFWS method to the coupled human-water system of the CCT. The outcome, i.e. the determined WS status, informs and enables water managers to apply resources more effectively. The combination of these interventions was considered for the secondary deliverable of RQ1, namely the impact of the drought strategy and augmentation of water resources on the WS status of the CCT as contained in CCT’s New Water Programme.

RQ2 was formulated to determine the risk elements associated with the WS status of the CCT augmentation options as proposed by the New Water Programme. The objective of this question was to examine the risk elements presented by the WS indicators selected in RQ1 and rank these elements using the Regional-Scale Risk Assessment Methodology. This enables water managers to focus on the probable risks in the IWRM process.

4.3 Research area

This research focused on the spatial unit of the CCT. The City covers a large urban area with a high population density and a concentrated movement of people, goods and services. The City is known for continuous wide-ranging development of numerous, residential, and commercial districts and industrial zones. The

Municipality embodies centres of economic activity with complex and diverse economies, contained in a single area with cohesive development planning and robust inter-reliant social and economic relationships among its component parts.

The CCT has a warm Mediterranean climate (Köppen *Csb*), with mild, moderately wet winters and dry, warm summers (Rohli et al., 2015; GAWSIS, 2020). Winter, which lasts from the beginning of June to the end of August, may see large cold fronts entering for limited periods from the Atlantic Ocean with precipitation and strong north-westerly winds. Winter months in the City average a maximum of 18.0 °C and a minimum of 8.5 °C (World Meteorological Organisation, 2018). Total annual rainfall in the City averages 515 millimetres. Summer, which lasts from early December to March, is warm and dry with an average maximum of 26.0 °C and minimum of 16.0 °C. The CCT includes the Cape Metropolitan Council, Blaauwberg, CCT CBD, Helderberg, Oostenberg, South Peninsula and Tygerberg (Western Cape Government, 2019).

The City's documented water records date back to 1834, where it's water needs were provided by 36 free flowing springs. The CCT has been dependent on storage of surface water and containment of water from springs for approximately 170 years, since 1850. With it being a winter rainfall area, summer water requirements made it dependent on surface water in several dams outside its jurisdiction. Continuous increasing demand on finite storage required the increase in storage capacity via the construction of reservoirs and dams (City of Cape Town, 2018b).

The municipality moreover built various small dams on top of Table Mountain during the 1880s, supplying water to an ever-increasing populace until the early 1900s. The Wemmershoek dam was the last built dam by the CCT municipality before responsibility of bulk water resources was mandated to the National Department of Water and Sanitation (DWS) through the 1956 promulgation of the Water Act. Thereafter, only three of the largest dams were built by DWS, namely the Voëlvlei, Theewaterskloof and Berg River dams. While most of the dams in the Western Cape can be refilled during and average winter season rainfall, Theewaterskloof needs two regular winter rainfall seasons to replenish its total storage capacity (City of Cape Town, 2018a).

Since 2015, the CCT has been experiencing its worse recorded drought in 100 years. The CCT is dependent on >95% of its water supply from outside its City boundaries, via the Western Cape Water Supply System (WCWSS), which is fed from High Water Yield Areas (HWYA) situated in the Boland, Groot Winterhoek and Langeberg Mountains. The WCWSS is a complex water supply system supplying the Western Cape region. It includes supply from HWYAs via the Riviersonderend-Berg River Government Water Scheme through an inter-linked system of 6 major dams, situated in the Boland Mountains east of the CCT, and several minor dams supplying raw water through a sophisticated reticulation system via inter-basin transfer to Water Treatment Plants (WTP) supplying potable water to the CCT.

4.4 Analysis

The analysis was conducted in the same three-part sequence as described by the methodology in the previous chapter to produce the three deliverables that answer the RQs, namely: (i) The current WS status of the CCT from 2006, 10 years preceding the drought of 2015-2018, when the drought conditions were lifted (RQ1); (ii) the influence on the current WS of the proposed augmentation projects to be implemented from 2019-2026 (secondary part of RQ1); and lastly, (iii) the relative risk assessment to determine the impact of the proposed augmentation projects as proposed by the New Water Plan and Cape Town’s Water Strategy, described in Chapter 3.

The data analysis conducted to address RQ1 consisted of applying the DFWS of Srinivasan et al. (2017) to determine the WS of the CCT from 2006-2018, which includes the period leading up to the drought of 2015-2018. The primary deliverable of RQ1 is presented in Figure 4.1 and tabulated in Appendix D. For the secondary deliverable of RQ1, the DFWS was applied to data from the CCT (tabulated in Appendix A and Appendix B) on planned water augmentation over the time period 2019-2026, to include the proposed impact of water augmentation projects (City of Cape Town, 2018b) (tabulated in Appendix E and Appendix F).

To answer RQ2, a Regional-Scale Risk Assessment was conducted using the RRM (tabulated in Appendices F to R) to assess the risks posed by the proposed augmentation projects of the New Water Programme (Figure 4.3). This RRM risk assessment was developed by Suter in 1993, expanded and improved by Landis and Wiegers between 1997 and 2007 and adapted to determine relative risk in surface freshwater ecosystems for South African applications by O’Brien in 2012. The RRM support the aim of water resource management to achieve sustainable use of water for the benefit of all users. The maximisation of long-term use of available resources challenges managers to use methods that establish a balance between usage and protection to guarantee continued sustainability in accordance with the Government Gazette of 1998 (RSA, 1998).

4.5 The WS status for Cape Town

This section presents the results and findings of the first deliverable as stated in RQ1. Collected data were processed using DFWS indices to determine the WS status of the CCT. The results are contained in a single graph (Appendix F) where the products of calculating the ratios of GDP/Population, represented by the Water Resources Utilisation Intensity indicator (PW/(P+I)), and Spatial Heterogeneity (PW/CW) in production and consumption, are plotted for the period 2006-2026 (Figure 4.2). According to the creators of the DFWS, water in/security can be mapped out graphically for a chosen spatial and temporal scale, which in this research is defined as the geographical domain of the CCT (Figure 4.1).

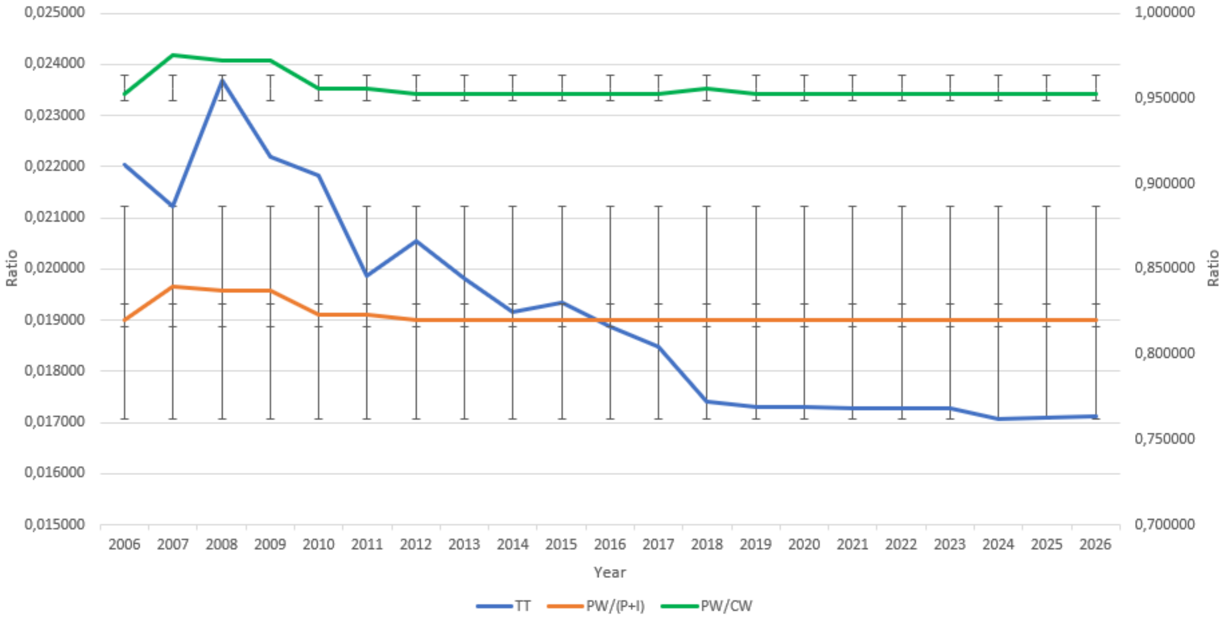


Figure 4.1: Trade and Technology (TT), Water Resources Utilisation Intensity (PW/(P+I)), and Production Water (PW)/Consumption Water (CW) use trend for 2006-2026 (Source: Author)

4.5.1 Trade and Technology (TT) indicator

The financial capacity to invest and develop infrastructure and systems to store, treat, dispense, and utilise water resources and/or purchase and import food and commodities on the global market as virtual water is represented by the GDP/Capita (TT) indicator and is presented in Figure 4.1. The results of plotting the data of TT = GDP/Population against the Y1 axis indicate that spending on water-related infrastructure has declined from 0.022 to 0.017 from 2008 to date.

This calculation (Appendix A) of TT considered both GDP activity and population numbers to represent the per capita value available for investment in trade, technology, and infrastructure. In Figure 4.1, the line graph in blue, representing TT, displays the result of GDP/Population over the period 2006-2026. The result of

GDP/Population is expressed as a ratio to make it independent of units, and this enables comparison to the other ratios in the DFWS. The result of the TT indicator shows a definite decline of 0.005 ratio points over the period 2006-2018, which represents a decline in general infrastructure spending, and which also impacts water infrastructure and water-related service delivery. An increase in economic capacity will allow society to initially increase their abstraction from local water resources to meet their needs and/or produce surplus goods.

When comparing the findings of the TT indicator to the budget allocations of the CCT on water infrastructure and operations, this research found that the data actually show a significant increase in expenditure, which indicates that the TT indicator might not be the best representative indicator for measuring actual water-related infrastructure expenditure. The TT indicator dynamics consisting of GDP/Capita seem to be too broad in this instance; a better indicator would be the actual amount spent expressed as a percentage of increase service delivery capacity versus population, as infrastructure expenditure may be financed via debt vehicles independent from the official GDP calculation.

The time frame choice of 2006-2026 for this research was explained in the data collection and selection in section 3.11. The TT indicator from 2006-2008, processed via the DFWS, was found to increase by 7.4% from a ratio of 0.022048 to 0.023690. The CCT reported a decline of 42.98% in water-related infrastructure spending between 2008/2009 and 2010/2011, which, if compared to the results from the DFWS over the same period, only reported a decline of 16.19%. During the period 2012-2014 the DFWS reported results of a decline of 25.82% in water-related infrastructure spending versus the increase of 62.8%.

By plotting TT (GDP/Capita) against the ratio of PW divided by Precipitation + Water Imports = (P+I), which represents the water resources utilisation intensity, the influence of the economy on water utilisation patterns can be quantified. This indicator represents water use by the population to produce food, goods, services, and electricity. The results of the WS risk assessment for the CCT found that the TT indicator as presented by the DFWS was not sensitive enough to present the water-related infrastructure spending for the CCT accurately. The predictive capability of the DFWS is also disputed as water-related infrastructure spending for the CCT will not be well represented by GDP/Capita form 2019-2026, as shown in Figure 4.1. This decline does not correspond with the planned investment represented in Figure 4.2.

Figure 4.2: Cape Town's water supply diversification from measured in 2018 to planned in 2040 (Source: City of Cape Town, 2020:30)

4.5.2 Water Resources Utilisation Intensity indicator (PW/(P+I))

PW and (P+I) are both stated in volumetric terms to produce a proportion of PW/(P+I) with no allocation of unit, which can be easily plotted in orange against TT (in blue) to indicate the status and trend towards WS or Insecurity. All goods and services contain/have some water-related impact value in terms of virtual water – a term defined by Hoekstra and Mekonnen (2011) in their original work on the water footprint of humanity.

Water resources utilisation intensity describes the water volume used to yield food, goods and services and is represented by production water as a proportion (ratio) of accessible water availability, precipitation, and water imports (P+I). The water resources utilisation intensity represented by PW/(P+I) will be constrained as the ratio approaches 1, the water reserves left in the WMA will diminish (nature + evapotranspiration and ecological flows); this may also indicate possible alternative water use such as unmeasured ground water abstraction, while the ratio is also an indication of total usage of the available water resource potential.

The closer the results of the PW/(P+I) ratio are to 1, the less water will be available in the catchment for the natural ecosystem, ecological flows, and ground water recharge. This indicator is not ideal for application to the CCT as >94% of the water for the CCT enters as imports from outside the WMA and therefore the CCT has no direct control over the ecological reserve.

As most of the CCT's water is imported via inter-basin transfers from outside the watershed via the WCWSS, this indicator cannot be attributed as definitive to the WS of the CCT, but rather as an indication that the CCT is currently totally dependent on Water Imports (I). This is supported by available open-access hydrological data as indicated in the data tabulated in Table 3.3. The results of this indicator show a steady increase over the period 2006-2009, which is confirmed and supported by available hydrological information in the public domain. (City of Cape Town, 2019a). This is followed by a decline over the drought period from 2009-2010, where the indicator then followed a steady gradient as could be expected by the fact that the CCT only imports raw water from the WCWSS as required.

The Water Resources Utilisation Intensity indicator (PW/(P+I)) can only be verified against the reported volume of water treated for distribution and water usage by the CCT. Bulk water supply data from the WCWSS to the CCT available in the public domain are only reported in percentage and not actual volumes.

To address the critiques of previous frameworks, the authors of the DFWS framework claimed to offer an historical understanding and predictive insight, which was incorporated in this study by expanding the DFWS to include the date from 2006-2026. The results of the impact of the augmentation projects proposed by the NWP and CCT Water Strategy are represented in Figure 4.2. The results from the DFWS indicator confirm that the CCT will be predominantly dependent on rain-fed surface water imported from outside its own watershed as depicted in Figure 4.2.

4.5.3 Production Water and Consumption Water (PW/CW)

The uneven relationship between water produced and water consumed in the production and consumption water footprints is represented by the ratio of PW and CW footprints respectively. This indicator (PW/CW), according to the creators, of the DFWS represents the dominant economic activity of the spatial domain measured. The dominant economic activity in the region usually has a pronounced effect on this ratio, where a water intensive industrial or predominant agricultural activity will result in PW/CW >1, and more service sector-oriented economy will result in PW/CW<1.

The CCT represents a diverse economy that historically focused more on agricultural and manufacturing activities, but in recent years have they been leaning towards a more service sector-oriented economy. This could not be measured via the DFWS as no measurable primary agricultural water uses hydrological data exist within the public domain.

The results demonstrate an increase of 2.52% in the PW/CW indicator from 2006 to 2007, a steady 0% gradient, with a decline of 2.05% from 2010. The results thereafter indicate no variance between 2010 and 2026, demonstrating no significant change in the predominant economic activity within the watershed. The DFWS results exclude the role of agriculture as one of its limitation as there are no primary agricultural activities within the watershed. The traditional flower and vegetable producers in the Philippi agricultural node make use of primarily ground water for irrigation, abstracted from the Cape Flats Aquifer and not water from the WCWSS or CCT.

Agricultural water use from the WCWSS was not considered as it falls outside the geographical scope of the study; the impact of agricultural water use is therefore unknown as ground water is not measured, recorded, and reported. The agri-business is thus not accounted for despite the extensive secondary processing, marketing, and transport logistics impact on the economy of the CCT.

This was reported as one of the limitations of the study as listed in section 1.17. The plotting of the three variables TT, PW/(P+I) and PW/CW against each other using the indicators and framework of the DFWS results in a graphical representation of WS for the CCT as displayed in Figure 4.1.

4.5.4 Summary of the WS status of the CCT

The aims of this research were to explore the WS status via the DFWS over the period 2006-2018 to provide both historical insight from the years of average rainfall leading up to the water crises of 2015-2018. The primary objectives of the research were to examine the WS influence of the coupled human-water system, integrating all open source hydrological information into representative indicators, and produce an integrated WS status for Cape Town.

The results of the WS assessment for the CCT found that the TT indicator was not sensitive enough to present the water-related infrastructure expenditure accurately. The predictive capability of the DFWS is also disputed as water-related infrastructure spending for the CCT will not be well represented by GDP/Capita ratio as the decline does not correspond with the planned investment.

When comparing the findings in terms of historical insight, the TT indicator versus actual budget allocations of the CCT on water infrastructure and operations actually showed a significant increase in expenditure, which indicates that the TT indicator might not be the best representative indicator for measuring actual water-related infrastructure expenditure (City of Cape Town, 2019a). The TT indicator dynamics consisting of GDP/Capita seem to be too broad in this instance; a better indicator would be the actual amount spent expressed as a percentage of increase service delivery capacity versus population.

The Water Resources Utilisation Intensity indicator describes the water volume used to yield food, goods and services and is represented by production water as a fraction (ratio) of accessible water resources (P+I), precipitation and water imports. This indicator was found not to be ideal for application to the CCT as >94% of the water for the CCT enters as imports from outside the WMA, thus the CCT has no direct control over the ecological reserve. As most of the CCT water is imported via inter-basin transfers from outside the watershed via the WCWSS, this indicator cannot be attributed as definitive to the WS of the CCT, but rather as an indication that the CCT is currently totally dependent on Water Imports (I).

The uneven relationship between water produced and water consumed in the PW and CW footprints is represented by the ratio of PW and CW water use footprints. The ratio (PW/CW) represented the dominant economic activity of the spatial domain measured. Agricultural water use from the WCWSS was not considered as it falls outside the geographical scope of the study; the impact of agricultural water use is therefore unknown as ground water is not measured, recorded, and reported. The agri-business is thus not accounted for, despite extensive secondary processing, marketing and transport logistics impact on the economy of the CCT. This was reported as one of the limitations of the study as listed in section 1.17, the delineation of the research.

The plotting of the three indicators TT, PW/(P+I) and PW/CW against each other produced a graphical representation of the WS for the CCT. The contribution of this research improved DFWS, built on the knowledge base, and improved comprehension of the fiscal, social, biophysical, technological and institutional influencers of the historical and current WS status for the CCT.

4.6 The impact of the augmentation projects on the WS analysis for the CCT

This section represents the second deliverable to RQ1, that is, Sub-RQ1, an expansion of the DFWS to include and determine the impact on the current status of WS for the CCT by the proposed augmentation projects described in the CCT’s New Water Programme and Water Strategy. The results of the expanded DFWS for the CCT from 2019-2026, bearing in mind the augmentation projects as described by the NWP of the CCT, are presented and the findings reported on in this section. A tabulated representation of the results obtained with calculations are presented in Appendix F and can be found in graphical format in Figure 4.3.

The NWP is the latest documented plan to augment water supply to the CCT from various alternative sources and is scheduled to be implemented in a phased approach from approximately 10% in 2019 to 68% in 2026. This will make the CCT less dependent on the singular supply from the WCWSS, currently at >95%, and the effect of climate change and the resultant rain-fed water supply limitations (City of Cape Town, 2020).

The results of the expanded DFWS for the CCT incorporating the proposed augmentation projects of the NWP are graphically presented in Figure 4.2. It is claimed by the CCT that augmentation, if implemented according to the NWP, will have a positive effect on the WS from 2019, with the implementation of mostly an increase in Water Re-Use (WRU), which is not rainfall-dependent and the optimisation of the contribution of Springs and Rivers (S&R) which is rainfall-dependent on the Total Water Potential (TWP) of the CCT to an estimated 10.24%.

As displayed in the results presented in graphical format in Figure 4.3, TWP will progressively be augmented by ground water exploration, water re-use, and surface water storage capacity. The CCT proposes a rigorous WC/WDM approach over the next few years, which can eventually add a planned 68% to the TWP for the CCT as calculated and tabulated in Appendix F.

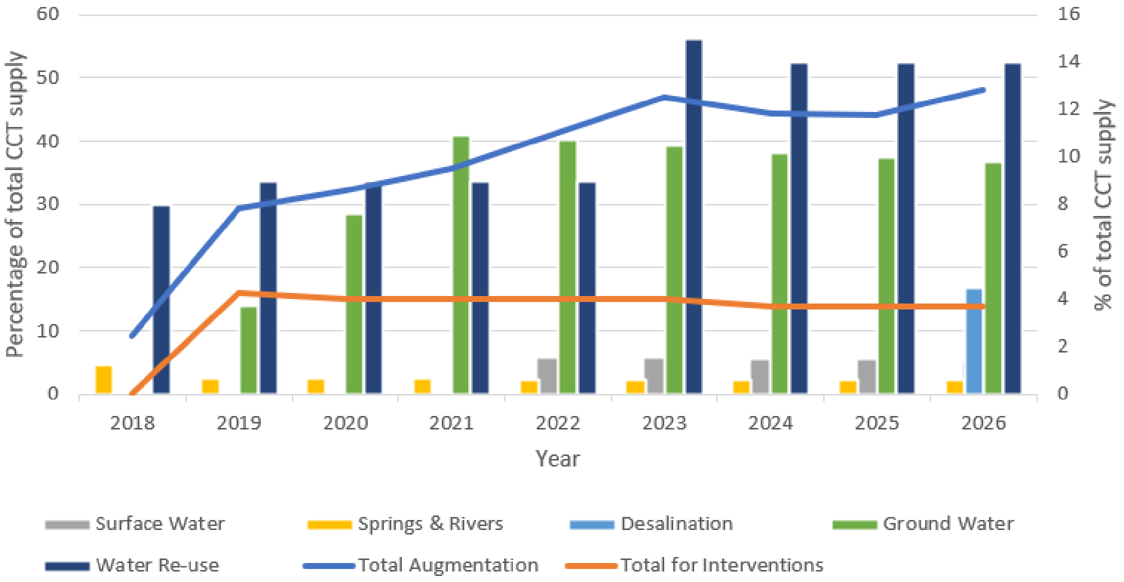


Figure 4.3: Augmentation water volume as a percentage of the Total Water Capacity (TWP) for Cape Town (Source: Author)

The DFWS for the CCT results presented in Figure 4.3 report on the contribution of the proposed augmentation projects to the historical and current WS status of the CCT. The results support the pattern identified by previous studies on WS

(Srinivasan et al., 2017; Padowski et al., 2015), namely that WS is predominantly influenced by four major contributing factors: (i) culture/society, societal water requirements; (ii) resource capacity, availability of fresh water; (iii) economic factors including the capacity for investment in infrastructure or importation of food, fibre or fuel containing virtual water; and lastly, (iv) governance, in terms of water-related legislation and capacity to control its use. The impact of governance and regime changes on the WS of the CCT was not included in this research.

The expansion of the DFWS to include the effect of the augmentation projects of the New Water Programme and Water Strategy (City of Cape Town, 2019c) on the WS status of the CCT delivered the results as displayed in the graphical presentation in Figure 4.2. The augmentation projects can be sub-divided into two major groups – rain and non-rain dependent water sources.

4.6.1 Rain-dependent water sources

i) Surface Water (SW) will contribute 5.85% to the total water available for the CCT by 2026 by extension of storage capacity to dams in the existing lotic systems.

ii) Springs and Rivers (S&R) incorporated into existing fresh water within the geographical boundaries of the City is reported to contribute up to 0.59% to the total water availability.

iii) Ground Water (GW) exploration and abstraction will be developed to deliver from 3.74% in 2018 to 9.81% by 2026.

4.6.2 Non-rain dependent water sources

i) Water Re-Use (WRU) is programmed to be ramped up to contribute from the existing 8% in 2018 to approximately 14% by 2026.

ii) Desalination (DS), which is by far the most expensive to implement because of capital, operational and energy costs can eventually contribute 4.46% to the total water availability for the CCT when implemented as planned in 2026.

iii) Water Conservation and Water Demand Management (WC/WDM) represents management interventions such as alien vegetation removal in the High Water Yield Areas (HWYA) of the catchments servicing the Western Cape Water Supply System (WCWSS). The WC/WDM intervention is reported to be capable of delivering a contribution of between 14% and 16% to the total water potential for the CCT.

4.6.3 Summary of the augmentation impact on the WS analysis for the CCT

The CCT has been making use of rain-fed surface water sources located in the HWYA outside its own catchments and geographical area for most of its water supply for more than a century. The CCT launched its new Water Strategy in early 2020 as an expansion of the augmentation projects and diversification of its water supplies contained in its New Water Plan established in mitigation of the drought period experienced from 2015-2018.

The aims and objectives of sub-research question 1 (Sub-RQ1) was to examine the influence of augmentation projects on the historical and current status of WS by including indicators representing the coupled human-water influence on the water resource system of Cape Town. The method employed for both parts of RQ1 was a quantitative systematic empirical investigation of WS indicators using a Dynamic Framework for Water Security (DFWS).

The findings delivered a perspective of the contribution of the augmentation projects as they came into production during a phased implementation scheduled over an eight-year timespan from 2019-2026, as proposed in the CCT Water Strategy. The reporting of the results and findings is presented as the percentage contribution of the different projects over the time span of their implementation. The results are set out and presented in a MS Excel spreadsheet attached as an appendix to this thesis as well as a graphical format within the body of the text as displayed in Figure 4.4 below.

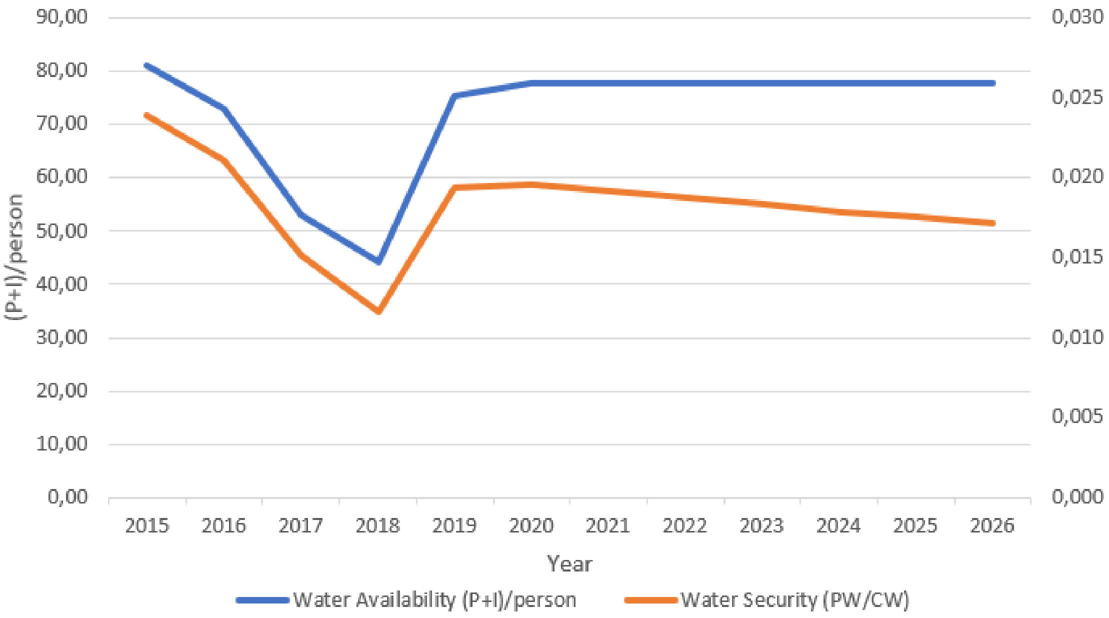


Figure 4.4: WS indicated by the Total Production Water (PW) footprint versus Spatial Heterogeneity (PW/CW) footprint (Source: Author)

4.7 Summary of the WS analysis for the CCT

The analysis, results and findings in this first section of the research successfully accomplished the aims and objectives for RQ1 and Sub-RQ1 sequentially, namely, what is the current WS of the CCT and what is the impact of the augmentation projects of the New Water Programme on the current WS? The results produced by the indicators of the DFWS for the CCT confirmed that the CCT has been historically water secure under normal annual average rainfall volumes. The current DFWS status corroborates the City's total dependence on a singular, seasonal, rain-fed lotic water system for dry-season water supply.

The indicator TT, representing the capability of the CCT to spend on infrastructure and equipment to store up, treat and reticulate water to the end user was found to be not suitable for this application, as discussed in Chapter 4. The results of the GDP/Capita ratio did not correspond to data published by the CCT in their annual budgetary reports on infrastructure spending and service delivery goals and were thus found to be inaccurate and not a viable proxy for measuring this indicator.

The Water Resources Utilisation Intensity indicator, PW/(P+I), excluded agricultural water use, as the limited formal agriculture existing within the geographical area of the CCT does not receive water from the CCT but utilises ground water for irrigation, which is not reported in the public domain. The contribution of ground water to the total Production Water (PW) footprint could not be calculated as data on ground water abstraction are unavailable via open-access hydrological information systems and will therefore will skew the results of the Water Resources Utilisation Intensity indicator PW/(P+I).

The third DFWS indicator, Spatial Heterogeneity (PW/CW), was based on the production and consumption water footprint and represented the ratio of water produced versus water consumed. The results confirmed that the CCT has been and currently is predominantly a water importer, with a >96% dependency on water from outside its geographical area. The results for Sub-RQ1 indicate that despite a 48% contribution by the augmentation projects to diversify the CCT's singular source dependence, the CCT will remain an importer of at least 75% of its annual water requirements by 2040.

The DFWS confirmed that the differentiation of water sources proposed by the augmentation projects in the CCT Water Strategy will enable the CCT to minimise the risks associated with a singular rain-fed surface water supply. The DFWS provided insight into the multi-faceted, dynamic nature of the WS of the CCT, despite the inaccuracy of the Infrastructure Status indicator and the broad representation of the Water Resources Utilisation Intensity indicator. The results of the Spatial Heterogeneity indicator acknowledged that human action is fundamental to the freshwater cycle. The results support the notion that societal, institutional, engineering and economic infrastructure cannot be merely superimposed on nature's ecological processes and capacities to assess water volumes accessible for human use.

The results of the DFWS during the drought period of 2015-2018 (Figure 4.4) confirm that the DFWS is sensitive enough to report human action as a major driver of change. The DFWS delivered results that followed the same water use gradient as the decline in water availability due to stringent water restrictions. The DFWS results delivered emergent patterns of function and dynamics, especially in analysing the impact of the individual augmentation projects in relation to their combined impact over the implementation period from 2019-2026.

The aim of the final research question, RQ2, was to determine the risk elements associated with the WS status of the CCT augmentation options as proposed by the New Water Programme. The objective of the question was to examine the WS indicators selected for the augmentation projects of the CCT Water Strategy and to determine and rank the risk elements of the WS status of the CCT using the RRA Methodology.

4.8 Relative Risk Model (RRM)

4.8.1 Background

The procedure of allocating degrees and likelihoods to the unfavourable consequences of anthropogenic events or natural calamities also described as threats form the basis of environmental impact assessments (Suter, 1993; Suter et al., 2017). The existence of a threat and the associated vagueness of its effect conclude in the creation of a risk. This risk represents the chance or possibility of a specified effect taking place and affecting a natural environment (Suter, 1993; O'Brien et al., 2018; O'Brien & Wepener, 2012).

Ecological Risk Assessment (ERA) therefore represents the process that evaluates the likelihood that positive or negative effects may occur as a result of exposure to one or more stressors (Suter, 2001; O'Brien et al., 2018; O'Brien & Wepener, 2012). The resultant causal relationship between stressors and effects identifies the consequences of alternative decisions. Risk assessments forms the dominant framework for technical support to environmental regulatory processes in industrialised democracies (Suter, 2001). This approach is the preferred and more commonly used decision-making methodology in recent times (Suter, 2001; O'Brien et al., 2018; O'Brien, 2012).

The RRM expands on the traditional ERA risk assessment methodology in order to include various stressors, historical events, spatial structures and endpoints in the assessment (O'Brien, 2012; Landis & Wiegers, 2005; O'Brien et al., 2018). Within traditional ERA, the measurement of exposure and effects represent the interactions between these components; the risk estimates for such an assessment would be calculated by measuring exposure and effects in relation to defined measurement (Landis & Wiegers, 1997; O'Brien et al., 2018). In regional-scale risk assessments, consideration of scale, complexity of structure and the regional spatial components of sources that release stressors in the habitats where receptors reside and impact the assessment endpoints, are considered.

The spatial components consisting of sources, habitats and impacts are similar to the traditional components, but highlight the locations and allow for the review of groups of stressors, receptors and responses or effects (Landis & Wiegers, 2005; O'Brien & Wepener, 2012; O'Brien et al., 2018). The inclusion of these spatial components allows for the review of risk on a complex scale, where various stressors can be considered to emanate from diverse sources to receptors in relation with a variety of habitats and where a singular impact can result in additional impacts (Landis & Wiegers, 1997; O'Brien & Wepener, 2012; O'Brien et al., 2018).

Spatial components can be transposed onto a dynamic backdrop of natural stressors, effects and historical events, supported by the DFWS (Srinivasan et al., 2017). On a regional-scale, stressors and receptors are represented as groups, inclusive of sources that represent a group of stressors and habitats that represent a group of receptors (O'Brien, 2012; O'Brien & Wepener, 2012; O'Brien et al., 2018).

Application of the relative RRM assessments identifies sources and habitats in various regions of the site, ranks their importance in each location, and combines this information to predict relative levels of risk O'Brien, 2012; O'Brien & Wepener, 2012; O'Brien et al., 2018). The number of possible risk combinations depends on the number of categories identified for each component. To explain this, consider that if two sources, two habitats and two impacts are identified, eight possible combinations of these components exists that can result in a potential risk (O'Brien, 2012; O'Brien & Wepener, 2012; O'Brien et al., 2018).

The RRM approach established by Landis and Wiegers (1997) is extensively used locally by O’Brien et al. (2018), and O’Brien and Wepener (2012). This approach was used to assess the risk of components at diverse locations in a region, rank the status of these locations, and combine this information to predict the relative risk among these areas. This allows for the evaluation of various stressors being derived from various sources impacting on a variety of indices in various habitats to a variety of endpoints (Landis & Wiegers, 2005; O’Brien & Wepener, 2012; O’Brien et al., 2018).

The working definition of a Regional-Scale Risk Assessment refined by Landis and Wiegers (1997:289) state: “A risk assessment to cover a region requires additional consideration of scale, complexity of the structure, and the regional spatial components: sources that release stressors, habitats where the receptors reside, and impacts to the assessment endpoints”, as has been widely accepted and extensively used in South Africa (Landis & Wiegers, 1997; Landis & Wiegers, 2005; O’Brien & Wepener, 2012; O’Brien et al., 2018).

Despite existing ERA guidelines for use in South Africa developed by Claassen et al. (2001), it is not widely utilised and no formal local methodology exists (O’Brien et al., 2018; O’Brien & Wepener, 2012; O’Brien, 2012). The Regional-Scale Risk Assessment Methodology for WS applied in this research is an adaption of the RRM to determine risk to WS management goals as endpoints. The RRM has been demonstrated effectively in the application of different scenarios and at various regional-scales (O’Brien et al., 2018; O’Brien & Wepener, 2012; Landis & Wiegers, 2007).

The RRM was refined over time and subsequently developed into an internationally applied work model on various ERA projects by various authors (O’Brien et al., 2018; O’Brien & Wepener, 2012; O’Brien, 2012; Colnar & Landis, 2007; Landis & Wiegers, 2005; Walker et al., 2001). The first application of the regional-scale RRM in the South African context was spearheaded by O’Brien (2012), O’Brien and Wepener (2012), and O’Brien et al. (2018). Their varied application validated its effective potential to be tailored to address the threats of various sources of various stressors to local habitats and endpoints, thus directly contributing towards the objectives of integrated water resource management (City of Cape Town, 2018b).

A Regional-Scale Risk Assessment using the RRM is a form of ecological risk assessment that is carried out on a spatial scale where considerations of various sources of various stressors affecting various endpoints or objectives are allowed

(O’Brien & Wepener, 2012; Landis & Wiegers, 2005). This transparent, adaptable, scientifically validated approach is being continually developed both locally and internationally and has been used extensively as a robust and reliable technique that importantly allows for the uncertainty associated with the outcomes to be carefully evaluated (O’Brien & Wepener, 2012; Ayre & Landis, 2012; O’Brien & Wepener, 2012; Landis & Wiegers, 2005).

The RRM has been shown to add significantly towards the administration and operation of surface aquatic ecosystems in South Africa to achieve a balance in the protection of biodiversity, while allowing for the social and economic needs of society (O’Brien & Wepener, 2012; O’Brien & Wepener, 2012). Regional-scale assessments using RRM have been carried out on scales from 62 km^2 to 33,570 km^2 and included diverse habitats, various stressors with unique receptors and corresponding endpoints.

This research demonstrates the use of the latest regional-scale RRM approach to contribute to the implementation of a WS risk assessment for the Western Cape Water Supply System (WCWSS) servicing the CCT. The graphical nature of the interface and outputs coupled with the ability of the RRM model to generate and evaluate alternative scenarios makes it a useful tool for resource management. Sensitivity and uncertainty of the RRM assessment were tested through 100,000 iterations of the Monte Carlo simulation.

4.8.2 Analysis

4.8.2.1 Step 1: Establish management goals as endpoints

The first principles of this model are based on the evaluation of risks related to individual sources, stressors and combinations thereof and their influence to defined endpoints for spatial and temporal research. As an extension of the DFWS for the CCT, the three management endpoints considered for this investigation were:

i) Sustainable Water Potential, TWP=PW/(P+I), described as Water Resources Utilisation Intensity (Srinivasan et al., 2017).
ii) Sustainable augmentation of New Water Programme Projects planned by the City of Cape Town (2018a).
iii) Sustainable WS Spatial Heterogeneity (PW/CW) in water production and consumption footprint.

The motivation for selecting these specific management endpoints as indicators for the risk assessment was that they are representative of the WS indicators of the DFWS utilised to determine the historical impact and current status of WS for the

CCT in RQ1 and to determine the impact of the augmentation projects on the WS for the CCT in Sub-RQ1. These management endpoints or goals support the aims and objectives of RQ2.

The RRM considered the ranking of the selected source and stressor combinations in relation to habitats of sub-areas for the research area presented in Table 4.1, designated as risk regions. Then, the RRM evaluated the potential impacts or risks to each risk region by considering the stressors affecting the defined habitats. Risks were based on the known interactions between identified sources, calculated stressors and selected habitats as presented in Table 4.1 and Table 4.2.

4.8.2.2 Step 2: Map with probable sources and habitats applicable to created management goals for the CCT are shown (section 3.13)

The detailed map presented in Figure 3.1 was introduced at this step to help with the recognition and description of potential stressors and sources of stressors present within the boundaries of the research area, and aligned to the management goals or endpoints. The possible variables, stressors, receptors, habitats and endpoints, spatial distribution and relationships between components and important topographical features used in this research can be referenced in Table 4.1, Table 4.2 and Table 4.3.

4.8.2.3 Step 3: Delineate the map into risk regions (RR) established on permutation of the sources, stressors, habitats and endpoints

The combinations of source and stressor information, habitat and management objectives as endpoints, were translated to formulate risk regions for relative analysis as schematically presented in Figure 4.5. The risk scores were calculated throughout the RRM assessment based on these risk regions (O’Brien & Wepener, 2012). Based on the map in Figure 3.1, the schematic representation of the sources, stressors, habitats and endpoints is presented in Figure 4.5. This figure is based on an arrangement of the sources and habitats within the risk region boundaries and their impact on the management goals, which was established after considering the habitat segments, the sources of stressors and exposure of the stressor pathways.

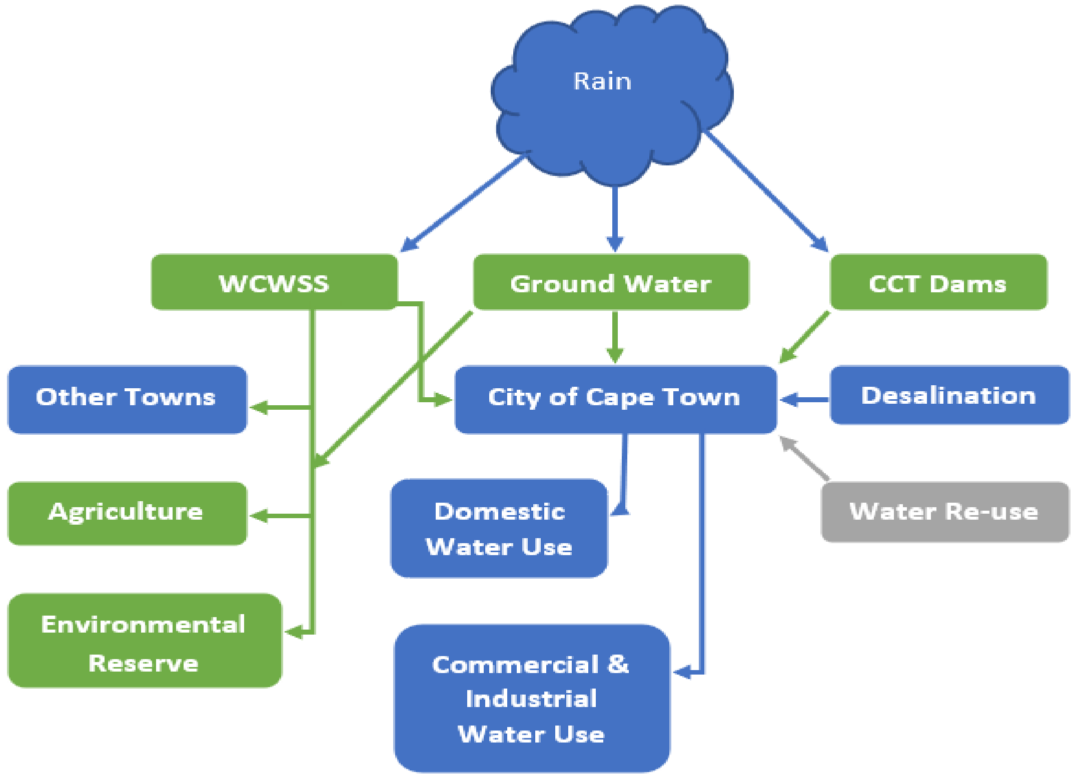


Figure 4.5: Schematic representation of mapping the research domain into regions based on a combination of management goals, sources and habitats (revised from O'Brien et al., 2018:959)

The limits of the risk regions were created after an understanding of the habitat sectors in which the stressor would impact; the sources of stressors were also considered within this context. The exposure pathways from these stressors were included in this consideration as displayed in the schematic presentation in Figure 4.1. Risk scores computed for this RRM assessment were based on the risk regions identified during this step in the model with calculations presented in Appendices F to R, with results represented in Table 4.1, and Table 4.2. This step in the RRM ensured that the applicable sources, stressors and habitats were integrated into the risk regions relevant to the aims and objectives of RQ2 of this study. The management goals selected from the DFWS indices for RQ1 and Sub-RQ1, correspond with the aims and objectives of this study to determine the risk elements associated with WS status of the CCT augmentation options as proposed by the New Water Programme.

4.8.2.4 Step 4: Conceptual model that ties causes of stressors to receptors and assessment endpoints

The conceptual model created for this research outlines the prospective links between sources, stressors, habitats and endpoints that was assessed for each risk region. The potential relationships considered for this research are presented in

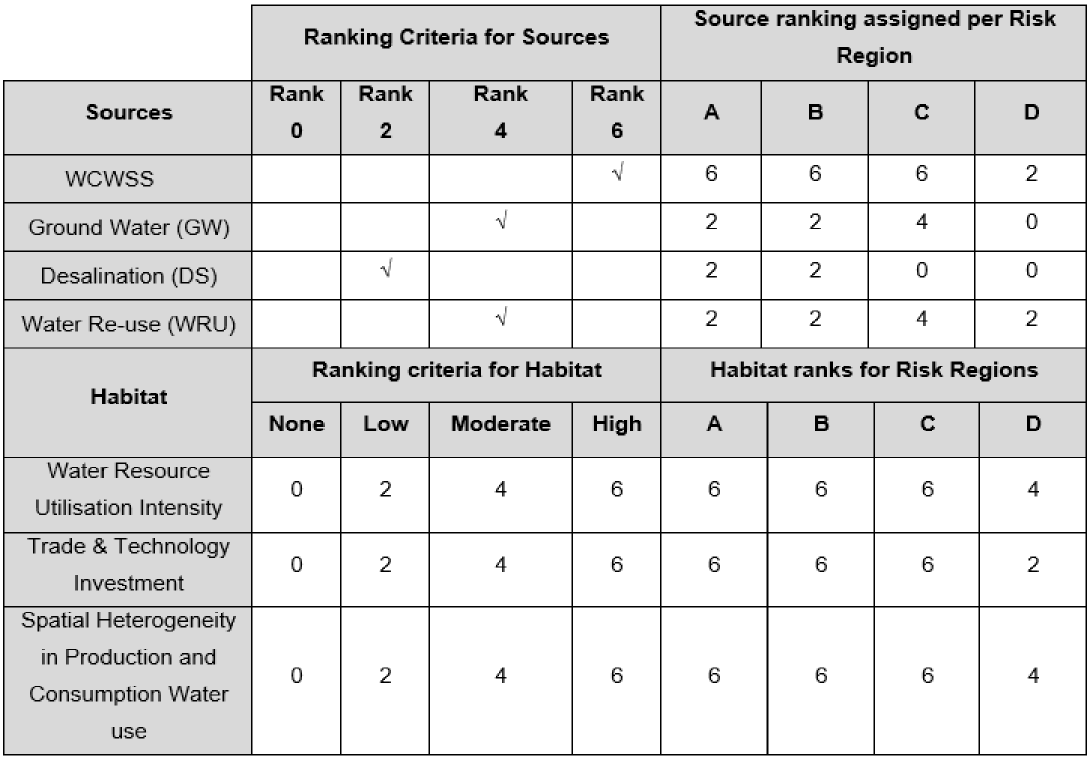
Figure 3.4 as part of the required development segment for this research. The conceptual model had to be properly structured and instructive to perform as an augmentation of the basic RRM structure. The conceptual model was populated through the creation of resource-use scenarios using information gathered from various databases, peer-reviewed and grey literature sources as presented in Table 3.2.

The more detailed conceptual model allows for the exclusion of some stressors because of a lack of exposure pathways and inclusion of different factors initially not considered part of the original scope of the assessment. Complex theoretical relationships between stressors and sources identified by the conceptual framework was not tested within the assessments as it falls outside the purpose of this research.

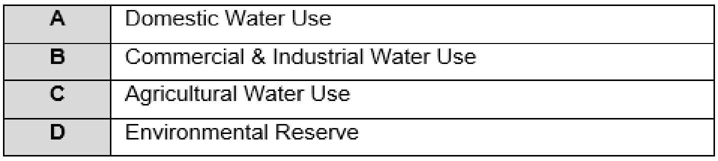
Development of the conceptual model was pivotal to the assessment and made full use of the sequential RRM steps, including the evaluation of uncertainty and sensitivity of the risk assessment in Step 7. The relationships between known sources, established stressors, chosen habitats and assessment endpoints for the risk regions considered for the CCT are presented in Figure 3.2. The relationships in the conceptual model are based on the pathways of potential exposure of stressors to habitats and the predicted effects of stressors to endpoints. Figure 3.2 also presents the relationships between the four identified source groups, namely WCWS, GW, DS and WRU, with stressors, habitats and endpoints.

Figure 3.4 is representative of the stressors identified in this study, categorised into four types of stressors namely, rain-dependent water supplies, water restrictions, water costs and water demand management impacts. Source-stressor relationships were then presented according to the habitats of interest in the study, namely Water resources utilisation intensity (PW/(P+I)), Trade and Technology (TT) investment, and Spatial Heterogeneity (PW/CW) in water production and water consumption (Figure 3.4). After these source-stressor-habitat relationships were established, they were compared to the established endpoints of the study (Table 4.1 and Table 4.2) to present strong, weak and no pathways of exposure from sources to endpoints. These relationships were applied to establish the RRM model for the study (Figure 3.2; Figure 3.3; Figure 3.4).

Table 4.1: Ranks assigned to Source (S) and Habitat (H) variables per Risk Region (RR) (revised from O'Brien & Wepener, 2012:159)



	Ranking Criteria for Sources				Source ranking assigned per Risk Region			
Sources	**Rank 0**	**Rank 2**	**Rank 4**	**Rank 6**	**A**	**B**	**C**	**D**
WCWSS				√	6	6	6	2
Ground Water (GW)			√		2	2	4	0
Desalination (DS)		√			2	2	0	0
Water Re-use (WRU)			√		2	2	4	2
Habitat	**Ranking criteria for Habitat**				**Habitat ranks for Risk Regions**			
	None	**Low**	**Moderate**	**High**	**A**	**B**	**C**	**D**
Water Resource Utilisation Intensity	0	2	4	6	6	6	6	4
Trade & Technology Investment	0	2	4	6	6	6	6	2
Spatial Heterogeneity in Production and Consumption Water use	0	2	4	6	6	6	6	4



A	Domestic Water Use
B	Commercial & Industrial Water Use
C	Agricultural Water Use
D	Environmental Reserve

Exposure evaluation comprises the following:

i) Source and related stressor identification

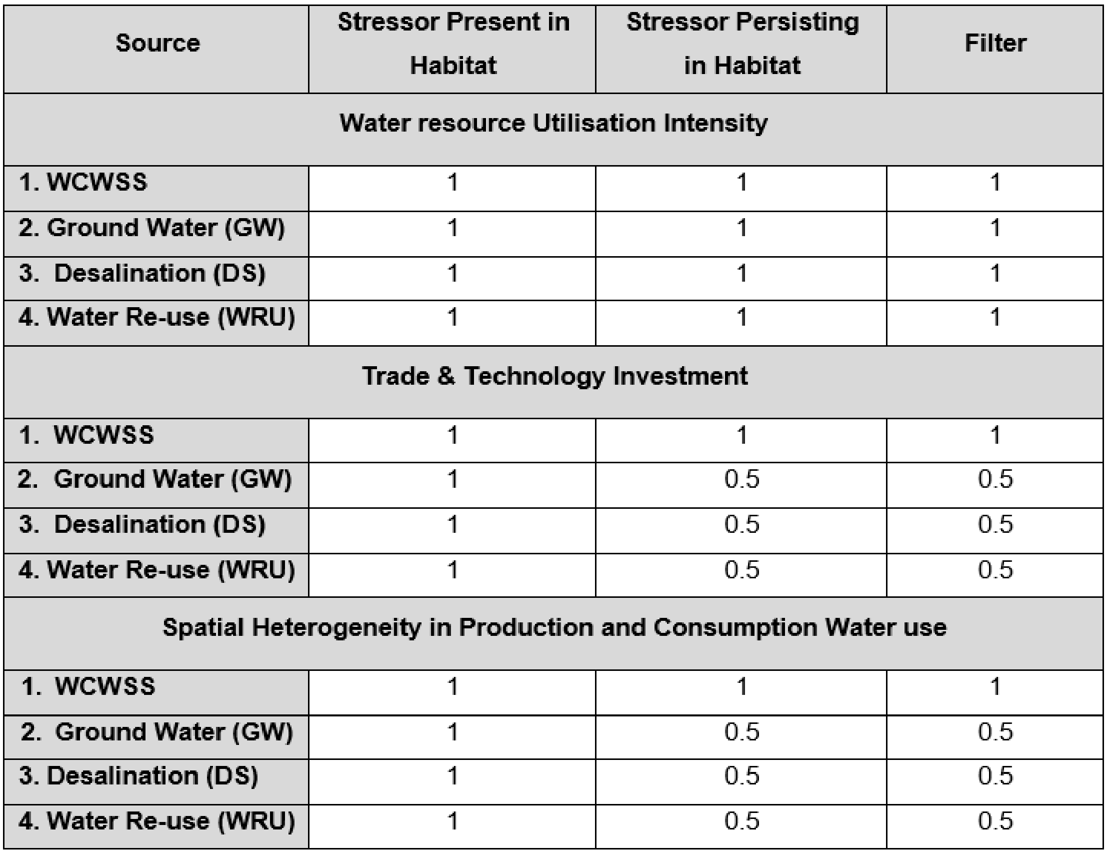
The sources and the related stressor interactions with these sources identified in the study area were determined based on the singular current water supply to the CCT namely the Western Cape Water Supply System (WCWSS) and the proposed alternative augmentation sources, namely ground water, desalination and water re-use, contained in the New Water Plan and Cape Town's Water Strategy. Surface water, water imports and ground water are rainwater-dependent, therefore precipitation will play a pivotal short, medium- and long-term role in water potential of these resources. However, desalination and water re-use is rainfall-independent and precipitation will not have a direct influence on these resources. Precipitation will have a direct material impact on water restrictions, water costs and water demand management.

Ground water abstraction by private individuals, agriculture and industry is very difficult to control as record keeping is dependent on feedback from the user. Water restrictions, water costs, and water demand management will only be effective in controlling ground water abstraction if it can be measured accurately. Water costs (Table 2.3) are directly related to the resource and range from the lowest cost, i.e. surface water at R5 per cubic meter costs, water imports, water re-use, and ground water, to desalination as the most expensive at R36 per cubic meter. The higher the assurance of WS, the higher the costs.

ii) Habitat identification

Three habitats were identified for use in the RRM to represent CCT water sources; all were identified and sourced from the indicators of the DFWS executed in the first part of this research for RQ1 and Sub-RQ1 in determining the historical impact, the current status and the future impact on the WS status of the CCT by the augmentation projects of the New Water Plan and Water Strategy (City of Cape Town, 2018b; City of Cape Town, 2019c). These habitats are: water resources utilisation intensity (PW/(P+I)), Trade and Technology (TT) investment, and Spatial Heterogeneity (PW/CW) in water production and consumption. The results are presented in Table 4.2.

Table 4.2: Allocation of exposure filters to Source (S) and Habitat (H) relationships (revised from O'Brien & Wepener, 2012:160)



Source	Stressor Present in Habitat	Stressor Persisting in Habitat	Filter
Water resource Utilisation Intensity			
1. WCWSS	1	1	1
2. Ground Water (GW)	1	1	1
3. Desalination (DS)	1	1	1
4. Water Re-use (WRU)	1	1	1
Trade & Technology Investment			
1. WCWSS	1	1	1
2. Ground Water (GW)	1	0.5	0.5
3. Desalination (DS)	1	0.5	0.5
4. Water Re-use (WRU)	1	0.5	0.5
Spatial Heterogeneity in Production and Consumption Water use			
1. WCWSS	1	1	1
2. Ground Water (GW)	1	0.5	0.5
3. Desalination (DS)	1	0.5	0.5
4. Water Re-use (WRU)	1	0.5	0.5

4.8.2.5 Step 5: Ranking system to determine the relative risk to assessment endpoints

i) Effects assessment

Based on the Regional-Scale Risk Assessment Methodology (Obery & Landis, 2002) and the subsequent local development of the application (O'Brien, 2012; O'Brien & Wepener, 2012), the effects assessment provides the criteria to rank sources and habitats based on their ability to impact established assessment endpoints as presented by Table 4.1, Table 4.2 and Table 4.3.

This step requires the formation of a ranking system for each source, stressor and habitat, which then translates into the setting up of the assessment end points (Landis & Wiegers, 2005; O'Brien & Wepener, 2012). Following the RRM approach (Landis & Wiegers, 2005; O'Brien & Wepener, 2012), ranks were assigned to sources and habitats on a two-point incremental scale, with rank 0 indicating no impact, 2 presenting a low impact, 4 as a medium impact, and 6 as a high impact. Ranking criteria applied to sources and habitats for the WS risk assessment for the CCT using the RRM are presented in Table 4.1 and Table 4.2.

The data are then translated to non-dimensional rankings so that the impacts of stressors on endpoints can be quantified and assessed (Landis & Wiegers, 2005; O'Brien, 2012). The ranking system of high, moderate or low are applied to sources, stressors and habitat variables according to the circumstances prevalent in the research region. Ranks are assigned according to site specific criteria and are based on size, frequency of sources and presence of habitat. The non-dimensional ranking system criteria should be applied in consideration of the available data.

The states represent the range of conditions in the research area, the levels of impacts and the management ideals as follows:

i) **Zero:** A stable state with no risk impact, comparable with a pre-anthropogenic state and used as benchmark.
ii) **Low:** A mostly natural state with low impact or risk, the ideal and most desired state.
iii) **Moderate:** A moderately used or modified state with moderate impact or risk representing the threshold of potential concern or alert.
iv) **High:** A significantly altered or impaired state with comparable high impact or risk.

The resource that was used to determinate impact is the Water Outlook Reports published periodically by the CCT (City of Cape Town, 2018b). This research followed the weight-of-evidence approach as recommended by O'Brien and Wepener (2012) and O'Brien et al. (2018) in reference to Burton et al. (2002). The ranking schedule for source and habitat variables at each risk region of the RRM assessment for the CCT is presented in Table 4.1. The ranks were allocated to sources with the stressor relationship founded on the existence of the source within the risk region and probable effects signified by its position and ensuing downstream effects (Table 4.2; Table 4.3).

The larger the quantity of stressors linked with a source the higher is the source rank, and the closer to the activity the higher is the impact and therefore the source ranking. The further downstream the activity is the lower is the source ranking, which incrementally lessens with an increase in distance from the stressor. The habitat regions for the identical risk region are established on the significance and sensitivity of every habitat relative to its significance as a system indicator function or threatened habitat.

Risk Regions considered in this research were:

i) A = Domestic Water Use (CW), which is directly influenced by Precipitation (P), Water Re-Use (WRU), Water Conservation (WC), and Water Demand Management (WDM).
ii) B = Industrial/Commercial Water Use (U+TT), directly influenced by P, WR, WC and WDM and greatly impacted by Trade and Technology (TT) investment.
iii) C = Agricultural Water Use (A), the single largest water user after CW and the first to be limited in case of drought, directly impacting food production, employment and therefore GDP (TT).
iv) D = Environmental Health (EH), impacted by P; mining of aquifers (over abstraction of more water than replaced by re-charge) of GW; Imports (I) between catchments; and ecological reserve usually representing the last 10% of water left in dams which are concentrate pollution factors and thus have a negative environmental impact.

4.9 Results of the relative risk for the City Cape Town

4.9.1 Step 6: Calculation of the relative risks (Appendices F to R)

In this section, filters were applied to determine relationships between risk components, inclusive of source, habitat and impact to assessment endpoints. The filter is a numerical weight factor (0 or 1) that indicates either a no, low (0) or high (1) probability that a risk relationship exists (Landis & Wiegers, 2005; O'Brien et al., 2018).

In RRM assessments, two types of filters are proposed by Landis and Wiegers (2005): an exposure filter and an effect filter. The exposure filters act as a screen for source and habitat types so as to identify combinations most likely to cause exposures, where the effect filter screens the source and habitat combinations for those most likely to affect the assessment endpoint of research objective (O’Brien et al., 2018). Exposure filters are determined by deducing which of the stressors are generated by the sources (Landis & Wiegers, 2005, cited by O’Brien et al., 2018; O'Brien & Wepener, 2012).

Two sequence-specific questions regarding each stressor in relation to specific source-habitat combinations were considered, namely:

i) Are the source releasing or causing a stressor?
ii) Will the stressor then occur and persist in the habitat?

A positive answer to either question will assign a value of 1 to the source-habitat combination filter, where a negative answer will produce a 0 value to the filter. Indirect relationships will result in a 0.5-value assigned to the filter. Effect filters are assigned in a similar way but have a separate filter for each assessment endpoint. An important consideration at this point is the re-evaluation of the management goals of the assessment to guarantee the variables of the endpoints produce the desired conservation, maintenance, mitigation outcomes. (O’Brien & Wepener, 2012; O’Brien et al., 2018). Effect filters were developed at this point to ensure management outcomes are addressed.

The answers to the following questions aid in the development of effects filters:

i) Will the endpoint be affected by the release of the stressors identified?
ii) Are the endpoint receptors susceptible to the stressor in the habitat?

A positive response to both questions will assign a quantity of 1 to the source-habitat and endpoint combination, where a negative response to both questions will result in a value of 0. An indirect or unclear potential relationship can be scored with a value of 0.5.

Beneficial source-habitat-endpoint relationships can be assigned a negative (-) filter value, which will indicate a positive contribution to the endpoint. This step also requires the construction of exposure and effect filters for the RRM and the incorporation of the ranks and filters to permit for the computation of relative risks (Appendix C).

The data considered to apply ranking scores consisted of the following:

- i) Surface water: CCT dependency is currently 100%
- ii) Water imports: CCT dependency is currently >94%
- iii) Ground water: CCT contribution is currently 3.74%
- iv) Desalination: CCT contribution is currently nil
- v) Water re-use: CCT contribution is currently 9%

4.9.1.1 Criteria applied in the allocation of source rankings

The ranking criteria applied in the allocation of source ranking are motivated as follows: Surface Water (SW) is totally dependent on Precipitation (P), Water Restrictions (WRU) and Water Cost (WC), which in turn is totally dependent on availability, where Water Demand Management (WDM) will be influenced by SW availability and determined by the level of WR and WC. Water Imports (I) is dependent on water availability, which is directly related to P, which is directly influencing and influenced by WR, WC and WDM.

i) Western Cape Water Supply System (WCWSS)

The impact of Domestic (CW), Industrial/Commercial (U) and Agricultural (A) water use will have pronounced effects on the water supply from the WCWSS; it is therefore ranked high for these risk regions, representing a significant altered or impaired state with comparable high impact or risk associated with it (Table 4.1: Ranks assigned to Source (S) and Habitat (H) variables per Risk Region (RR) (revised from O'Brien & Wepener, 2012:159).

By comparison, the Environmental Reserve (Q+N) will have a mostly natural state with low impact or risk on the WCWSS and is therefore ranked **low** (2). The reverse is actually true in that N will be adversely affected by a drought as less water will be released from the WCWSS for ecological health. The impact of the WCWSS on the environmental reserve was excluded from this research.

ii) Ground Water (GW)

The impact of Ground Water (GW) on Domestic and Industrial/Commercial (U) water use is an unknown factor as the effects of abstraction versus natural and artificial recharge is mostly unknown; record keeping, and reporting data are unavailable in the public domain and available data are either incomplete and/or unreliable. GW is therefore ranked **low** (2). The impact of GW on Agriculture (A) is greatly influenced by P and also greatly influences the WDM of water allocations by the WCWSS, and is therefore ranked **moderate** (4). Accurate monitoring and reporting on GW abstraction and artificial recharge will create a better understanding of this indicator.

iii) Desalination (DS)

Desalination (DN) is not P dependent, but greatly affects the WC and WDM reactions due to costs and its undetermined environmental impact. DN is therefore ranked **low** (2) for impact in the Domestic (CW) and Industrial/Commercial (U) water use and **Zero** (O) for its risk impact on Water Re-Use (WRU).

iv) Water Re-Use (WRU)

The WRU potential for the CCT is immense in Singapore; as much as 75% of effluent is treated and recycled for WR. The CCT Water Strategy states that its recycling volume will only increase from 9% in 2019 to 14% in 2026 of its total water used. Notwithstanding the less process cost per cubic meter desalination, only SW and GW cost less to produce (Table 2.3).

4.9.1.2 Criteria applied in the allocation of habitat risk rankings

The habitat risk rank for every Risk Region (RR) was founded on the significance and sensitivity of every habitat in its relation to its significance to WS and/or the existence of a threat or risk to the WS (Table 4.1). Habitat risk ranks for RR’s were determined by considering the following WS indices:

i) Water Resources Utilisation Intensity (PW/(P+I))

Water Resources Utilisation Intensity (PW/(P+I)) is very sensitive to Domestic Water Use (DWU), Industrial/Commercial Water Use (U) and Agricultural Water Use (A) patterns. It is considered a very important influencer and is scored a 6 in every risk region except for Environmental Reserve (Q+N) because of the unknown effect of DWU patterns on the environment. As all surface water in the WCWSS stems from High Water Yield Areas (HWYAs) situated in protected areas and the limited availability of ground water abstraction data in the public domain, the score is a 4.

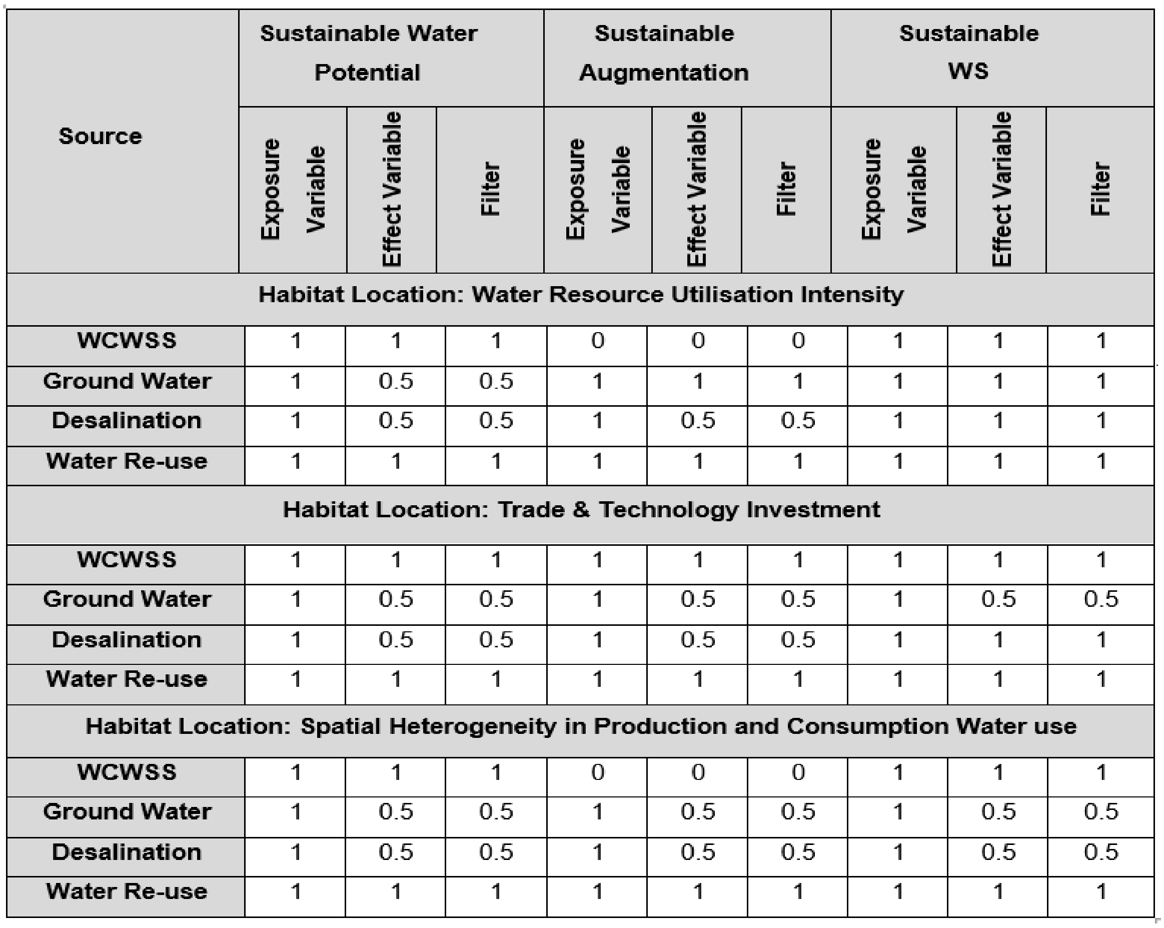
ii) Trade and Technology (TT)

TT investment as a WS indicator is considered sensitive to all the habitats specified because of its drastic influence capacity, and is thus scored a 6, and least so to the ER as ensuring access to water for humans will unavoidably have an effect on water-related ecosystems. The trade-off will be speculative at this stage and is therefore scored a 2 for this research.

iii) Spatial Heterogeneity (PW/CW)

Spatial Heterogeneity (PW/CW) in water production and consumption is sensitive and greatly influential on the habitats specified in Table 4.3; it is therefore scored a **high** (6) across DWU, C+IWU and AWU. The sensitivity and influence on EH are considered **moderate** (4) as data available to substantiate a higher score are limited. In this phase, the ranks and weighting elements are linked through multiplication, the result of which produces a relative risk estimate in each risk region. The final risk scores (RS) are the product of the ranks and associated weighting factors for each risk region. The final risk scores generated for Cape Town's WS using the RRM are presented in Table 4.4.

Table 4.3: Allocation of exposure and effect filters to Source (S), Habitat (H) and Endpoint (EP) relationships (revised from O'Brien & Wepener, 2012:161)

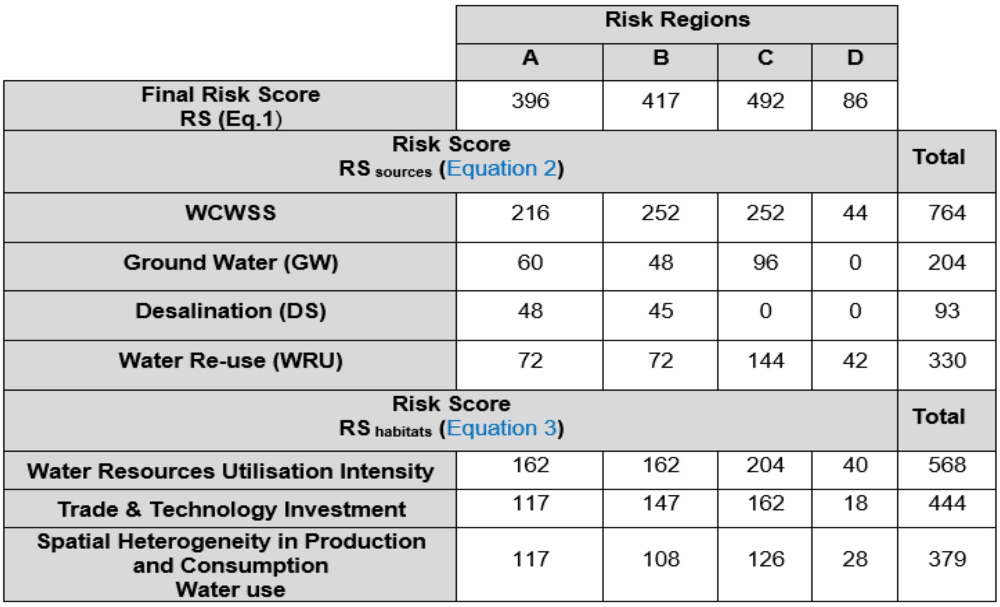


Source	Sustainable Water Potential			Sustainable Augmentation			Sustainable WS		
	Exposure Variable	Effect Variable	Filter	Exposure Variable	Effect Variable	Filter	Exposure Variable	Effect Variable	Filter
Habitat Location: Water Resource Utilisation Intensity									
WCWSS	1	1	1	0	0	0	1	1	1
Ground Water	1	0.5	0.5	1	1	1	1	1	1
Desalination	1	0.5	0.5	1	0.5	0.5	1	1	1
Water Re-use	1	1	1	1	1	1	1	1	1
Habitat Location: Trade & Technology Investment									
WCWSS	1	1	1	1	1	1	1	1	1
Ground Water	1	0.5	0.5	1	0.5	0.5	1	0.5	0.5
Desalination	1	0.5	0.5	1	0.5	0.5	1	1	1
Water Re-use	1	1	1	1	1	1	1	1	1
Habitat Location: Spatial Heterogeneity in Production and Consumption Water use									
WCWSS	1	1	1	0	0	0	1	1	1
Ground Water	1	0.5	0.5	1	0.5	0.5	1	0.5	0.5
Desalination	1	0.5	0.5	1	0.5	0.5	1	0.5	0.5
Water Re-use	1	1	1	1	1	1	1	1	1

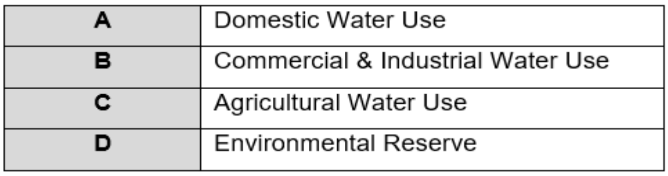
The findings (presented in Table 4.4) resulted in a broad array of risk scores per risk region found between 0 and 764. The risk outcomes were measured in relation to the determined endpoints with RS values relative to each other and only significant when judged in the context of this study. Therefore, RS values above 300 were associated with high levels of risk, levels from 100 to 300 were considered at moderate risk level, and below 100 as low risk level (Figure 4.6). The combination of various stressors influencing various sources resulted in the highest risk impact occurring in Risk Region C = Agricultural Water Use; this was expected as this system is mostly dependent on rain-fed surface storage and ground water.

The risk to industrial/commercial water use (risk = 417) and agriculture water use (risk = 492) is much higher than domestic water use, as restriction due to water shortage from the WCWSS would affect these risk regions to a higher degree. Risk Region D = Environmental Health, which incorporates the ecological reserve resulted in a low risk score, indicates a low risk of impact.

Table 4.4: Results of relative Risk Scores (RS) summarised (Revised from: O'Brien & Wepener, 2012:161)



	Risk Regions				
	A	**B**	**C**	**D**	
Final Risk Score RS (Eq.1)	396	417	492	86	
Risk Score RS $_{sources}$ (Equation 2)					**Total**
WCWSS	216	252	252	44	764
Ground Water (GW)	60	48	96	0	204
Desalination (DS)	48	45	0	0	93
Water Re-use (WRU)	72	72	144	42	330
Risk Score RS $_{habitats}$ (Equation 3)					**Total**
Water Resources Utilisation Intensity	162	162	204	40	568
Trade & Technology Investment	117	147	162	18	444
Spatial Heterogeneity in Production and Consumption Water use	117	108	126	28	379



A	Domestic Water Use
B	Commercial & Industrial Water Use
C	Agricultural Water Use
D	Environmental Reserve

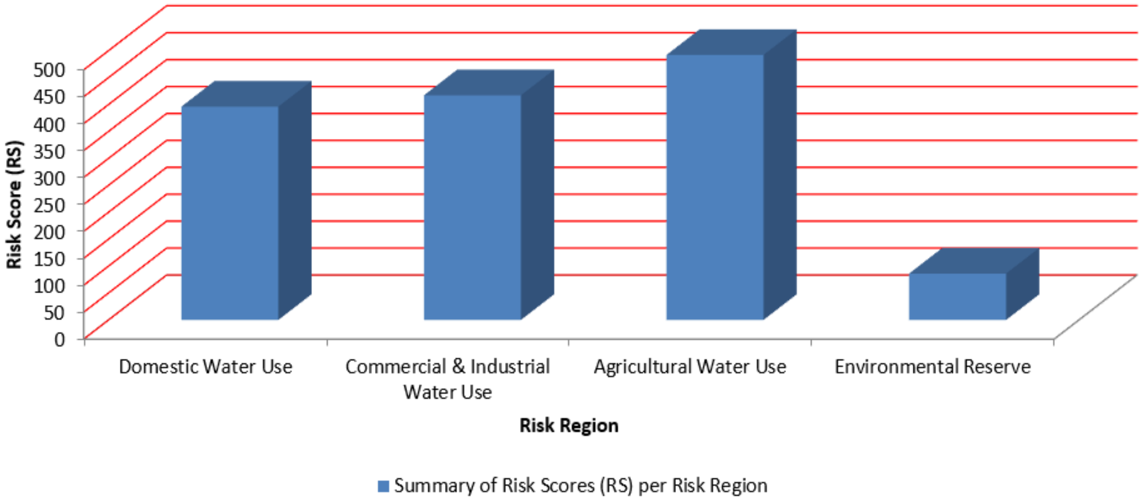


Figure 4.6: Summary of Risk Scores (RS) per Risk Region (RR) (adapted from O'Brien & Wepener, 2012:162)

In considering the total risk over all the regions, the resultant risk posed to the water resource utilisation habitat by all the sources (RS_{source}) was found to be in the order of total risk score WCWSS, with the highest total risk score per region, followed by water re-use and ground water, with the total risk posed to WS by desalination as a water source to be negligible (Figure 4.6).

The WCWSS risk lies in domestic water use, ground water and agricultural water respectively, in order of magnitude of risk (Figure 4.7). For the environmental reserve, there is only a small risk compared to the aforementioned categories. Agricultural is at high risk for ground water depletion, while domestic and industrial/commercial water use as well as environmental reserve are at a lower risk. Desalination has the lowest risk exposure measured in the assessment. The results indicate that agriculture seems to be the most dependent on supply from the WCWSS and ground water at this time, with water re-use as the most viable alternative resource.

The CCT Water Strategy however rates water re-use as their third priority by planning contribution to the augmentation of water supplies at 14% by 2026 versus a possible 80+% of total water used being recyclable. Total augmentation supplies will have a potential 48% contribution to the total water potential for the CCT according to the Water Strategy for the CCT, as published in 2020. Augmentation supplies will be implemented in a phased approach from 2019-2026 as per Appendix B.

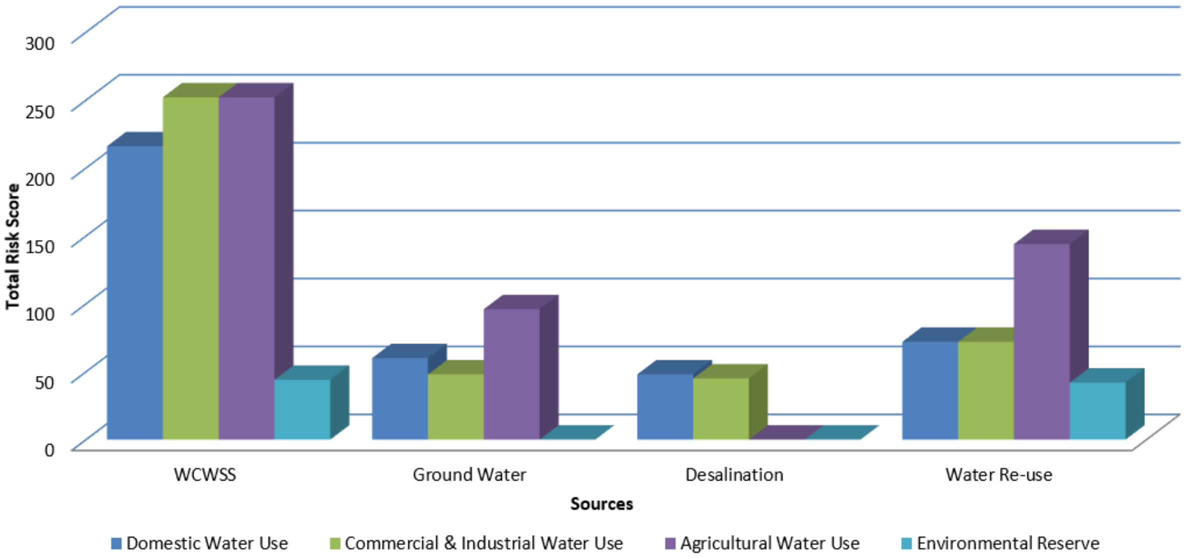


Figure 4.7: Total risk per region for all sources (adapted from O'Brien & Wepener, 2012:162)

When considering the total risk per risk region for all sources, the results identified agriculture as most, and industrial/commercial second most at risk to supply restrictions from the WCWSS during periods of drought. Water re-use and desalination are risk averse to drought as they are not rainfall-dependent as a source of supply. This result is supported by findings in Figure 4.8 stating that agriculture is mostly dependent on rain-dependent surface water and ground water, whereas the results for desalination display a moderate risk to domestic and industrial/commercial water users and the lowest risk impact for agriculture and environmental health due to cost (City of Cape Town, 2018b).

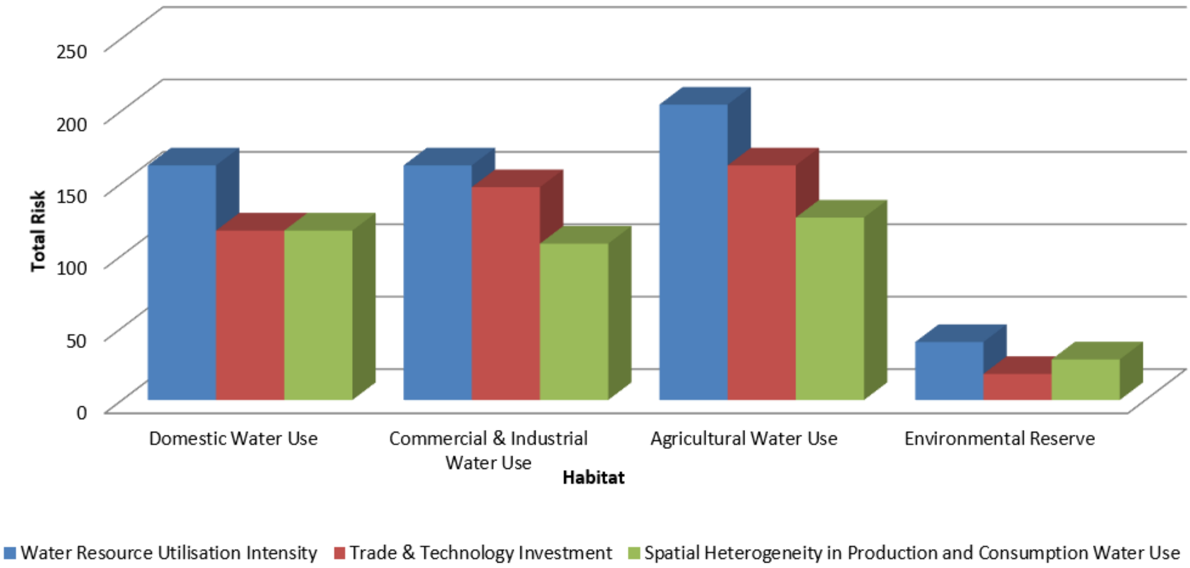
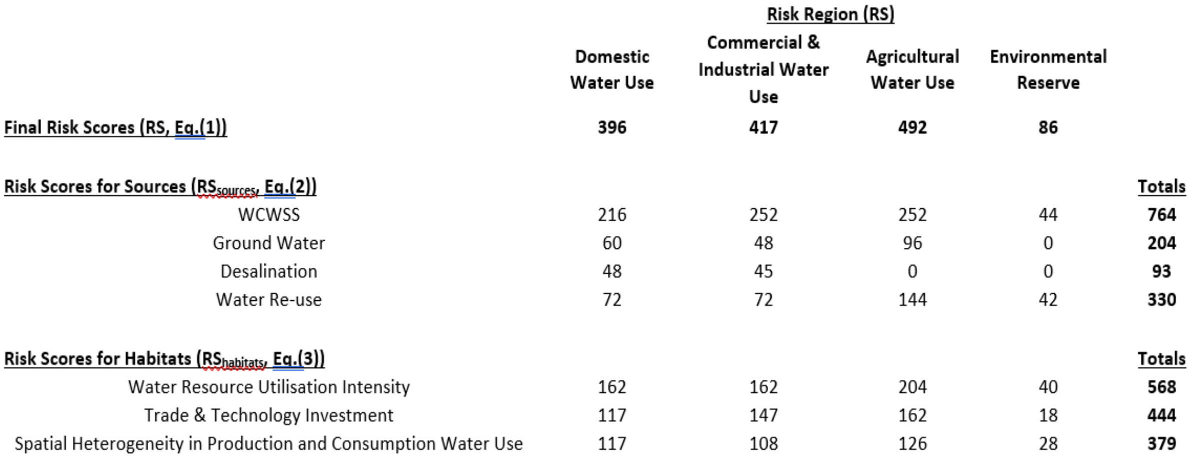


Figure 4.8: Total risk posed to each Habitat (H) per Risk Region (RR) (revised from O'Brien & Wepener, 2012:162)

The RS values are relative to each other and values so obtained will only be meaningful when considered in the context of this research (Table 4.5).

Table 4.5: Summary of all Risk Scores (RS) (revised from O'Brien & Wepener, 2012:161)



	Risk Region (RS)				
	Domestic Water Use	**Commercial & Industrial Water Use**	**Agricultural Water Use**	**Environmental Reserve**	
Final Risk Scores (RS, Eq.(1))	**396**	**417**	**492**	**86**	
Risk Scores for Sources ($RS_{sources}$, Eq.(2))					**Totals**
WCWSS	216	252	252	44	**764**
Ground Water	60	48	96	0	**204**
Desalination	48	45	0	0	**93**
Water Re-use	72	72	144	42	**330**
Risk Scores for Habitats ($RS_{habitats}$, Eq.(3))					**Totals**
Water Resource Utilisation Intensity	162	162	204	40	**568**
Trade & Technology Investment	117	147	162	18	**444**
Spatial Heterogeneity in Production and Consumption Water Use	117	108	126	28	**379**

4.9.2 Step 7: Uncertainty and sensitivity analysis of relative risk rankings

4.9.2.1 Uncertainty analysis of relative risk rankings

As part of implementing the RRM, it is essential to tackle concerns that may affect uncertainty or impact confidence in the results concerning the risk categorisation of the research. It is a requirement of the RRM to track and account for each component in the risk assessment process, such as the use of professional judgement, which is an acceptable instrument in the determination or risk thresholds.

With the progress in computer simulation software, a popular and effective quantitative method is the Monte Carlo (MC) simulation process, which can be utilised to generate a range of values to simulate uncertainty. It is a probabilistic method that computes the variation in model outputs or risk scores as a function of model inputs or ranks and filters. A trail version of *Palisade @Risk a Microsoft Excel* add-on software was used to run the MC simulations to test the uncertainty of the RRM.

The MC simulation executes risk analysis by constructing models of potential results by replacing a range of values in a probability distribution for any factor that has inherent uncertainty. It then re-calculates results repetitively, each time using a different set of random values from the probability functions. Depending on the number of uncertainties and the ranges specified for them, a MC simulation could involve thousands or tens of thousands of recalculations before it is complete. MC simulation produces distributions of possible outcome values. By using probability distributions, variables can have different probabilities of different outcomes occurring. Probability distributions are a much more realistic way of describing uncertainty in variables of a risk analysis.

The MC approach contains an initial ranking of uncertainty for each filter component, which is ranked as low, medium or high, based on the confidence of the assigned values and justified by the available information. The medium and high ranks and filters are assigned discrete statistical distributions to represent uncertainty. Record is kept of the range of statistical distributions utilised to address uncertainty of every rank and filter, where low uncertainty values for ranks and filters keep their original values. The MC simulation was then executed at 100,000 iterations (Figure 4.9) after uncertainty classifications were assigned to account for all the uncertainty in the model.

The results of the MC simulation indicate that the CCT will have a 90% assurance (depicted in Figure 4.9) that the average water potential of the CCT will be water secure for the period analysed (2019-2026), considering the influence of all water resource indicators as planned by the NWP of the CCT. Resource diversity clearly has a positive impact on WS.

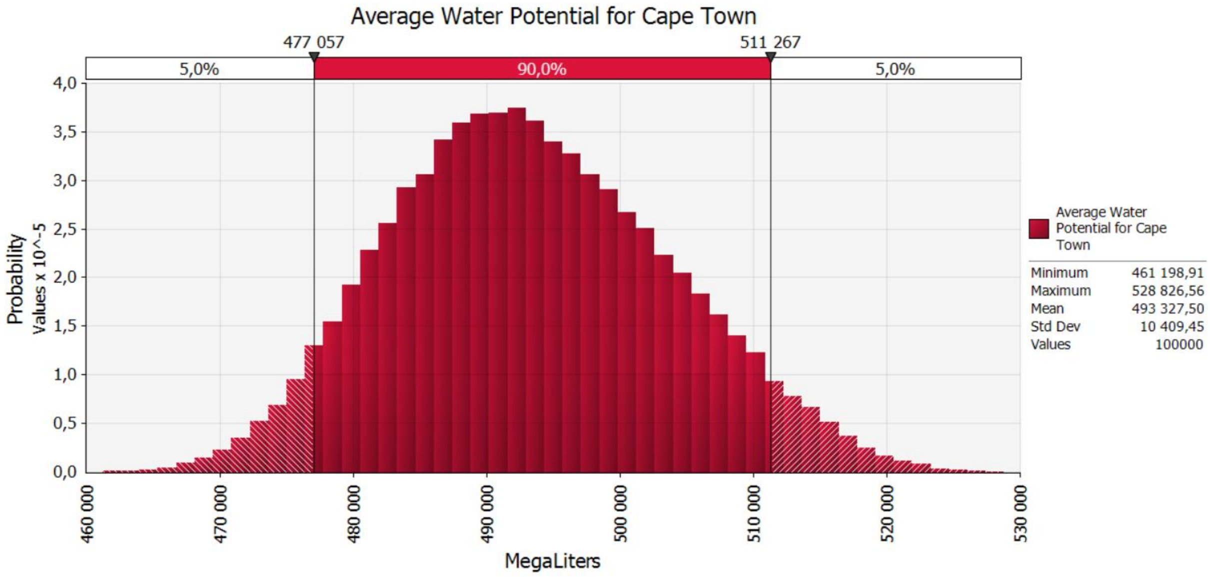


Figure 4.9: Monte Carlo simulation of 10,000 iterations to test for uncertainty of augmentation projects on the WS of Cape Town (Source: Author)

4.9.2.2 Sensitivity analysis of the relative risk rankings

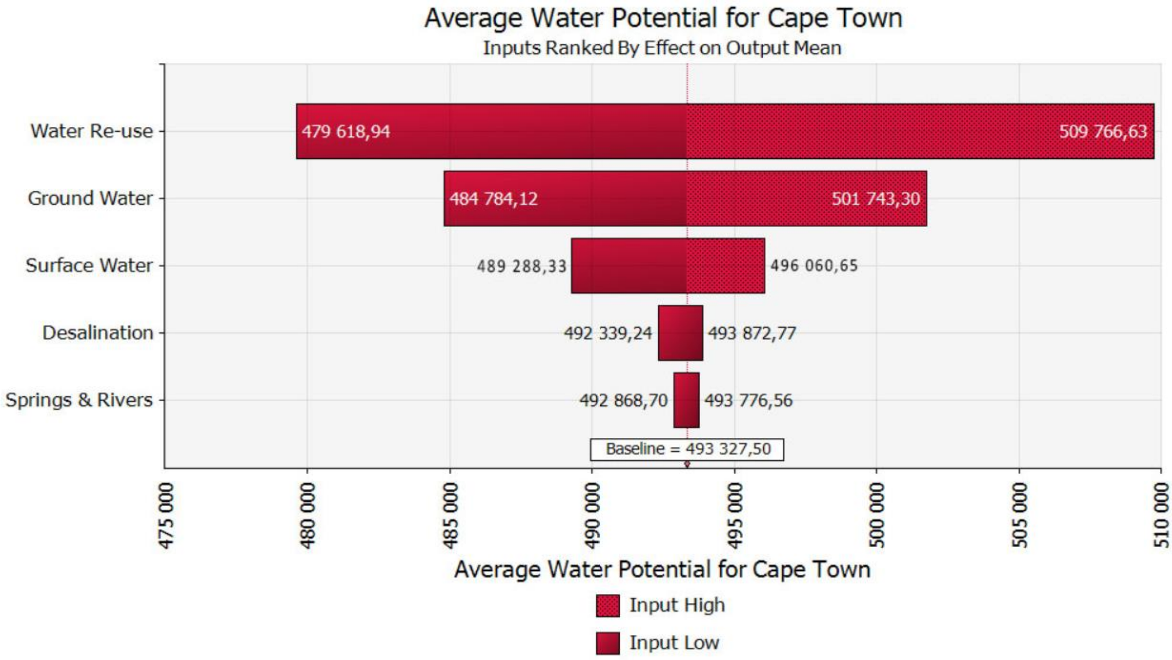


Figure 4.10: Sensitivity analysis of augmentation projects on the water potential for Cape Town (Source: Author)

The sensitivity analysis in Figure 4.10 indicates that Water Re-Use (WRU) has the greatest potential positive impact on WS of all the augmentation projects proposed in the NWP. Ground water and surface water augmentation are the second and third most influential contributors respectively to the average water potential for the CCT (Figure 4.10).

SW and DS have a lesser impact on the average water potential for the CCT due to their limited volume and timeframe of completing the infrastructure. When considered in terms of the period of this research, completion of added storage capacity for surface water in 2022, and 2026 for permanent desalination plants, the total contribution to the average water potential for the CCT will be approximately 5,86 and 4,55%, respectively. Springs and river sources are rain-fed, and will therefore be climate dependent as well as influenced by the alien vegetation clearing as part of the WC/WDM programme. The alien vegetation impact has not been considered as part of this research.

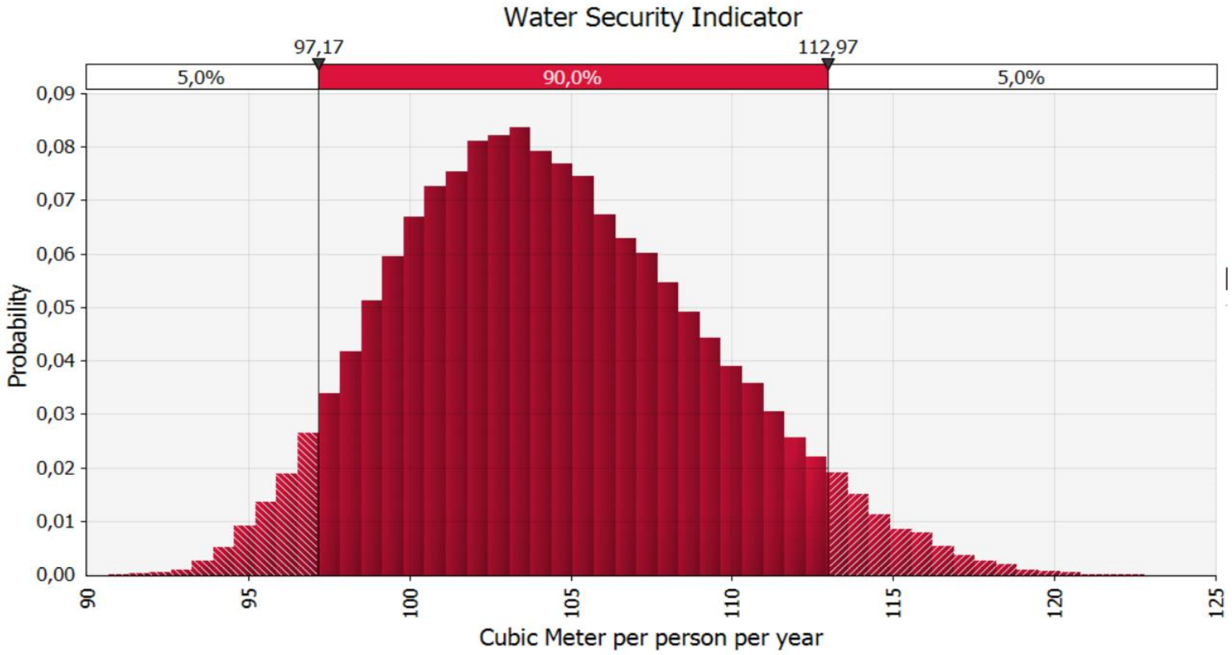


Figure 4.11: Water Security (WS) Indicator per person for Cape Town (Source: Author)

The results in Figure 4.11 represent the WS risk assessment of the probable water availability per person for the CCT considering current water supply capability against projected population growth. The results indicate that the CCT will have a 90% probability of being water secure under normal rainfall hydrological years through the existing WCWSS water supply system. The results present a 5% probability of either drought during low rainfall years or floods during excessive rainfall years.

The sensitivity analysis in Figure 4.12 utilised to test the sensitivity of WS in term of input indicators identified the Population indicator as the input indicator which the WS is most sensitive for. The balance of the input indicators, according to the sensitivity analysis, in order of impact on the WS for the CCT is water re-use, ground water, surface water, desalination and lastly, springs and rivers. These results rank the contribution of the augmentation projects on their volume contribution impact on the total WS for the CCT. Using cubic meter of water available per capita as an output mean to test the sensitivity for WS of the CCT, the results indicated unknown population growth and urbanisation will by far have the biggest influence on WS for the CCT.

This is supported by the data in Appendix B, which indicate the indicator contribution impact ranking in numerical format over the research period from 2019-2026 of the implementation program of the augmentation projects as population growth 16%, water re-use 14%, ground water 9.81%, desalination 4.46%, and springs and rivers 5.36% of the total water availability.

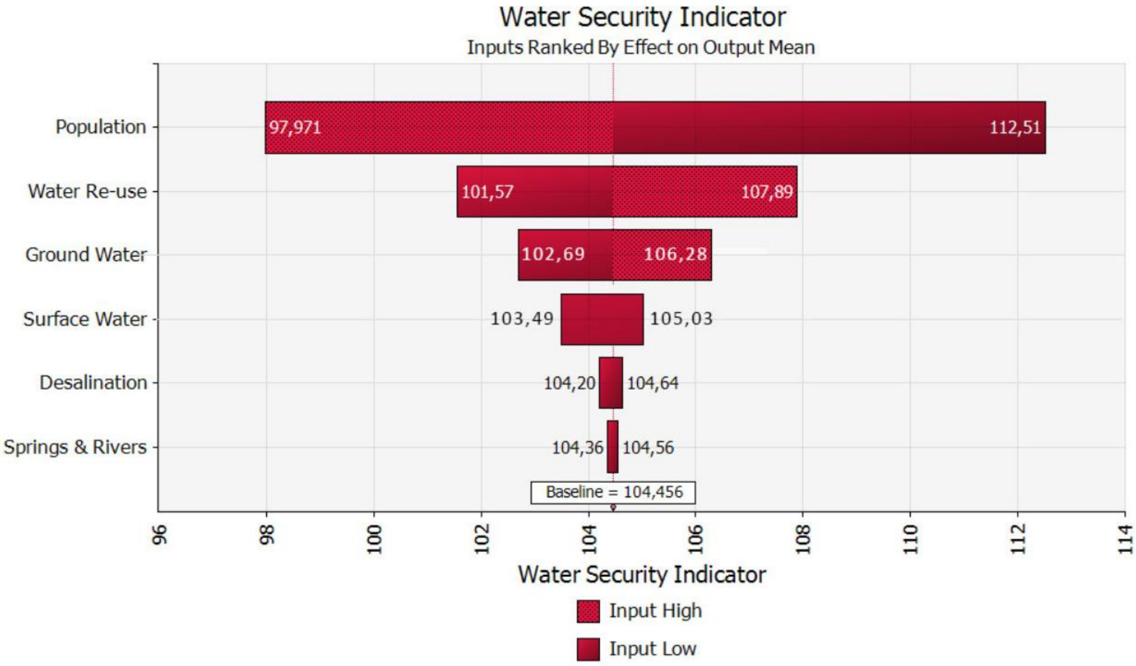


Figure 4.12: Sensitivity analysis of Augmentation Projects vs. Population on the WS of Cape Town (Source: Author)

WS is sensitive to the impact of water re-use and ground water abstraction, while surface water, desalination, and springs and rivers have a lesser impact when measured for influence on the WS for the CCT. This might be because of the low volumes and delayed influence over the 2019-2026 implementation period analysed for this research.

The uncertainty analysis of the probable rainfall in Figure 4.11 confirms the uncertainty analysis of WS in Figure 4.12 that the CCT will be water secure at a 90% probability under normal rainfall years, with a 5% probability for drought and flooding over the period considered in the research, respectively. These assessments test and simplify the impact of specific factors and indices, with relationship factors produced to rank model factors corresponding to their contribution to calculate uncertainty.

Please note that the risk outcomes need to be considered in relation to the established endpoints for this research, namely:

- Sustainable water potential
- Sustainable augmentation
- Sustainable WS

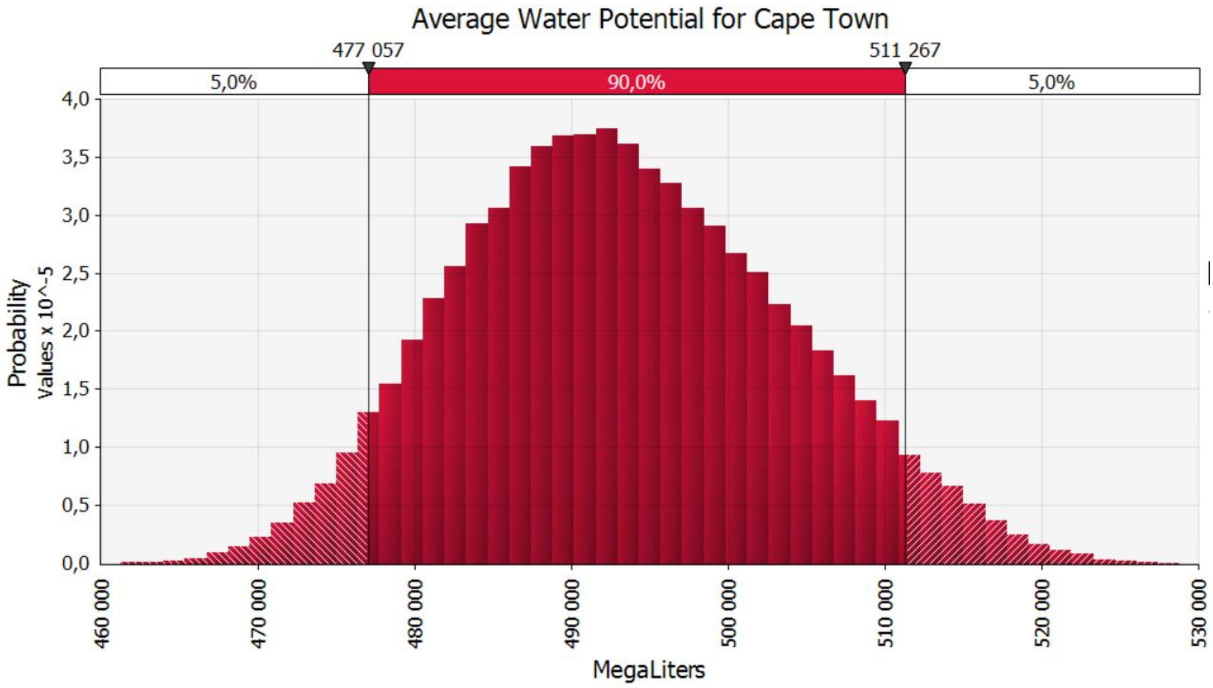


Figure 4.13: Average water potential for Cape Town (Source: Author)

The results of the MC simulation of the uncertainty analysis on the average water potential for the CCT in Figure 4.9 represent the culmination of all three management endpoints in the WS risk analysis. The average water potential in Cape Town represents the WS of the CCT as sustainable water potential, sustainable augmentation projects, the sustainable WS. The results indicate a 90% probability of sustainable WS considering the average water potential for Cape Town.

The accompanying sensitivity analysis in Figure 4.10 rank the impact of the indicators according to the augmentation projects from high to low as follows:

i) Water re-use
ii) Ground water
iii) Surface water
iv) Desalination
v) Springs and rivers

The results are based on the probable volume contribution to the WS and does not consider costs, sustainability, or environmental impact. The total risk posed to the management endpoints depicted in Figure 4.8 verify the impact of water resources utilisation intensity as the biggest probable risk to agricultural, industrial/commercial, domestic and environmental reserve, in order of impact severity, respectively.

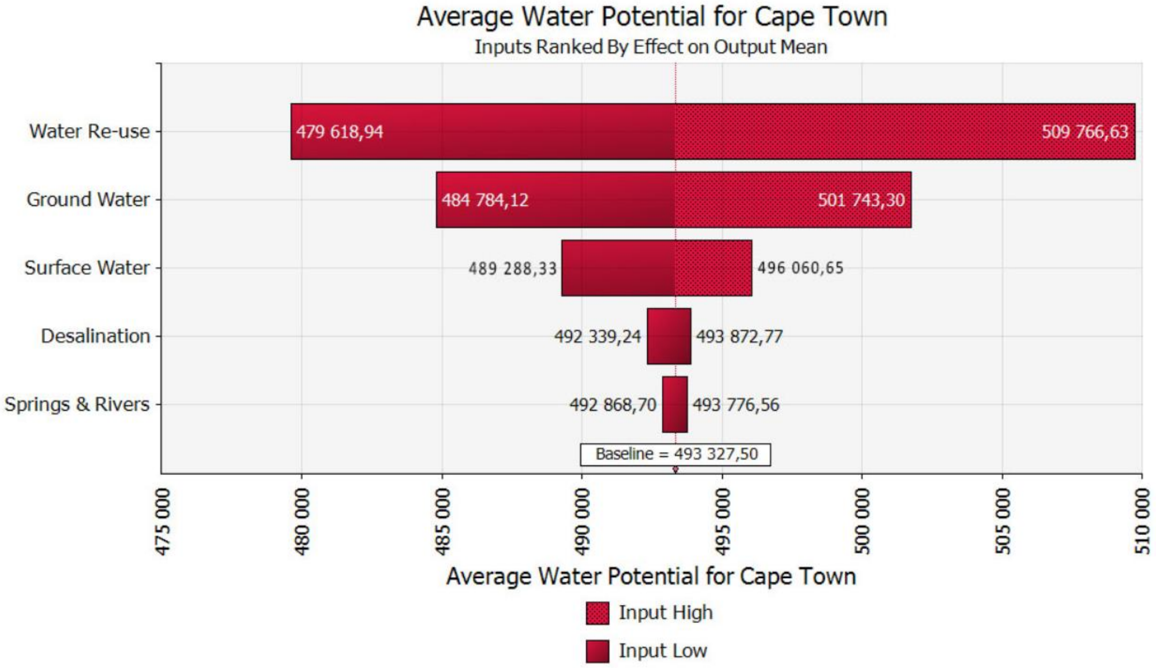


Figure 4.14: Impact of the augmentation projects on water potential for Cape Town (Source: Author)

4.9.3 Step 8: Create a testable hypothesis for future field and laboratory research to minimise uncertainties and to confirm risk rankings

To confirm the risk ranking results produced by the RRM and further reduce uncertainties with primary data, this step requires the establishment of a suitable hypothesis for field and laboratory testing. This step was not included in this research due to time and cost implications as this research was self-funded and may be considered for future research.

4.9.4 Step 9: Test the hypothesis proposed in Step 8

This step forms part of the hypothesis generated in Step 8 and was excluded from the study for future research.

4.9.5 Step 10: Communicate the results effectively portraying the relative risk and uncertainty in reply to the management goals

The DFWS and RRM used in this research benefitted from years of research by leaders in various specialities. To progress with the development of WS and RRM frameworks and methodology in South Africa, especially when considering the threat of a *Day Zero*, not so long ago, it is important that the application and findings of DFWS and RRM case studies be published for peer-review and be made accessible to all.

4.10 Chapter summary

Hydrological, financial, and social data from 2006 to 2018 were collected from open-access secondary, academic and grey sources, analysed via the DFWS and presented in chronological format as results emerged to represent the WS status of the CCT as required for the first deliverable of RQ1.

The DFWS was then expanded to include data and analysis over a time period of 8 years, from 2019-2026 to deliver on the secondary part of RQ1, in determining the impact on the WS status of the CCT by the augmentation projects contained in the NWP for the CCT.

The results were displayed in graphical format to enable a concise report of various WS indices spanning over a total of 20 years of data. The DFWS proved to be sensitive to the indices analysed and successfully reported on the WS status and the influence of the augmentation projects proposed by the NWP of the CCT. The DFWS confirmed and supports literature, theory and practice of WC/WDM as reported in the Water Outlook Report of the City of Cape Town (2018b), the NWP, and the CCT Water Strategy of the City of Cape Town (2019c).

The DFWS confirmed that the CCT is currently totally dependent on rain-fed surface water imports from outside the CCT watershed and municipal boundaries. The results produced by the DFWS indicate that water use patterns analysed identified the CCT as a virtual water exporter, with an economy predominantly based on agricultural and manufacturing production, despite the fact that economic indicators indicate a translation to a more service-oriented economy.

Results produced by the DFWS indicate a slowdown in spending on key water infrastructure since early 2000 in correlation with the available literature as it was used as source material. The influence of the anthropogenic influence of socio-hydrology on water use patterns and governance, in the perspective of effective controls over water usage and environmental protection in effective management of water over an extended period, was not included in this application of the DFWS.

The non-linearity of urbanisation, lifestyle inequality, values and norms of culture makes societal influences a critical aspect of WS and should be included in any further assessment of the WS of the CCT. Data from the augmentation projects contained in Cape Town’s New Water Programme was processed through a RRM to assess risk to water sources on a regional-scale spanning a time frame of 2006-2026. This temporal scale was used as it contains historical data on IWRM for 10 years before the onset of the drought, the three-year duration of the drought, and eight years of planned intervention until the conclusion of augmentation in 2026 with the implementation of full-scale permanent desalination.

The results from the RRM contributed several insightful perspectives to the risks posed to WS by the augmentation projects, as well as ranking the impact drivers through a sensitivity analysis. The results delivered by the application of the RRM confirmed its benefits as a validated structured methodology that is simple to apply, sensitive to the dynamics of individual case studies, locally applicable, and informative and comparable with RRM assessments of a similar temporal and spatial scale.

Future assessments may consider the combination of the DFWS and RRM methodologies to include the unique socio-hydrological influences in well-defined spatial applications over extended time-periods to enable sensitivity of the framework in order to slow changing long-term influences and impacts.

The next chapter is dedicated to the discussion of the results and findings and linking them to the literature reviewed in Chapter 2, thereby addressing how the research informs the practice of IWRM and its application to the knowledge and interpretation of hydrological information in the determination of the CCT’s WS status and identification and ranking of risks and threats to its future WS.

CHAPTER 5: DISCUSSION

5.1 Introduction

Chapter 4 presented the results and reports on the findings of firstly, the WS status, secondly, the impact of the proposed water augmentation projects and finally, the relative risk rankings of the WS indices for the CCT.

The DFWS methodology was utilised, then expanded to incorporate the future impact of the proposed New Water Programme augmentation projects on the current WS status. The research concluded with a Regional-Scale Risk Assessment of the augmentation projects. The assessment incorporates the WS indices via the Relative Risk Model (RRM) to achieve the goals of this study. This was accomplished by identifying stressors from various sources affecting various endpoints when considering the local fresh water supply system dynamics and their influencing characteristics. The results are presented both in tabular and graphical format, indicating the relative risk rankings of the current WS indices, and the influence of the proposed augmentation projects over its planned implementation period. The chapter concluded with the contributions made by the research outcomes, the limitations identified during the research process and recommendations for further research.

Hydrological, financial and social data between 2006 and 2019 were collected from open-access secondary, academic and grey literature sources. Processing of data were conducted through a DFWS, thereby determining the historical and current status of WS in the service area of the CCT over a timeline of 2006-2019. The DFWS framework was then expanded over the period from 2019-2026 (Table 3.5) to establish the impact of the water supply augmentation projects over this chronological and within this regional-scale. These same indicators were subsequently processed through a Regional-Scale Risk Assessment. This was done by utilising a relative risk analysis methodology (section 4.8) to determine the risk rankings of the WS indices and the impact of augmentation on WS indices for Cape Town.

The results of the WS status of the CCT utilising the DFWS were presented as the outcome to the research objective of RQ1. The expansion of the framework to include the water augmentation projects described in Cape Town’s New Water Programme, resulted in outcomes presented as the research objective of the second part of RQ1, namely Sub-RQ1.

Outcomes of the WS indicators processed through the Regional-Scale Risk Assessment using the RRM to determine their relative risk scores and rankings present the research objectives of RQ2. The results were presented chronologically as they emerged, in graphical format with narrative description.

This chapter discusses and assesses the results and findings in terms of the expected outcomes and deliberates the relationship and relevance with the literature referenced in Chapter 2. Weaknesses and limitations are identified, and the implications and significance of this research is discoursed. The chapter is presented as follows: (i) introduction; (ii) background; (iii) outcomes in reference to the research objectives pertaining to RQ1 and Sub-RQ1; (iv) the benefit of using the Dynamic Framework; (v) outcomes pertaining to RQ2; (vi) benefits of the RRM; (vii) limitations; (viii) implications and significance of this research; and (ix) the summary.

5.2 Background

During the latter part of 2017, Cape Town, South Africa was experiencing the cumulative effects of a three-year drought with the threat of the CCT running out of reticulated fresh water. The *Day Zero* Plan, the term coined for the day when WCWSS storage capacity reached 13.5% and the entire population of the CCT would have their regular water supply switched off in exchange for strict water rationing, was a very real prospect. This was to be enforced by strictly controlled water collection points, limiting the daily domestic potable water supply and consumption to a daily 25 ℓ/per/person (May, 2018; Winter, 2018). The CCT water crises was and still is a hotly contested matter, with the reasons for the severity of its impact varying from poor planning and management of the WCWSS, dysfunctionality, politically fractured multi-tiered national water management regimes, the severity and longevity of the drought, to the anthropogenic impact of population growth and urbanisation (Bourblanc & Blanchon, 2018).

Water awareness highlighted the threat to supply as far back as 1970 with predictions that Cape Town’s fresh water supply would be fully utilised by 2007 (Ismail, 2018; Streek, 1990). This was followed by Davies and Day (1998), warning that WS in South Africa was threatened by demand rapidly outstripping supply. Barnes (2016) argued that government was alerted by meteorologists to a drought risk for the CCT timeously and that the 2015-2018 drought in the Western Cape has been expected for at least a decade.

Open-access data on rainfall, water storage, treatment, use and population growth are readily available. There are limited weather stations measuring and accumulating rainfall data in the High-Water Yield Areas (HWYA) and storing run-off consisting of the WCWSS, thus supplying the CCT with >94% of its water. Data available from the DWS and SAWS databases do not overlap, so verification of readings is limited. Furthermore, not all stations have good rainfall records with the existence of several data gaps over various time periods. Wolski (2018) in his analysis of the 2015-2017 drought estimated the recurrence time of the weather-related drought in the catchment of the WCWSS dams and reservoirs at 311 years with a 90% certainty rating, which confirms that the drought of 2015-2017 was very rare and severe.

Data on the gradual scaling of water restrictions from Level 2 in January 2015 to Level 6 in December 2017, which limited domestic and industrial/commercial water use by 45% of the normal non-restrictive use level, were incorporated in this research. During this same period, agriculture experienced a 60% cut to water allocations with resultant economic losses of 20.4% in production and 30,230 labour positions (World Wildlife Fund, 2017).

The literature consulted concurs that the key to future WS for the CCT is proficient and suitable long-term preparation, made more robust by developing its water resources to be more diverse and rainfall-independent. The presumption that WC/WDM will stabilise existing supplies in isolation of timeous alternative augmentation has been proven to be false (Visser, 2018).

5.3 Context

In 2017, information on the management of the drought in the Western Cape was limited, which resulted in misinformation, distrust and suspicion between national, local government and its citizenry. The CCT has been dependent on surface water supply since the first documented water history from 1834 when water was sourced predominantly by 36 naturally flowing springs to establishing and increasing surface water storage capacity over time in line with demand. Today, almost all its water supply to the tune of >94% is from rain-fed surface water sources.

The CCT supplies only 6% of its water requirements from its own internal sources. The balance is sourced from the WCWSS located outside the CCT spatial domain. The WCWSS consists of six major rainfed surface water dams feeding a complex reticulation system consisting of pipelines, channels and pump stations supplying bulk water to several municipalities and agriculture (City of Cape Town, 2018b).

The CCT allocation from the WCWSS is based on a 1:50 (98%) year assurance of supply, indicating that there would under normal circumstance be a 49 out of 50-

year probability that water restrictions will not be required. Otto et al. (2018) report that findings from a risk-based multi-method study examining the part of climate variation in a drought episode determined that anthropogenic influenced climate change increased the probability of the 2015-2017 drought threefold if viewed from a historic precipitation and dam inflow data perspective.

The CCT's water latest strategy follows a three-pronged approach, incorporating: (i) the management of the residual water contained in dams; (ii) driving water consumption demand as low as possible; and (iii) building of increased water capacity from alternative sources such as ground water, water recycling and desalination of sea water. The CCT's New Water Programme project identifies several water augmentation supply projects to diversify sources and to make it less dependent on rain-fed surface water. The supply augmentation projects include increased surface water storage and transfers from outside the CCT catchment, exploration of ground water, optimising supply from springs and rivers, water re-use and desalination. Appropriate decisions and reactive managing responses to water supply and demand hinge on the quality and quantity of available data. This was demonstrated with the experience during the 2015-2018 drought. Quality data depicting the status of the water supply, its availability and the status of the catchment were not available or well understood or communicated (Ziervogel, 2019).

Despite drawing on the same data sets and sources, the DWS and the CCT applied different analysis and modelling criteria, which contributed to uncoordinated management outcomes and confusion. This has been proven in the lack of the enforcement of water restrictions and subsequent exceeding of seasonal allocations by several irrigation boards during the height of the drought from 2015-2016. This created a misalignment of input data by the CCT in developing the forecast of *Day Zero* (Ziervogel, 2019). The robustness of water systems to supply the CCT is dependent on a broad systems approach. The approach needs to include environmental, physical, social, economic and political parameters beyond infrastructure capacity as with the DFWS and the Regional-Scale Risk Assessment employed during this study. Diversity of water sources as confirmed by the results of this study is required to minimise the threat to, and reliance on a central supply of rain-fed systems. This strategy can contribute to long-term security of supply and adaptive capacity in times of extreme events.

5.4 Outcomes in reference to the research objectives

The outcomes of the research objectives of the RQs are presented as a progression of the WS of the CCT over a 20-year timespan (2006-2026). Firstly, the determination of the WS status of the CCT considering the period 2006-2019 to produce a historic view of WS from before the drought period up to and including the current status (2020). Secondly, the impact and probable outcome of the augmentation projects implemented from 2019-2026 was considered. These outcomes represent the research objectives of RQ1. Lastly, the risk assessment of various stressors from various sources affecting the various endpoints, which are the outcomes of the research objectives for RQ2 is presented in the following sequence: (i) a discussion of the resulting WS status of the CCT; (ii) commenting on the outcomes pertaining to RQ1; and (iii) discoursing the benefit of using the Dynamic Framework to determine the WS of Cape Town.

5.4.1 WS status of Cape Town

The DFWS's dynamic approach proposed to address the shortcoming of static indices, has been achieved by plotting the diverse types of WS and presenting causality that drive water use versus water availability. In so doing, this method accounts for the anthropogenic interrelatedness of humans and water systems as well as the vast number of pathways these indices follow to co-evolve. Liu et al. (2013) named this dynamic inter-connectedness of human and natural systems via distant processes 'telecoupling'. The authors contend that the speed, scale, complexity, and consequences of these interactions have profound implications for challenges such as WS, environmental protection and human well-being.

In applying the DFWS over the timespan of 2006-2026, the results produced both historic and predictive insight. As social, institutional, engineering and economic infrastructure indicators play such a significant role in fluctuating water resource systems, Kumar (2011) contends that these indicators will not be effective if used individually or in isolation to evaluate water availability for human use. A benefit of the DFWS is that it considers the cross-dependencies between human and natural systems (Carter et al., 2014; Liu et al., 2017).

Telecoupling elements such as *inter alia* tourism, migration, and labour demands by way of urban centres generating rural-urban migration, do greatly impact WS (Carter et al., 2014; Liu et al., 2017). The findings confirm the impact of telecoupling as presented graphically in Figure 4.1, where the Trade and Technology (TT) indicator shows a decline in infrastructure spending due to a decrease in economic capacity. This finding is further supported by the results indicating the influence of the economy on water utilisation patterns, which is quantified by the results. The indicator represented by the Production Water (PW) footprint as a ratio of the Total Water Availability (P+I) characterises the portion of water used by the population to produce food, goods, services, and electricity versus the total available resource (Srinivasan, et al., 2017). Kumar (2011) reports that the results of these combined elements often lead to unpredictable outcomes not predicted by individual indicators.

According to Srinivasan et al. (2017), the WS indicators, PW/CW, utilised in the DFWS relate human-water use to water availability. Therefore, a description of terms to differentiate between human-water use and consumptive water use is as follows: CW describes water removed from the system and is no longer available. Water abstraction refers to blue water, abstracted from the system for use but some of it is returned as fractional return flow. Green water, as with hydro-electric schemes, returns to the water course as raw or grey or black water, often polluted water or treated through recycling. This terminology to differentiate between water sources was first coined by Falkenmark and Rockström (2006). Water uses for this research included green, blue and grey water, but without making a distinction between them.

In retrospect, the DFWS could have benefitted by utilising these water utilisation indicators of blue, green and grey water in their individual capacity as opposed to grouping them together as a total under the CW footprint indicator. The benefit derived from this application would be that it provides a clear and specific reference to where water is utilised as opposed to just how much.

The CW footprint represents water contained in commodities and services used by people residing in a specific region. The PW footprint represents the quantity of water utilised to produce commodities and services within the region (Mekonnen & Hoekstra, 2010). In the DFWS, the total physical water volume accessible in the watershed is divided into direct and indirect human benefits and is represented by Precipitation (P) inside and Imports (I) from outside the watershed (P+I). The results are discussed in the next sections in relation to the (i) RQs, (ii) aims, and (iii) objectives, in consideration of the literature.

This research followed a dynamic framework to determine the WS status of the CCT. This approach produced the outcome for the first objective of RQ1 by modelling the WS indicators over the time period 2006-2018. This time period was selected to produce results of linked human-water schemes to incorporate substantial data over a suitable time span preceding, during and following the current WS status. These temporal parameters were expected to predict watershed reactive outcomes under human influence, forecast water WS, and advise suitable actions. The research then expanded the DFWS timeframe to include 2019-2026 in order to determine the effect and impact of the phased implementation of water source augmentation projects on the WS as defined by the New Water Programme and Strategy as outcome of the secondary research objective of RQ1.

5.4.2 Outcomes pertaining to RQ1

The primary research objective of RQ1 required determining the current WS status of the CCT versus the secondary objective of determining the impact status of the augmentation options on the WS as proposed by the New Water Programme.

5.4.2.1 Trade and Technology indicator

The results of the DFWS for the CCT is presented in Figure 4.1, by plotting the three indicators: (i) Trade and Technology (TT); (ii) Water Resources Utilisation Intensity (PW/(P+I)); and (iii) Production Water (PW) and Consumption Water (CW) use. These indicators are derived from inspiring work in 2017 by the creators of the DFWS, where TT represents the capacity to invest in water-related technology and infrastructure, PW/(P+I) relates to Water Resources Utilisation Intensity, and PW/CW to Spatial Heterogeneity in water production and consumption (Srinivasan et al., 2017).

Indicator TT represents a ratio used as a proxy to determine the capacity of populations to invest in infrastructure by dividing the Gross Domestic Product (GDP) of the CCT by the population, thus, TT = GDP/Capita. Over the timescale of 2006-2026 analysed, TT shows a marked decline from 2008-2018 (Figure 4.1). This indicator represents the ability of populaces to spend on technology and infrastructure and represents the capability to accumulate run-off, create storage, treat, reticulate and access water sources or purchase food, energy, and other commodities on the global market (Srinivasan et al., 2017). The declining blue line (Figure 4.1) representing the TT capability of the society under research, confirms the decline in expenditure on water-related infrastructure experienced over the time period of the research (2006-2018).

The outcome is corroborated by Visser (2018) and Muller (2017) stating that the delay and lack of implementation of augmentation schemes was due to the false sense of WS created by the successful application of an eight-year WC/WDM strategy by the CCT since 2007. This was in addition to the limited impact of climate change experienced from 2007-2014 (Visser, 2018; Muller, 2017). Furthermore, this outcome is confirmed by the severe impact of water restrictions on the economy experienced due to the lack of capacity as reported by Taing et al. (2019).

Data sources varied in terms of real population growth rate over the period 2007-2017. Figures released by grey literature reported an excess of 70% versus the 17% increase in water storage capacity for the CCT. Data available from the DWS and CCT show an estimated population growth of 30% versus the 17% contribution in water storage capacity delivered by the commissioning of the Berg River Dam during the period 2006-2018 (City of Cape Town, 2018b).

The graphical representation of TT (GDP/Capita) against water utilisation intensity represented by the proportion of PW/(P+I) (Figure 4.1), results in quantifying the influence of the economy on water utilisation patterns (Srinivasan et al., 2017; Padowski et al., 2015). The results indicate an increase in TT from 2006-2008, which is supported by reports obtained from the CCT (City of Cape Town, 2018b). This, however, does not directly indicate any detail on spending to increase the capacity of water infrastructure by the CCT during this period (City of Cape Town, 2018b; Winter, 2018).

Maintenance negligence by the national DWS attributed to incapacity, financial mismanagement and constraints caused an unquantified water loss due to the lack of essential repairs to water storage facilities (Barnard, 2017; Bourblanc & Blanchon, 2018). The CCT Water Strategy Draft, promulgated in 2019, lacks meaningful indicators to measure the progress towards becoming a water-sensitive city. Surface water quality, safe access to water and sanitation data, and data on measurement of the implementation of the water source augmentation projects are lacking (Winter, 2018).

The outcomes and findings of the indicators TT and PW/(P+I) of a sharp increase in the Water Resources Utilisation Intensity versus the decline in economic capability during the period 2008-2018 support the observation by Stosch et al. (2017) and Theron and Brits (2018) that the national government largely focused on remedial action rather than preventative measures through timeous investment in water infrastructure. If unchecked, the nature of the economic capacity decline between 2008 and 2018 and its projected downward trajectory during the New Water Plan strategy implementation towards 2026 (Figure 4.1) may result in an over-abstraction of water to the detriment of the environment or the requirement of an increase in the importation of water (World Wildlife Fund, 2017; Muller, 2017; Muller, 2018).

Urbanisation and population growth as indicated in Figure 4.2 will dilute the positive effect of infrastructure spending such as the water source augmentation projects planned by the New Water Programme (Muller, 2017; World Wildlife Fund, 2017; City of Cape Town, 2018b). This will have a negative influence on the Water Resources Utilisation Intensity indicator, represented by PW/(P+I) (City of Cape Town, 2018b). (Figure 4.1).

The importance of the TT indicator in determining the WS of the CCT is confirmed by the CCT in their Water Outlook Reports, published at regular intervals with updates on implementation progress. They found that financing augmentation has been difficult due to the need to rearrange city budgets and secure additional finance (City of Cape Town, 2018b). The findings tabulated in Annexure A indicate that the proposed augmentation projects will only contribute 18% to the total water availability by 2020 and, of that, 9% will be contributed by the exploration of ground water (City of Cape Town, 2019c). It is stated that cross-subsidisation of water projects is endangered since former high-water consumption homes’ utility bills declined substantially due to less water use, so water services as a whole became under-funded (City of Cape Town, 2018b; Kretzmann & Joseph, 2020). The decline in the TT indicator in the results displayed in Figure 4.1 brings the financial achievability of the planned augmentation projects into dispute.

The drought required several financial interventions, including a proposed drought charge for higher value properties, which, after severe public resistance, was replaced by a general connection charge based on connection pipe diameter to compensate for the financial deficit. The shortage of accessible funding for disaster management from other departments of government and the loss of income negatively impacted on economic stability for the region as the municipal water financial model relies on water consumption income, which is skewed with regard to safeguarding future WS. Concern for further negative revenue impact limited enabling conditions for the promotion of water efficient technologies by domestic and industrial/commercial users (City of Cape Town, 2018b). The financial indicator representing the technology and infrastructure investment capability, TT, used in the DFWS, does not include the negative revenue impact on economic capability of the CCT, as data specific to this phenomenon are not available in the public domain.

In summation, this indicator representing the economic capacity of the CCT to invest in water-related technology and infrastructure was found to be too broad; a more accurate and specific range of indicators could have presented a more focused analysis. The raw data elements of GDP and population census data available in the public domain only represented historical data. It is proposed that better results will be produced by differentiation along Living Standards Measures (LSM) and the creation of applicable service delivery indicators. The GDP and population census data utilised by this research were unverifiable outside its formal sources (City of Cape Town, 2019c; Stats SA, 2011b). Data on population growth are mostly undeterminable due to unmeasured migration and the impact of informal settlements on the utility functions of the CCT (City of Cape Town, 2019c).

5.4.2.2 Water Resources Utilisation Intensity indicator (PW/(P+I))

The fraction of the available water resource being utilised is described by the DFWS as the Water Resources Utilisation Intensity (represented by the indicator PW/(P+I)) and defined by the Food and Agricultural Organisation of the United Nations (FAO, 2020) and Sullivan (2002) as the water used by the population to produce food, fibre, and energy. This indicator is symbolised by PW, which represents a fraction or ratio of the total water utilised against the total water availability denoted by Precipitation (P) representing water sources inside the area of research, plus Water Imports (I) representing water imported from outside the area of research, thus, (P+I) (Srinivasan et al., 2017).

As both PW and (P+I) are stated in volumetric terms, the result is expressed as a ratio with no unit. The ratio of PW/(P+I) embodies the portion of accessible water supplies utilised by the population in the research area. The ratio of PW/(P+I) can indicate WS in term of water availability versus water utilised. A ration of less than 1 indicates that not all available water is used, whereas a ration greater than 1 indicates an overutilisation and therefore possible water insecurity (Srinivasan et al., 2017).

The Water Utilisation Intensity (PW/(P+I)) results for the CCT range from 0.013 in 2006, with a spike in 2018 of 0.026 and a projected ratio of 0.015 in 2026. The ratio indicates a high WS throughout with the results of 2018 indicating the negative impact of the drought (Figure 4.1). The following can be derived from the results: The DFWS indicator PW/(P+I) is sensitive to data as it displays the effect of the progressive water restrictions during 2015-2018 on water availability from 2017-2018 in Figure 4.1 and Figure 5.1.

The tabulated representation in Appendix A of the results obtained in this research supports the claim of Srinivasan et al. (2017) that DFWS indicators can indicate historical and predictive insight in forecasting WS. An excerpt of the results obtained in Appendix A is discussed in this section and represented in Table 5.1.

Table 5.1: Excerpt of results for the U, PW and CW indicators obtained in Appendix A

Indices	Indicator	Megalitres (Mℓ)				
		2015	**2016**	**2017**	**2018**	**2019**
Industry and Commerce	**U**	36 916	33 684	31 456	28 445	47 513
Production Water Footprint	**PW**	268 685	245 164	177 318	160 347	280 292
Consumption Water Footprint	**CW**	276 389	252 194	185 505	167 750	294 306

From 2015-2018, Industry and Commerce (U) showed a historical decline of 22% in average water consumption with a 67% increase in 2019 after the relaxation of the water restrictions. The PW footprint shows a steady decrease of 40% and an increase of 74% to previous water usage levels in 2019 (Muller, 2018). Consumption Water (CW) footprint shows the same trend as U and PW with a decrease of 39% and a sharp increase of 75% over the same period. The total water availability for the CCT declined by 44% between 2015 and 2018. Daily individual water consumption declined from 223 ℓ/person/day to 121 ℓ/person/day, representing a 56% decline (Figure 5.1). The lines representing the PW and CW footprints indicate a steady increase in pace with population growth, which proves the capability of the DFWS to indicate the influence of coupled human-WS during the period 2006-2019. The Industry/Commerce indicator mimicked the Total Water Capacity indicator for water use versus water availability for the CCT.

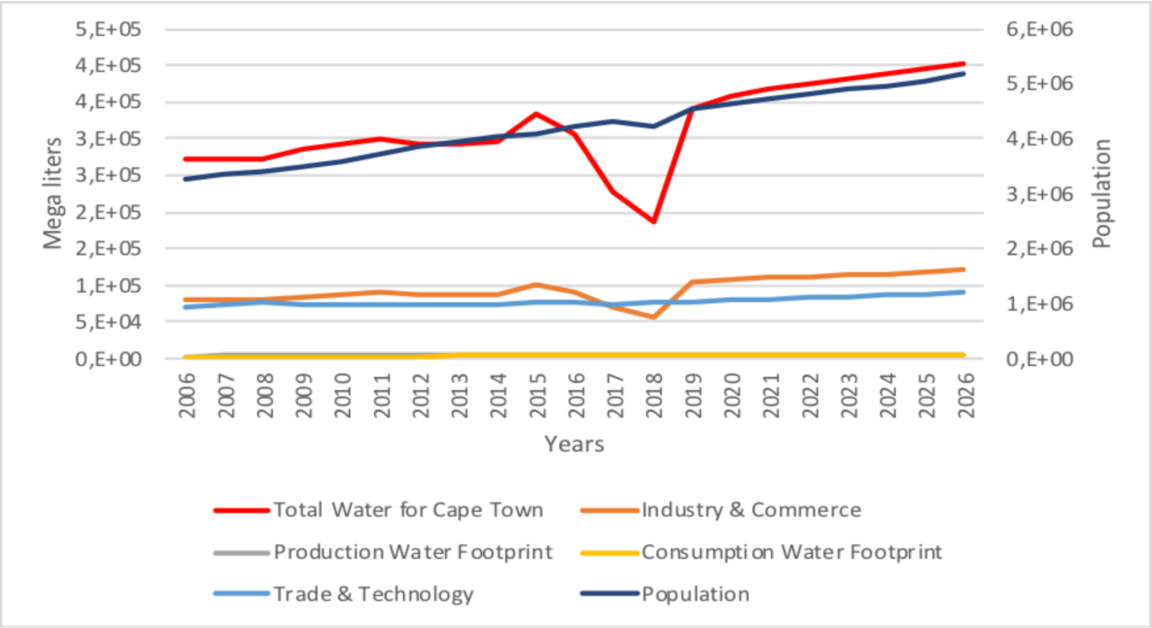


Figure 5.1: Historical and predictive insight of the DFWS indicators for Cape Town (Source: Author)

The anticipated watershed trajectories under anthropogenic influence is represented by the graph for the period 2020-2026. Informed appropriate action can be deduced from the results as the indicators are represented graphically in relation over the research period 2006-2026. Future impact can be mapped, indicating possible scenarios for physical resource availability, infrastructure and economic choices. This mapping of possible scenarios can be seen in the results of the DFWS represented in Figure 5.1, indicating that the total water capacity for the CCT will grow at the same rate as the projected population growth. This may be explained by the fact that the CCT's water capacity planning is based on the projected population growth (City of Cape Town, 2019c).

The spike in PW/(P+I) to greater than 1 from 2016-2018 shows the positive impact of the CCT's WC/WDM program. It also shows the effect of restrictions and punitive tariffs, whereas the downward turn of the spike in late 2018 confirms the water use PW/CW impact of the lifting of restrictions (City of Cape Town, 2018b). This result from the DFWS is a confirmation of a known fact that the CCT receives >95% of its water from the WCWSS as described in the literature review in Table 3.3 (City of Cape Town, 2018b). The literature supports the finding that despite PW/(P+I) being smaller than 1 at 0.026 in 2018 and 0.015 from 2019-2026, the CCT will only be able to supply 68.22% of its own projected water requirements by 2026. This indicates that WS in the CCT will always be dependent on Water Imports (I) from outside the watershed.

Further examination of the results obtained in Appendix B confirmed the implications of the PW/(P+I) as an indicator for WS for the CCT at its current constant measure of 0.015 from 2019-2026, which indicates less water available for the natural ecosystem (N), ecological flows (Q), and ground water (GW) recharge in the CCT as more water will be abstracted via ground water exploration, more water being recycled for re-use, as reported in Table 5.2.

Table 5.2: Excerpt of results for the Q, N and GW indicators obtained in Appendix A (Source: Author)

Indices	**Indicator**	**Megalitres (Mℓ)**							
		2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Production Water/ (Precipitation + Imports)	**PW/(P+I)**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**
Natural Ecosystem	**N**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
Ecological Flows	**Q**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
Ground Water	**GW**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

There were no data obtainable on volumes of water available for the natural ecosystem, ecological flow data or ground water abstraction or recharge data in the public domain. As it stands, the requirement for measuring and reporting ground water abstraction has not yet been promulgated as a legal requirement by the DWS and is governed by a CCT bylaw, which is currently not strictly enforced.

Clear, verifiable data on increased Water Imports (I) either by way of inter-basin transfers from outside water catchment areas, ground water abstraction or virtual water imports contained in food, goods and energy, are not readily available in the public domain. Calculations to quantify these missing data points for this research are mostly based on water use patterns per capita (City of Cape Town, 2020). Where PW exceeds (P+I) it may indicate ground water depletion or excessive water imports. Unfortunately, data on ground water abstraction in South Africa as a whole and the CCT specifically is unavailable.

The DWS is at this time formulating a broad ground water use by-law for implementation at local government level. Until then, the ecological effect of increase in intensity of borehole usage on the underground water table and consequential water quality remains unclear (Ziervogel, 2019). Borehole registrations in the CCT increased from 1,500 per year in 2016 to 26,000 in 2018 (City of Cape Town, 2018b), whereas weekly submission of abstraction volumes required by DWS is lacking (Okedi, 2019; World Wildlife Fund, 2017).

Physical water stress indicated by PW/(P+I) may be alleviated by either importing (I) more water or decreasing water abstraction (PW) from the current resources. When more water is imported (I) from outside the watershed through infrastructure, or less water is used inside the watershed the PW/(P+I), the indicator will mimic the water volume variation by the ratio increasing or decreasing respectively, proving that the DFWS is sensitive to changes to the indicators utilised in the framework.

5.4.2.3 Production Water and Consumption Water (PW/CW) footprint

Spatial Heterogeneity of water production and consumption is described by Srinivasan et al. (2017:16), as “the ratio distribution in production and consumption water use is represented by the ratio of Production Water (PW) and Consumption Water (CW) footprints”. PW and CW in underdeveloped societies are interdependent in that CW will be totally dependent on naturally available PW. Economic capable societies invest in infrastructure to capture and store an increasing fraction of rainfall run-off and imported water from outside the catchment or watershed and so increase their PW capability (Srinivasan et al., 2017).

As societies develop and interconnect economically, PW and CW grow to be progressively more separated; thus, whereas PW and CW correspond in underdeveloped societies, they have a tendency to deviate in developed civilisations. PW will exceed CW as a result of infrastructure expansion where increasing water is allocated to the production of food, fibre and energy, which will result in surpluses containing virtual water being exported outside the watershed. If the CW for the catchment is significantly more than the PW, it indicates that the catchment is a nett importer of virtual water from outside. Physical Water Imports (I) enable a society to increase their water resource capacity inside their catchment. Water imports can be composed of natural water system inflows from upriver of the watershed or infrastructural inter-basin transfers as is the case with the CCT.

Figure 5.2 represents a graphical excerpt of data tabulated in Appendix A as applied for the research (City of Cape Town, 2019c).

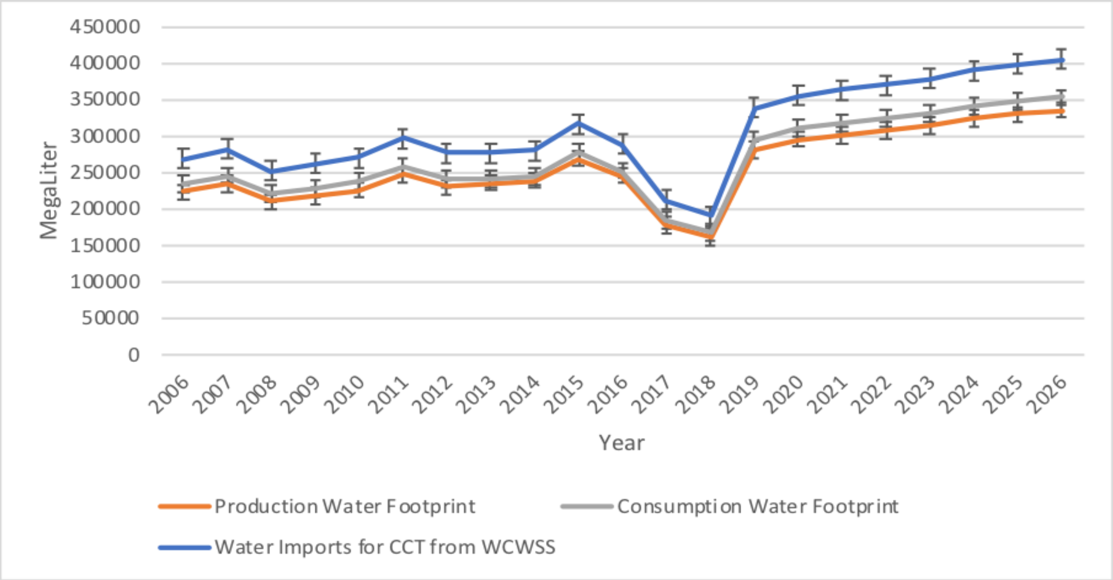


Figure 5.2: Excerpt of results for the PW, CW, and I indicators obtained in Appendix A (Source: Author)

Srinivasan et al. (2017) contend that a spatial unit does not have to be a defined watershed, but can also be a political unit defined by legislative boundaries, as is the case with the CCT. The challenge with a political spatial unit is the complications in calculating the physical inflow and outflows across system boundaries. These challenges include: (i) information silos; (ii) uncompleted records; and (iii) data gaps; and are typical of the complications experienced in obtaining meaningful and verifiable data from DWS, Western Cape Government and the CCT. Spatial boundaries of a political unit challenge the calculation of WS due to the necessity to grasp the impacts of both local and non-local water supplies within legislative boundaries versus the natural boundaries of a physical watershed. In mitigation, all local and non-local water receipts were considered via the CCT Water Outlook Report and the Water Footprint assessment principles for application of the DFWS (City of Cape Town, 2019c; Hoekstra & Mekonnen, 2011). The following deductions can be made from the graphical presentation of the results of the WS for the CCT (Figure 4.1):

First, the flat line of both PW and CW in the ratio produced by PW/CW of 1.216, indicates that the CCT is still predominantly an agriculture and manufacturing economy. This is in line with the CCT's State of the City Report of 2017. The report states that measured as a percentage of GDP, the agriculture and manufacturing industries have weakened at the same time as financial, business services, transport and logistics have expanded, thus indicating the expansion in specialised services sectors of the regional economy. Fishing, clothing and textiles, wood product manufacturing, electronics, furniture, hospitality, finance and business services are industries in which the CCT's economy has the biggest comparable advantage (City of Cape Town, 2016/17). The principle of comparative advantage depicts that under free trade, an agent will produce more and consume less of a commodity for which they have a comparative advantage (Avinash, 1980).

Secondly, the results show a linear trend between 2006 and 2019 (Figure 5.3). This may indicate that the economic activities have not changed drastically during the said period or that the specific indicators in the DFWS are not sensitive enough. The change in economic activity will also take place over a longer timeframe. This will, with a more gradual impact, require a more sensitive indicator or measurement over a longer timeline.

Thirdly, the results indicate a higher PW than CW, which, according to Srinivasan et al. (2017), represents a water exporting society, being that a surplus of goods and services is produced and exported. A higher water use for PW than for CW indicates a nett water exporter, as in the case of the CCT, whereas when CW is bigger than PW indicates a nett water import scenario, as confirmed by the literature where the CCT is dependent on more than 95% of their water supply from outside the watershed (City of Cape Town, 2018b). Here the situation needs to be clarified, as the result will be reported that the DFWS for the CCT delivers a PW greater than CW. This indicates more water exported than consumed in terms virtual water contained in surplus goods and food. In real terms, the CCT is a nett importer of water resulting in a low to negative WS scenario. In the light of PW being higher than CW for the CCT, the DFWS does not indicate any WS pressure on the ecological reserve inside the CCT watershed. The threat of unmeasured alternative water uses such as ground water abstraction may have a pronounced impact on the future, but unfortunately no comprehensive database with ground water use statistic for the CCT currently exists (Department of Water and Sanitation, 2019).

The CCT forms part and imports >94% of its raw water from the WCWSS, which comprises a system of 6 major and 8 minor dams, controlled by the state-run Department of Water and Sanitation (City of Cape Town, 2018b). Srinivasan et al. (2017) predict smaller watersheds or spatial units to display a more homogenous water use, either mostly urban or mostly agricultural, whereas larger spatial units such as the CCT will display a mix of water use types. The CCT's water use data represent a diverse mix, as confirmed by the results produced by the DFWS (Figure 5.2). The dominant economic activity is historically focused on agricultural and manufacturing activity.

As agriculture plays a neglectable role within the geographical boundaries of the Metro, the results (Figure 5.3) support the statistics from the CCT, which indicate a move to a more service-oriented economy (City of Cape Town, 2019c). The DFWS results for PW/CW over the research period indicate a stable ratio between 2006 and 2026 (Figure 5.3).

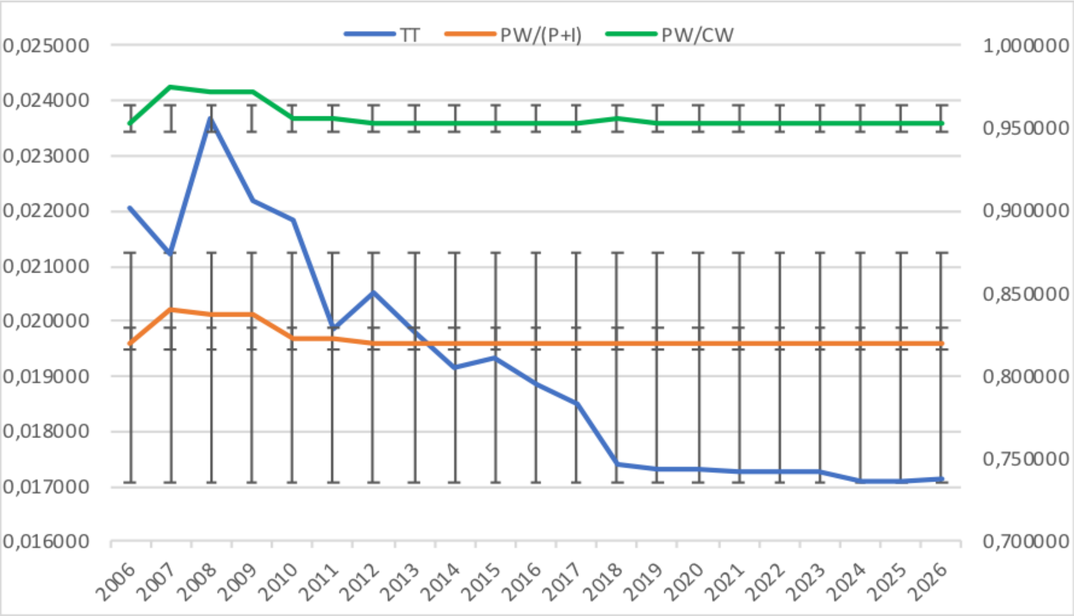


Figure 5.3: Excerpt of results for the PW/CW, TT and PW/(P+I) indicators (Appendix A) (Source: Author)

According to Mekonnen and Hoekstra (2016) and Hoekstra and Mekonnen (2011), the dominant economic activity in the region influences this ratio where PW/CW > 1 indicates an agricultural/industrial based economy, while PW/CW < 1 represents a service-oriented economy. The results are mostly skewed in terms of the high-end users versus informal settlements, according to Muller (2017), who contends that water-related data available in the public domain are underrepresented as measurable indicator (Winter, 2018; Muller, 2018; Visser, 2018; Wolski, 2018).

From the graphical representation of the results in Figure 4.12 it can be said that population growth and rainfall contributed the two greatest unknowns to WS for the CCT. The impact of unmanaged population growth and urbanisation presents the biggest threat to current and long-term WS. This assumption was tested in the deliverable defined for RQ2 and analysed using the RRM. Interpretation of the results led to conclude the following statements, which are confirmed and supported in the literature that were consulted for this research (see section 2.7.1).

Firstly, under normal average rainfall years, the CCT has sufficient water storage capacity versus water use to maintain a positive WS status. Rain-fall storage capacity and stringent WC/WDM are essential to WS; population growth, water resources utilisation intensity, spatial heterogeneity in production and consumption water use are determining factors to WS. The impact of the augmentation projects has a gradual effect as it is only measurable in real terms after implementation, because so much of the New Water Programme projects have other challenges, advantages and disadvantages as described in Table 3.6.

Historical experience has proven that delays in the implementation of augmentation projects from 2007-2015 have profound long- to medium-term knock-on effects, such as the management decision by the DWA WCWSS reconciliation strategy to delay the implementation of augmentation projects because of the positive effects of WC/WDM and sufficient rains pre-2015.

The results of the DFWS confirm that it can contribute more accurately to the IWRM long-term planning whereas the two approaches used in WC/WDM by the CCT before, namely growth in annual water consumption and growth in peak week water requirement, failed to predict the current WS drought. The research confirms that WS for the CCT improves with the implementation of the New Water Programme augmentation projects and strategy, which proposes to distribute water supply over various sources, including some of which are not rain-water dependent.

5.5 Benefit of using the Dynamic Framework to determine the WS of CCT

The DFWS has been proven beneficial as a water analysis tool for the following reasons: (i) DFWS can indicate positive and/or negative WS trends over extended time frames, both in the historical and predictive context; (ii) the DFWS for the CCT is sensitive enough to propose WS mitigation actions but does not address the risk inherent in the proposed augmentation projects proposed by the NWP; (iii) the DFWS can provide predictive insight on how a spatial and temporal space may become more water secure or insecure over time; (iv) it can also provide emergent outcomes; and (v) can indicate major influential factors of WS such as culture/ societal water use patterns, resource capacity, economic capacity and governance and regime influence, for example whether there are sufficient regulations to determine who is allowed water use, how much, and for what purpose.

The DFWS provides a casual framework to model WS as the influence of urbanisation, climate change and dependence on singular water sources. The outcomes indicate coupled human-WS, supported by the facts that in the 1950s, only 30% of the world’s people was urbanised, whereas by 2007 this proportion had escalated to more than 50%. It is projected that by 2050, two-thirds of the globe’s inhabitants will be urbanised (United Nations, 2015b). In numerous instances, the rapid pace of urbanisation is greater than the capability of authorities to act in response, creating an array of water-related challenges, for example insufficient water supply, shortage of sanitation, deteriorating storm water management, and ecosystem collapse (Somlyódy & Varis, 2006; Narain et al., 2013; Sadoff et al., 2015).

The results and findings of the DFWS predict the watershed trajectories for the CCT. This is under anthropogenic influence by forecasting and predicting WS by describing the anticipated impact and contribution of the various augmentation projects as proposed by the NWP. It also informs appropriate mitigation via the results, which also indicates that despite augmentation projects planned, to eventually contribute 68% of the CCT the Total WC, and WS will be not dramatically improved by augmentation supplies but be impacted mostly by population growth, urbanisation and dependency on rain-fed water sources. The DFWS charts actual water supply accessibility, infrastructure and economic alternatives by confirming that investment in water resource development must increase. Water usage rates have to take cognisance of the real cost of water as augmentation projects significantly influence the cost of water.

The framework findings in Figure 5.3 answer the “so what” question. It gives a clear indication of the contribution of each of the indicators. It indicates the impact on WS and can be displayed and communicated in historical, current and predictive long time periods in accurate, concise and understandable terms. The four determinants central to indicating WS across all definitions, namely (i) environmental constraint of water availability, (ii) cultural and economic capacity, (iii) infrastructure capacity, and (iv) governance capacity can all be incorporated into the DFWS. The DFWS methodology underwrites the core idea underpinning WS, which is the balance between sustainable water use and the environment, inclusive of its dynamic and multi-faceted challenges.

5.6 Outcomes pertaining to RQ2

The research objective for RQ2 required the determination and ranking of the risk elements associated with the WS status of the CCT augmentation options as proposed by the New Water Programme (City of Cape Town, 2018b). The objectives were achieved and reported on in Figure 4.3, Figure 4.4 and Figure 4.5 using the regional-scale implementation of the RRM (O'Brien & Wepener, 2012).

5.6.1 Regional-Scale Risk Assessment using the Relative Risk Model

The anthropogenic impact of water utilisation has transformed the welfare of aquatic ecosystems and the benefits communities receive from it (Dudgeon, 2014). Ecological threat evaluations have been carried out all over the world at various spatial dimensions using the developed RRM ever since the mid-1990s (Landis & Wiegers, 2007). South Africa's water policy underwritten by Water Act 36 of 1998, is unapologetically anthropogenic in its advancement of a more even-handed distribution of advantages and expenditures correlated with the usage of water-dependent commodities and services. (Van Wyk et al., 2006). In support of this statement, the findings of the risk assessment (Figure 4.3) describe the risk ranking of the environmental reserve in relation to domestic, industrial/commercial and agricultural water use patterns. In Figure 4.4, the findings display the relative total risk impact of the augmentation projects on the other water use impacts mentioned. Figure 4.5 graphically depicts the findings of the total risk posed by the DFWS indices on the environmental reserve.

The RRM is based on ten procedural steps, described in section 4.10.1, and has been applied world-wide since its development (Landis & Wiegers, 2007; O'Brien et al., 2018). In 2012, the model was applied and contextualised to evaluate a range of natural and anthropogenic stressors impacting on water resource management in South Africa (O'Brien & Wepener, 2012; O'Brien et al., 2018). The RRM is a progression of the traditional Environmental Risk Assessment (ERA) methodology, established to identify and rank threats in relation to established management objectives. The identification of the extent of a threat and the linked uncertainty culminate in the creation of a risk (O'Brien, 2012). Risk is the "probability or likelihood of a prescribed undesired effect occurring and impacting a system or environment" (O'Brien & Wepener, 2012:153). Application of the Regional-Scale Risk Assessment using the RRM optimises the balance of utilisation and sustainability of freshwater systems (RSA, 1998; Department of Water Affairs, 2012).

The dynamic and diverse nature of freshwater systems makes it difficult to manage efficiently and effectively. However, the effective management thereof is imperative to the survival of both humans and ecosystem services (Palmer et al., 2004). Sound management protocol based on the identification and ranking of threats to the freshwater supply system are thus required (Suter, 1993). The regional-scale RRM was conducted on the defined spatial and temporal scale of the CCT, considering various sources of Stressors (S) affecting various management Endpoints (EP), inclusive of local freshwater systems dynamics and characteristics affecting the risk estimate.

5.6.2 Outcomes and results of the Regional-Scale Risk Assessment

The risk scores resulting from the assessment is presented in Table 4.5. The summary risk scores for each risk region considered in the research is represented by RS (Equation 1) alongside the RS Source (Equation 2) and RS Habitats (Equation 3). Note that the RS values obtained as outcomes in this application will only be significant when considered in the context of this research.

Results from the risk assessment represent a range of final risks scores per risk region of between 93 and 764. In an RRM assessment, a variety of methods can be integrated to ascertain risk-level limits (Landis & Wiegers, 1997; Landis & Wiegers, 2007). One method includes the presentation of risk results relative to each other, where larger RS for a specific risk region, habitat or endpoint would imply a larger risk of impact and consequently justify a higher risk level (Landis & Wiegers, 1997). The method applied here makes use of skilled assessment to adjust stressor and habitat rankings in order to consider reasonable risk scenarios as applied in this case (Landis & Wiegers, 2007).

For this research, RS values above 300 were correlated with elevated levels of risk, where levels in the range 100-300 were considered as moderate and levels below 100 as low risk when considered in the context of this RRA (Figure 4.3). The results of the risk assessment calculations were presented in graphical format in Figure 4.3, Figure 4.4, and Figure 4.5.

The conceptual representation of the RRM applied in this research is presented in Figure 3.2, Figure 3.3 and Figure 3.4. The model differentiates between sources, stressors, habitats, effects and endpoints as follows:

i) Sources represent the point of origin, the cause or entrance of a stressor into the system being investigated.
ii) Stressors characterise the external stimulus or event impacting or seen as causing the state of stress or strain to the system being investigated.
iii) Habitat corresponds to place, setting or environment where phenomena being studied is found.
iv) Effect is a change that is the result or consequence of an action or stressor impact.
v) Endpoint is the resultant stage or effected status of a measurable management goal for a defined outcome.

5.6.2.1 Summary of final Risk Scores (RS, Equation 1) per Risk Region (RR)

The summary of the final Risk Scores (RS) per Risk Region (RR) was considered as part of the objective of RQ2, which was to examine the WS indicators for the CCT used in the DFWS in RQ1. This was achieved by calculating and ranking the risk status of the WS indicators of the CCT by applying a Relative Risk Assessment using RRM. The following results were produced:

Figure 4.3, which is the graphical representation of the risk scores tabulated in Table 4.5, identified Agricultural (A) water use with a final Risk Score (RS) of 492 as the Risk Region (RR) with the highest relative risk; second was industrial/commercial (U) water use with a RS of 417. Consumptive Water Use (CW) with a RS of 396 in the resultant risk rankings and the Environmental Reserve (Q+N) at RS 86 are significantly less at risk compared to the preceding risk regions.

The results led to conclude that the total combined effect of all the stressors produced by all the sources within the research parameters, exposed Agriculture (A) and Industrial/Commercial (U) water use to the highest risk of impact. In considering the total risk across all regions, the relative risk posed by Sources ($RS_{sources}$) considered in this research consisted of the water supply from the Western Cape Water Supply System (WCWSS), and the alternative water supply from the proposed augmentation projects of the CCT Water Strategy, namely Ground Water (GW), Desalination (DS) and Water Re-use (WRU).

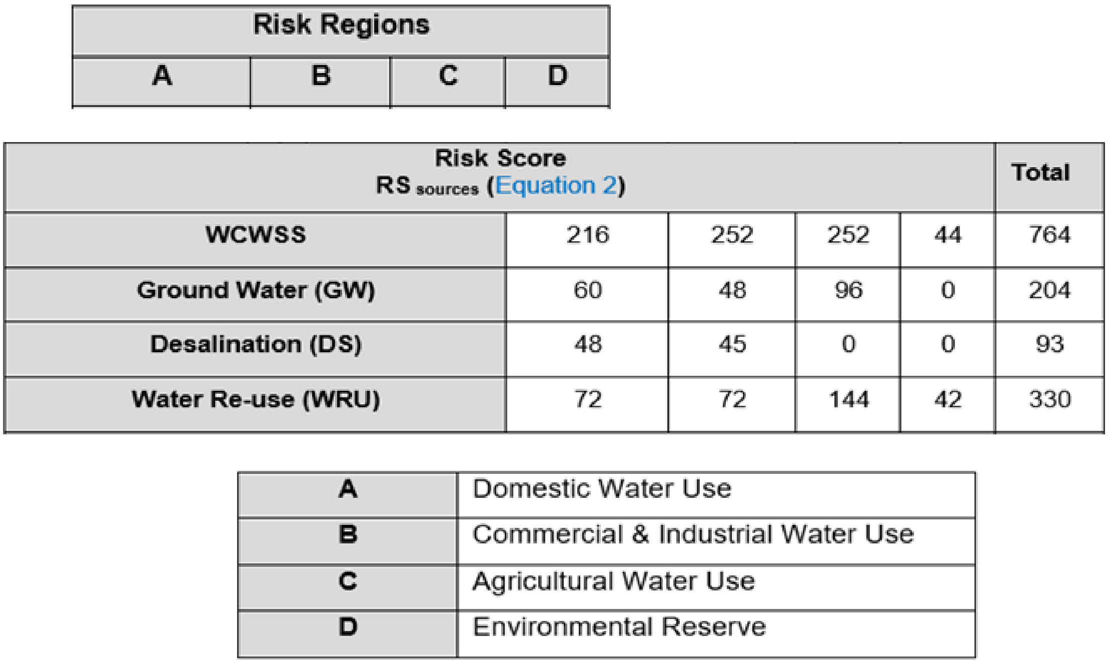
The production of water from the above-mentioned Sources (S) was measured for impact using the following stressors: sources being rain-dependent, sources influenced by water restrictions, sources influenced by water costs, and sources controlled by water demand management. Risk scores were calculated based on habitat ranks and the influence of exposure and risk filters.

5.6.2.2 Total risk per region for all Sources ($RS_{sources}$, Equation 2)

The consideration of total risk impact over all regions found that the relative risk posed by individual stressors on sources to the different risk regions were from a high RS of 764 for the WCWSS, with Water Re-use (WRU) at RS 330, Ground Water (GW) at RS 204, and Desalination (DS) at RS 93 (Table 4.5).

The combination of the various Stressors (S) (Figure 4.4), resulted in the highest risk of impact occurring in Agricultural (A) water use, Industrial/Commercial (U) water use and Domestic (CW) water use in Risk Regions (RR), in declining order, with risks of impact in all these RR being considered high based on the research outcome. The graphical presentation of results produced in Figure 4.4 and tabulated for ease of reference in Table 5.3, concurs with the expected outcome in that it confirms the negative economic impact of the drought experienced by agriculture and industrial/commercial risk regions due to water restrictions. Domestic water use displayed a moderate risk, with the environmental reserve being the most risk averse. This outcome is confirmed and supported by current literature including Taing et al. (2019), Ziervogel (2019), Muller (2018), Muller (2017), and World Wildlife Fund (2017).

Table 5.3: Total Risk per Region for all Sources (adapted from O'Brien & Wepener, 2012:161)



	Risk Regions				
	A	B	C	D	
Risk Score $RS_{sources}$ (Equation 2)					Total
WCWSS	216	252	252	44	764
Ground Water (GW)	60	48	96	0	204
Desalination (DS)	48	45	0	0	93
Water Re-use (WRU)	72	72	144	42	330

A	Domestic Water Use
B	Commercial & Industrial Water Use
C	Agricultural Water Use
D	Environmental Reserve

5.6.2.3 Total Risk posed to each Habitat per Risk region ($RS_{habitats}$, Equation 3)

The risks findings in Figure 4.5 present the total risk posed to each habitat per risk region ($RS_{habitats}$). Habitats represent the WS indicators used in RQ1, namely: Water Resources Utilisation Intensity (PW/(P+I)); Trade and Technology investment (TT = GDP/Capita); and Spatial Heterogeneity (PW/CW) in water production and consumption. The habitat is the place, setting or environment where the phenomena being studied is found.

The greatest risks posed in the PW/(P+I), TT and PW/CW habitats were found to be to the agriculture (RS 204, 162 and 126) and industrial/commercial (RS 162, 147 and 108) water use Risk Regions (RR), displaying a risk score of 50 to 100 risk units higher than the risk region for domestic water use at RS 162, 117 and 117 respectively. This indicates that water restrictions due to water shortages from the WCWSS would affect these risk regions to a higher degree than confirmed by the restrictions applied during the drought as reported by the CCT (2017) and Muller (2017). The RR (Figure 4.5) reveals that all risk regions except Environmental Reserve (Q+N) are also found to be affected by these water use restrictions, with a positive effect on WS brought on by effective water demand management practices executed by the CCT (Ziervogel, 2019; Muller, 2018). The environmental reserve represents 10% of the total water capacity to be retained in the watershed for use and protection of ecosystem services as promulgated by the National Water Act 36 of 1998. This reserve has limited benefit for other uses, as the reticulation infrastructure cannot abstract or draw down lotic water systems beyond this level. The last 10% of water in dams are also more polluted because of the concentration of pollutants, and are thus costly to abstract, treat and transport (City of Cape Town, 2019c). It is important to note that the Risk Score (RS) values are in relation to each other, and values so acquired will only be meaningful when considered in the context of this research.

The combination of the stressors (rain-dependent water supply, water restrictions, water costs, and water demand management) influencing the various Sources (S) (WCWSS, GW, DS and WRU) and the augmentation projects proposed by the CCT, resulted in the highest risk score of RS 492 for its impact measured in Risk Region C, agricultural water use. The RS scores for domestic, industrial/commercial and environmental reserve were found to be 396, 417 and 86, respectively (Figure 4.3). This outcome was expected as the system is mostly dependent on rain-fed surface water storage from the WCWSS and Ground Water (GW) (City of Cape Town, 2018b; Muller, 2018; World Wildlife Fund, 2016).

The results identified the RR with the lowest risk of impact from a volume perspective as environmental reserve. This is supported by literature, which confirms that the last 10% of water contained as surface water cannot be abstracted for human consumption due to infrastructure constrains and the high costs of abstraction and purification (Parks, et al., 2019; City of Cape Town, 2019c). The low water capacity does not only threaten the environment and ecology of the natural water systems due to volume, but also because of the concentrated pollution potential (World Wildlife Fund, 2016;; Steyn, et al., 2019; City of Cape Town, 2018b; Parks et al., 2019).

In summation, the results can be presented as follows: When considering the results for total risk over all regions, the research produces outcomes indicating relatively high probability of risks posed to the total water availability for the CCT by the subsequent Sources (S):

i) Western Cape Water Supply System (WCWSS), RS 764, being total rainwater-dependent.
ii) Water Re-Use (WRU), RS 330, which will require large capital and operational investment in water treatment infrastructure.
iii) Ground Water (GW), RS 204, also rainwater-dependent, threatened by unmeasured over-abstraction and pollution in ground water recharge zones, threatened by uncontrolled informal settlement establishments close to, and in natural water courses.
iv) Desalination (DS), RS 93, having the lowest impact on the total water availability of the CCT because of its limited contribution and major cost implications.

The outcomes presented by the results for the sources per risk region identified agricultural RS 492, and industrial/commercial RS 417 water use, posing the highest risks impact (Figure 4.4) to the WCWSS, with domestic water use at RS 396 a close second. The greatest risks posed by Water Resources Utilisation Intensity PW/(P+I) occur with agricultural usage at RS 204, with risks to domestic RS 162, industrial/commercial RS 162, and the environmental reserve RS 40 in order of severity (Figure 4.5). The findings of this research found ground water and water re-use to present the highest impact risks to agricultural water use due to its dependence on rainwater for recharge (Figure 4.3).

When considering the total risk per risk region for all sources, the results identified agriculture RS 492 as most at risk to supply from the WCWSS, This is supported by literature, which states that agriculture is mostly dependent on rain-dependent surface water and ground water (Department of Water and Sanitation, 2019; World Wildlife Fund, 2016; Muller, 2018; Ziervogel, 2019), whereas the results for desalination display a moderate risk to domestic and industrial/commercial water users and the lowest risk impact for agriculture and environmental reserve (City of Cape Town, 2018b). The greatest risk posed to the RS habitats occur primarily in agricultural water use, which is confirmed by the research results and outcomes of the risk assessment (Figure 4.3, Figure 4.4 and Figure 4.5). Industrial/commercial and domestic water use received a similar risk scores of RS 162, with the Water Resources Utilisation Intensity (PW/(P+I)) posing the greatest risk impact of RS 568. These results agree with the expected outcome and are supported by Taing et al. (2019), Ziervogel (2019), Muller (2018) and Wolski (2018).

Trade and Technology (TT) investments were identified (Figure 4.5) as posing the second highest risk impact of RS 444 to domestic, industrial/commercial and agricultural activities, with limited risk impact on the environmental reserve. Financial implications of alien vegetation clearing and upgrading of water producing ecosystems in the HWYA were not considered as part of this research as verifiable data could not be found and accessed (Marais et al., 2004).

Lastly, the risk results were judged in relation to the various end points established for the research area, namely the sustainability of total water potential, augmentation projects, and the total WS of the CCT. The results derived from findings indicate that management actions should focus on the following priorities identified by the WS risk assessment applied to the CCT:

i) Firstly, the development of models to proactively manage the allocation and restriction of water supply aligned with the Total Water Potential (PW/(P+I)) available in the water storage facilities at the beginning of the hydrological year. This prevents reactive WDM restrictive measures based on the financial model used in the past, which implemented restrictions too late (Winter, 2018).

ii) Secondly, to develop diverse water supplies to minimise the dependency on the WCWSS and importing water from neighbouring watersheds. The research prioritises investment in wastewater re-use, which at optimum be able to recycle and contribute up to 80%+ of wastewater generated versus the 9-10% at this time. Water re-use, being more expensive than ground water abstraction, is vindicated as a priority as it is not directly impacted by adverse rainfall. Water re-use is more cost effective and sustainable than desalination and does not negatively impact the environment. Water re-use is more viable over the long-term as it is not rainfall-dependent. Investment in wastewater treatment (WWT) plants benefit human health and the environment. Furthermore, water re-use can minimise pollution and use much less energy than desalination, a view supported by Swana et al. (2020).

iii) Thirdly, the GDP/Capita indicator used in this research indicates a definite decline in the per capita financial capacity (Figure 5.3). This DFWS indicator monitors the financial capacity of a society to invest in infrastructure, as a sustainable water infrastructure system is dependent on reliable, systematic investment. This result corresponds with the expected outcomes and is confirmed by the CCT Water Strategy Draft Note (City of Cape Town, 2019c) that one of its primary objectives of the Water Strategy is to increase its water revenue collection from 70% in 2017/18 to 95% and even more in the not too distant future.

The Water Strategy commits to invest R5.4 billion in the identified alternative water sources in terms of re-use, ground water and desalination. It is proposed to reduce the dependency on the WCWSS from 95% of the CCT’s supply to 75% by 2040 (Winter, 2018). As part of the investment programme, R850 million will be invested in the 25-wastewater treatment works in this financial period, increasing to R1.4 billion by 2023 (City of Cape Town, 2020).

5.6.2.4 Sensitivity and uncertainty evaluation of relative risk rankings

According to O’Brien and Wepener (2012), best ecological risk assessment practice necessitates the assessment of uncertainty and sensitivity of input data. The Monte Carlo simulation comprising 10,000 iterations was used to account and simulate for variability and uncertainty in the RRM. The outcome displayed in graphical format (Figure 4.6) resulted in a 90% probability that the augmentation projects will provide between 461,2 Mm^3 and 528,8 Mm^3 water to the total water potential per year, if implemented according to the CCT New Water Plan and providing the projects deliver the volume of water envisaged (City of Cape Town, 2018b).

The sensitivity analysis evaluates the impact of the individual indices against the range of parameter values according to the secondary part of Step 7 of the RRM (Colnar & Landis, 2007; O’Brien and Wepener, 2012). In this assessment, relationship factors are produced to rank model constraints corresponding to their impact to forecast uncertainty. High-ranking factors are those of significance in affecting uncertainty contained by the model (Colnar & Landis, 2007). The sensitivity analysis was conducted for the impact of individual augmentation projects on both the total water potential and the WS of the CCT.

The results presented here rank the augmentation projects in sequence of positive impact and their contribution to the total average water potential for the CCT as follows: (i) water re-use (planned 14% versus potential of 80+%); (ii) ground water, 9,81% but sustainability questionable; (iii) surface water (5,36% planned); (iv) desalination (4,46% planned); and (v) springs and minor rivers (0.59% reported during normal rainfall years). For the impact on WS for the CCT, the augmentation project impacts are ranked as follows: Population growth will have the highest negative impact on the total water potential for the CCT with the sequence of positive impact and contribution effect to the total water potential, being: (i) water re-use, which can contribute up to 80+%; (ii) ground water, 9,81%; (iii) desalination, 4.46%; and (iv) the lowest impact produced by springs and minor rivers at 0.59% (Appendix B).

5.7 Benefits of the Regional-Scale Risk Assessment

The benefits and contributions include providing resource users, conservationists, and regulators with a range of benefits, such as: (i) an authenticated, structured methodology sensitive to changing aspects of the application in individual (different) case studies; (ii) educational; (iii) locally relevant; and (iv) universally comparable. The outcomes of the methodology can contribute to effective management of balance between protection and use of freshwater systems (O’Brien & Wepener, 2012).

The RRM approach is inherently unsophisticated and acquires few assumptions. RRM is not limited to the requirements for controls and reference sites; it states or provides assumptions concerning community dynamics, ancillary results, or one-dimensionality of responses (produces an output that is claimed to be proportional to the input) (Landis & Wiegers, 1997; O’Brien & Wepener, 2012). It allows for stressors on the availability of limited information and for consideration of future decisions making, based on ranking procedure. Assumptions and confidence issues impacting an assessment should be well documented to validate the dynamic nature of the application. Sensitivity and uncertainty assessment of the RRM should be highlighted, and where feasible, validations (field and laboratory work) of determined hypotheses ought to be embark on to assess risk outcomes (Landis & Wiegers, 1997).

Further benefits include that the RRM contributes to answering the requirements of the National Water Resource Strategy (Department of Water Affairs, 2012); permits for objectives/goals of stakeholders and participants; contributes to the requirements of local communities to supply in basic human needs; and the upkeep of acknowledged consumption activities, including the delivery of water to preserve agricultural, industrial and commercial activities.

5.8 Limitations of this research

The limitations of this research may also be viewed as the rationale for expanding and future development of the research methodology. The following are identified as limiting factors:

i) The Regional-Scale Risk Assessment utilising the RRM should not be done in isolation from field or laboratory work, but as a method to incorporate, test and consider implications associated with scenarios of water system usage in the context of water resource system structure and management functions.

ii) This research did not operationalise the WS paradigm by incorporating stakeholder participation. Not including stakeholder buy-in from all actors made the framework less robust and implementable. With stakeholders involved, the educational requirement of accessibility and usefulness may have increased for the public as per the commitments of the CCT Water Strategy.

iii) Water governance is not considered as part of this assessment. This indicator would have represented how well water resources are managed through policies and institutions, which is identified in literature analysing the effect of the drought in the CCT as an area lacking effective management and accountability.

iv) Although the CCT does not use its water allocation for agricultural purposes, agriculture does have a major co-dependency on the same water resources from the WCWSS and has a 32% allocation of total water available during a normal hydrological year. Drought impact on the supply capacity of the WCWSS does present a direct risk to the water supply of the CCT.

This assessment was based on the availability of data from open-access hydrological information systems (HISs); freely available data were inconsistent, difficult to verify and contained data gaps. Open-access operational information is available on a limited basis as is the latest census detail.

The framework could have been strengthened by the addition of more specific indicators for which there is no open-access data available, namely indices to measure the level of safe access to water and sanitation, measuring the volume of untreated effluent, measuring the surface water quality of waterways and wetlands, and a progress indicator for the CCT becoming a water-sensitive city.

The timespan of four years to complete this research was in retrospect viewed as negative, as it complicated the decision of what to incorporate and what to leave out in the light of the plethora of available literature and the wide and complex interpretation of the WS paradigm.

5.9 Implications and significance of this research and results

The usage and application of the RRM in South Africa presents a method with the prospective capacity to offer resource consumers, resource preservationists and officials with a variety of advantages. These incorporate: (i) the formation of a proven, coordinated methodology that is responsive to the dynamic range of individual case studies; (ii) comparatively uncomplicated to execute; (iii) particularly educational, locally relevant; and (iv) universally comparable with other similar RRM assessments. This methodology has the capability to significantly add to the usefulness and efficacy of integrated water management actions to maintain equilibrium between usage and safeguard of aquatic systems and the urban water cycle.

From a local perspective, the benefits of the RRM stem from its ability to be tailored to consider the threats of various sources of various stressors towards local habitats and endpoints, thereby supporting the aims of integrated water resource management (IWRM) in South Africa (Department of Water Affairs, 2012). RRM can offer resource consumers, conservationists, and managers of freshwater systems a variety of advantages by enabling researchers and decision makers to access timely, accurate, and consistent water-related data. The WS risk assessment enables readily available data and automation of information; even though nearly all environmental and water data are accessible electronically, it is not always freely available. The assessment enables its users to automate data-sharing and reduce generally availability and compatibility challenges.

RRM can promote standardisation of data structure; each section of data has a composition, but data structures vary from one organisation to another, not always matching, thus making assimilation of information problematic. The WS risk assessment methodology promotes real-time accessibility, where outmoded data-sharing systems frequently produce delays and conflicting interpretations. The WS risk assessment methodology applied in this study can contribute to faster, more accurate, and universal application and processing of data than previous systems.

In conclusion, the WS risk analysis contributes by providing better data through universal actionable indices and outputs; better decisions can be made based on quality information in real time repeatable analyses. Data sharing and processing are inexpensive in terms of employing the methodology, thus contributing to more accessible, affordable data, which allows for making for better water management decisions.

The methodology and results support the Water Research Commission's (WRC) key strategic area of Water Resource and Ecosystem Research, the themes and focal areas of UNESCO's International Hydrological Programme (IHP) for WS, and its Sustainable Development Goal 6.

The WS risk assessment supports the CCT's approach in the perspective of whole-of-society methodology. This includes: (i) safe and secure accessibility of water; (ii) sensible consumption of water; (iii) adequate, consistent water from various sources; (iv) collective benefits from local sources; (v) becoming a water resilient city by 2030; and (vi) achieve a sensitive city status by 2040.

5.10 Chapter summary

This chapter explained and discussed the results and expected outcomes of the research project, including results that agree with the majority of expected outcomes and challenge the validity of others. The chapter commenced with an elaborate background and context analysis to inform and correctly position the research in relation to the WS paradigm.

Discussion of the results were validated and referenced with both existing and new literature along the vertical plane to answer the how and why and along the horizontal planes, to incorporate other fields that speak to this research project.

The results delivered by the Dynamic Framework for Water Security (DFWS) methodology was discussed in relation to expected outcome of the WS status for the CCT as a primary research objective. The framework was expanded to incorporate and determine the impact of the water augmentation projects proposed by the CCT's New water Plan as the second research objective.

The results successfully produced the expected outcomes of determining the WS status, forecasting the impact of the augmentation supplies on WS over the implementation period and informing appropriate mitigation actions to support WDM in the CCT.

The third deliverable employed a regional-scale risk evaluation employing the Relative Risk Methodology producing its results in several graphical representations of the relative risks posed by the indices in the risk region, the total risk in all the risk regions for all the sources and stressors considered in this research and also the total risk posed to each habitat per risk region.

The augmentation projects contribution to the total water potential per year was then processed through a Monte Carlo simulation comprising 10,000 iterations to simulate variability and uncertainty in the Relative Risk Model. The resulted outcome displayed the variability of total water supply in graphical format.

The individual augmentation supply projects were analysed for sensitivity via a tornado graph which produced the effectiveness and sustainability of the augmentation projects on average water potential and ranked them according to impact potential. The results delivered the sensitivity to risk impacts from high to low in graphical format.

The sensitivity analysis of the water augmentation projects on the WS of the CCT was similarly processed and the results presented through a tornado graph. The results identified the WS of the CCT being mostly sensitive to population pressure and the impact of water re-use.

The chapter continued with comments on the short comings and limitations of the research projects and discourse on the level of achievement of the research objectives, the possible implications and significance of the research project and results achieved.

The next and final chapter contains the conclusions and recommendations of the research project.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introductory statement to the research

Dynamic hydro-climatic and socio-economic circumstances progressively exert strain on freshwater resources and are expected to aggravate future WS conditions. The CCT in recent times experienced acute water shortages caused by several continuous years of drought. Scarcities are exacerbated by a misplaced confidence in water conservation and demand management methodologies to even out availability with requirements in the precipitously expanding Metropole.

The relationship and interactivity between the supply-side planning approach and the less methodical demand-side system approach contributes to the delayed implementation of water augmentation schemes. Political precedence and weaknesses as well as skewed views of and opinions towards WS risk prejudiced demand projections and development outcomes. This understanding demonstrates the significance of a more methodical approach to demand projections to identify and decrease the risk to WS.

The CCT has experienced severe drought from 2015-2018. Subsequently, since May 2019, the average normal winter rains have caused a reprieve to the residents of the CCT. Apprehension that the water supply may possibly run out in the summertime of 2019 have been allayed, however the City remains at risk.

This research was established on the perception that people and nature coexist on the planet, resulting in complex social-ecological systems. These elements of complex systems bring about for the most part the stubborn problems that arise out of water resource administration. Thus, key foundational methodologies for water research incorporate complexity thinking since the systems by their very nature is complicated and transdisciplinary.

This research pursued a paradigm shift and attempted to dismantle the complex and problematic issues of WS risk assessment into its simplest parts. It offered approaches for simultaneous knowledge expansion and distribution across disciplinary frontiers, among communities, researchers and practitioners.

The research framed the balance between human and environmental water demand by combining a set of markers that correlate human-water usage to the water resource capacity. The research further mapped these markers to distinct categories of WS or insecurity. Lastly, it presented a group of casual elements driving both human-water usage against the water resource capacity. The indices have been evaluated through a DFWS in combination with a relative risk assessment to model the indicators and produce a WS risk assessment. The investigation followed a quantitative systematic empirical approach within a positivist paradigm into a WS risk assessment of the Water Management Area of the CCT, using data from open-access HISs.

The outcomes modelled the linked human-water interactive systems investigated in this study to: predict ecosystem responses under anthropogenic influence, describe WS, and inform appropriate management action. The results and findings benefit WC/WDM strategies by contributing to an effective Integrated Water Resource Planning approach and focusing resources to managing water demand.

This data collection was not participant driven, but all data have been accessed and used ethically. The data accessed are freely available in the public domain; no proprietary artefact has been produced as a result of this research, therefore no significant ethical implications exist.

6.2 Background to the research

Throughout the drought period of 2015-2018, the necessity to react precipitously to a fluctuating water usage against supply capacity with unpredictable water demand was well-defined and poorly executed. The lack of coordinated management decisions based on quality information, followed by assertive actions, added to the water shortage problem. This is despite existence and general availability of large open-access hydrological information systems for decision makers to utilise.

The impact of the drought, delayed interventions and doubtful decisions lead to severe economic and social challenges for the people of Cape Town. Debate exists about the efficacy and timing of several interventions varying from new dams and subterranean water sources to water re-use and reverse osmosis of sea water. All which are currently in play to mitigate the present situation. These interventions are mostly reactive in that implementation is planned over the long-term, with limited current impact. It is argued that South Africa will continue to experience a water deficit that requires urgent management, mitigation and interventions.

Therefore, the WS risk assessment using open-access HIS provides a more systematic non-specialist approach to demand forecasting by identifying and reducing the risk to WS in Cape Town. The findings of this WS risk assessment support the suggestion that the sum of the cross-dependencies between human-natural interaction every so often lead to evolving relationships of structure, function and dynamics. This dynamic combination then delivers results that would have been difficult to predict from the understanding of the behaviour of the separate elements.

Significantly, the accessibility and diverse open-access sources of water-related data from statutory HIS allows for cost and time effective data collection over a longitudinal time frame of 20 years. As such, this dissertation endeavours to determine the influence of open-access HIS on the interrelatedness of the human-natural influences on the decision-making processes.

6.3 Aims of the research

The aim of this research was to explore the impact of open-access HISs to effective decision-making regarding WS risk assessment. Moreover, the research explored the effect of the augmentation projects proposed by the New Water Programme and the related risk factors of water produced and consumed within the spatial boundaries of the CCT. A further aim of this research was to explore how the open-access HISs can be applied and utilised to quantify the interrelatedness of the human-natural influences and inform the decision-making processes.

This research evaluated WS quantitatively as a product of a human-water influenced system. This was done by aligning the objectives of the WCWSS reconciliation strategy to future water supply demands with provision for a 25-year forecasting horizon. An adaptive framework is proposed for decision-making, thus considering equally the safeguarding of the water supply capability and subsequent water demand management by utilising open-access HISs for the CCT Water Management Area.

Founded on the outcomes of the quantitative assessment of the role of HISs in the WS risk assessment for the CCT, it can be stated that the aims of the research were addressed and achieved. The subsequent conclusions are reported on as follows: firstly, the data available from open-access HIS do not fully comply with the specific and detailed requirements of the WS framework. This is especially valid considering water use data across sectors, water-related financial data, and ground water data. Secondly, the lack of detailed and specific data to inform the WS indicators negatively impacts on the efficacy of the DFWS as detailed in the results. Thirdly, the results indicate that the CCT will be water secure under normal annual rainfall.

By analysing changing representations of urbanisation on population growth via the DFWS, this research shows that telecoupling, or the human-water impact of PW and CW on the water supply system, will continue to have a significant impact on the WS of the CCT as is expected. The contribution of the proposed augmentation supplies to diversify the CCT water supply from singular dependence on the WCWSS will be less than 50% if implemented as planned. It can be further concluded that the augmentation supplies are directly or indirectly all dependent on supply or recharge from rainfall.

The integrated risk assessment confirms its applicability as part of the WS analysis. It may be concluded that it presents a robust technique for WS risk evaluations that meet the contemporary criteria of best scientific practise. It can produce constructive contributions to the sustainable managing of the CCT water supplies and thus WS.

6.4 Objectives of the research

The primary objective of the research was to examine the influence of the coupled human-water system utilising the DFWS to determine the WS status of the CCT. A second objective was to expand the timeframe of the framework to incorporate the proposed/planned augmentation projects of the New Water Programme. During the research period the City's New Water Plan evolved into the CCT Water Strategy. The research integrates open source hydrological information into applicable WS indicators producing an integrated WS status for Cape Town.

The research attempted to bridge the knowledge gap of historical and predictive insight into the WS of the CCT by applying and expanding the Dynamic Framework over a 20-year time frame to address historical as well as possible future WS for the CCT. The research expanded and assessed these WS indices for their risk to WS for the CCT via the Relative Risk Model.

A further objective is to address criticisms of constant indicators by accounting for both the interrelation among human and water networks and the varied routes by which these networks change over the chosen time period. The research framed WS as an outcome of a coupled human-natural water systems along the precepts of the Dynamic Framework for Water Security. The research further proposes that human adaption to environmental transformation coupled with ever-increasing water consumption specialisation across societies in the contemporary world require a more adaptable and dynamic view of WS.

The aforementioned research objectives have been executed successfully via the DFWS methodology applied in this research. It is further concluded that despite the lack of specific and detailed water use and water-related financial data, the DFWS framework successfully presented the historical, current status and future WS of the CCT. The contribution of the diversification and augmentation of the CCT water supplies to the CCT WS has shown to be still impacted by PW and CW influenced by population growth and rain-fed surface supply from the WCWSS.

The research further determines the risk elements associated with the WS status of the CCT, differentiating said elements in order of impact. It also contributes to the IWRM of the CCT by means of a proposed guideline or improved DFWS. This in turn contributes and builds on the knowledge base and better understanding of the economic, social, biophysical, technological, and institutional influencers of the current and future WS of the CCT.

It is concluded that the integration of the risk assessment into the WS assessment for the CCT was successfully executed to fulfil these objectives. The approach provided accurate transparency and compliance alternatives for holistic WS management in considering sustainable social and ecological trade-offs in balancing the PW and CW use and the protection of water resources. The results indicate continuous dependence on rain-fed surface-water resources despite the diversification provided by the augmentation supplies. The major risk impacts on the WS for the CCT remain population growth regarding CW use, water re-use, and ground water as PW potential augmentation supply sources.

6.5 Research questions

Based on the application of a quantitative systematic empirical investigation of WS indicators using firstly a DFWS and thereafter a RRA methodology, it may be concluded that the aims and objectives of the research questions have been accomplished successfully.

The primary RQ1 assessed both the historical, current WS status of the CCT, as well as the expansion of the framework via sub-RQ1, to incorporate the future impact on the WS of the proposed augmentation options as proposed by the New Water Programme and Water Strategy. The results indicate that the determined WS status will enable water managers to make better informed decisions and apply resources more effectively.

The aims and objectives of RQ2 posed to determine the risk elements associated with the WS status of the CCT augmentation options by employing a Regional-Scale Risk Assessment analysis methodology. The research objectives of RQ2 were successfully discharged by identifying and ranking the risk elements of the WS status of the CCT as discussed in Chapter 5.

6.6 Dynamic Framework for Water Security (DFWS)

The DFWS confirms in conclusion that diverse water consumption patterns cause indistinct categories of WS or insecurity. In summation the DFWS delivers and confirms three Regional-Scale Risk Assessment elements of WS which are:

i) When the key challenge is enough water, users do not have admission to sufficient volumes of quality, reasonably priced water to maintain a healthy, and fruitful living.
ii) Where over-allocation of resources is the primary concern the catchment will encounter susceptibility to drought. Conflict will be evident among human and ecosystem demands throughout periods of water scarcity.
iii) Where production water use exceeds total water availability the challenge will be long-term sustainability of existing water resources.

6.6.1 Trade and Technology indicator (TT)

The DFWS delivers insightful conclusions of the TT indicator, supported by official sources, from the findings that the spending on water-related infrastructure declined from 2008 to 2019. It might be said that the TT indicator considers both GDP activity and population numbers to represent the per capita value available for investment in trade, technology, and infrastructure. Moreover, the TT indicator considers the financial capacity to invest and develop infrastructure to contain, treat, reticulate, and utilise water resources and/or purchase and import foodstuffs and products on the international marketplace as virtual water.

On the whole, it may be concluded that although financial capacity is well represented by this indicator, it presents limitations in its inability to differentiate between sectoral contributions or infrastructure investments across diverse living standards categories. GDP is thus not considered an accurate gauge of fiscal impact on WS for this framework, as the true economy incorporates unmeasured natural capital assets, impacts of informal settlements in or near water courses, private, industrial, and agricultural ground water use.

The influence from nature, being immeasurably valuable but non-quantified as ecosystem services, are not represented as to what contributions these natural assets deliver. These ecosystem services incorporate regulating of natural processes such as decomposition, erosion, water purification, and flood control, carbon storage, climate regulation, water supply, pollination, and recreational facilities. These natural assets have been projected to add substantially more to human well-being than represented or reflected by GDP as indicator. It may be said that historical and current failure to protect these natural contributions of ecosystem services has led to considerable reduction in the value of these assets.

Moreover, in place of GDP, literature suggests consideration of a gauge that accounts for fluctuations in social and natural capital is the Genuine Progress Indicator (GPI). GPI modifies individual usage by revenue distribution, includes non-marketed essential services such as volunteer and domestic labour, and deducts the expenses of ecological capital reduction such as air and water pollution. Universally, GPI per capita has not increased ever since 1978, yet at the same time GDP per capita has more than doubled. It may be concluded that the world has been subjected to an ‘un-economic growth’ ever since 1978.

6.6.2 Water Resources Utilisation Intensity indicator (PW/(P+I))

All goods and services contain or have some WS-related impact value. Water Resources Utilisation Intensity presents the water volume employed to produce food, commodities and essential services and is represented by PW as a portion (ratio) of accessible water supplies, precipitation, and water imports (P+I). In summary, this indicator provides a very wide view of the WS and does not consider water imports via goods from outside the geographic area of the CCT.

In the final analysis it may be concluded from the results obtained by this indicator that the CCT will be dependent on water imported via inter-basin transfers from outside the watershed despite the planned augmentation and diversification of its water supply. It is also concluded that the future WS of the CCT will be dependent on more factors than only water availability versus water usage, but rather a safe three-dimensional operating sub-space, mapping WS along tangible supply accessibility, infrastructure, and fiscal objectives. Telecoupling in the form of human-water interactive structure simulations can then be used to predict potential WS trajectories, forecast WS and advise suitable engagement.

6.6.3 Production Water and Consumption Water (PW/CW)

Uneven distributions in production and consumption water footprints is represented by the proportion of Production Water (PW) and Consumption Water (CW) footprint indicator PW/CW. A prominent claim of the DFWS that the dominant economic activity in the region represented by this indicator usually have a pronounced effect on this ratio, where a water intensive industrial or predominant agricultural activity will result in a PW/CW >1 and more service sector-oriented economy will result in a PW/CW<1. In light of this it may be concluded that the CCT represents a diverse economy that historically focused more on agricultural and manufacturing activity, but in recent years have been leaning towards a more service sector-oriented economy.

6.7 Impact of augmentation projects on the WS analysis of Cape Town

The New Water Programme has been transformed into the CCT Water Strategy, which is the latest documented plan to augment and diversify water supply of the CCT from various alternative sources and is scheduled to be implemented stepwise to contribute approximately 10% in 2019 to 68% in 2026. This will make the CCT less dependent on the singular supply from the WCWSS, currently at >95%, and the effect of climate change and the resultant rain-fed water supply limitations.

This implies that the assurance of supply for the CCT will be increased from a 98% to 99% by the implementation of the NWP/Water Strategy. The increase in assurance of supply and therefore WS of the CCT does not identify, rank or consider the risk elements to the WS. The additional risk assessment of the WS portion of the research successfully consider the uncertainty and sensitivity of the WS elements as set out in the RQs.

Thus, it may be concluded that the DFWS delivers a successful composite assessment of WS by considering all three the elements mentioned above. This has been achieved by including indicators representing: (i) total water resource consumption; (ii) human demand or consumption; and (iii) human development. Overall, it may be said that some of the indicators used in the WS analysis are more successful than others. Moreover, the results lead to conclude that:

i) The Water Resources Utilisation Intensity Indicator, PW/(P+I), although representing the fraction of water consumed to produce food, fibre and energy as a portion of total accessible water volumes, is too broad in the CCT context that it does not account for ground water use, data of which is currently mostly unmeasured by the CCT and DWS and thus unavailable in the public domain.

ii) The economic capacity of a society reflected in the GDP/Capita (TT) indicator, as discussed in Chapter 5, this indicator was concluded sensitive enough to indicate infrastructure expenditure, but not the sectorial water-related financial implication of WS for the CCT.

iii) The ratio of PW and CW use, representing the Spatial Heterogeneity and telecoupling influence in the catchment, clearly indicated the lack of a dominant economic activity, and thus confirmed a balance between agriculture, commerce, industry, and financial services.

All in all, modelling these three variables against each other present a composite index of WS in a graphical representation of indices and trajectories of coupled human-water systems (telecoupling), that is presented as a developing effect. To conclude the DFWS successfully delivers on the premise that results that will advise four sets of factors contributing to the WS status of a catchment, namely:

i) Culture and economic activity that indicate what people require water for.
ii) Supply capacity, what volume of water is accessible.
iii) Economic capacity indicating whether the population has the capability to invest.
iv) Governance that indicates the checks and balances managing available resources.

To summarise, firstly the DFWS delivers on its claims to generate indices and trajectories that model human-water systems as emergent WS outcomes informing the four sets of factors mentioned previously. It may be said that it is a good quality framework to use as a basis to develop a more regionally representative application. Secondly, the framework functioned well as a unifying framework for WS, historically critiqued for being fragmented and empirical. On the whole it is concluded that the DFWS can be supported to provide a sound basis to define, categorise, measure and model WS over different timescales within a defined watershed or domain.

6.8 Relative Risk Assessment (RRA)

The research followed an integrated approach in applying the Relative Risk Model (RRM) to execute and complete the WS risk assessment portion for the CCT. The RRM was successfully adapted for South African environments by previous research and comprise of ten sequential steps that are comparatively simply employed.

The application and use of RRM within the South African context is shown to have the capability to deliver resource consumers, conservationist, and officials of WMA with a variety of advantages. These advantages incorporate the formation of an authentic, well-defined approach that is responsive to the changing aspects of varied spatial and temporal scales, particularly illuminating, locally relevant and may be compared with RRM appraisals covering a variety of watersheds and catchments. It is therefore concluded that the practice of the RRM method in South Africa has the ability to significantly add to the efficacy of water resource management, maintaining the equilibrium among the sustainable consumption and safeguard of water biomes.

6.9 WS risk assessment

From the findings of the WS risk assessment for the CCT it may concluded that the combination of various stressors influencing various sources resulted in the highest risk impact occur in agricultural water use. This is expected as this system is mostly dependent on rain-fed surface storage and ground water.

Overall, it may be said that the risk to industrial/commercial and agriculture water use is much higher than for domestic water use, as restrictions due to water shortage from the WCWSS would affect these risk regions sooner and to a higher degree. Environmental health, which incorporates the ecological reserve resulted in a low risk score indicating a low risk of impact, which when measured against existing studies lead to conclude insufficient or absence of suitable data or indicators to provide meaningful results in this WS risk assessment framework.

It may be concluded that while studying the total risk across all the regions, the risk caused to water sources are found to be in order of risk score, WCWSS, water re-use and ground water, with risk posed by desalination as a water source to be negligible. WS is risk sensitive to the impact of WRU and GW abstraction, while SW, DS and S&R have lesser risk impacts when measured for influence on the WS for the CCT. This might be because of the low volumes and late influence over the period analysed.

6.10 Practical applications/implications

6.10.1 Open-access Hydrological Information Systems (HISs)

The open-access HISs available in the public domain provide basic and sometimes undefined information on water supply in general and the CCT specifically. Dam levels are revised weekly on the CCT’s municipal website, which, in addition, offers data on every one of the dams supplying water to the CCT via the WCWSS. However, beyond the basic data, it becomes difficult to access and verify historical records on precipitation and dam levels. Volumetric data on water use by sector is not available from a central database; current and historical water use data are only available from CCT reports in percentage water use per sector. Data for this research were converted from percentage to volume of water supply to residential, industrial/commercial, and agricultural water. Data on the revenue and capital directly employed in water-related supply are only available in broad terms and without supporting detail.

6.10.1.1 Rainfall

Open-access and free of charge precipitation information for Cape Town International Airport, from January 1960, are readily available, however the information set stops in 2002 when the SAWS initiated a payment system to make precipitation measurements available. Moreover this information is also of restricted use for this study for the reason that precipitation at the airport does not contribute to a water catchment area providing one of the WCWSS supply dams, but does contribute to the recharge of the Table Mountain Group Aquifer.

It may be said that the current methodology to determine water use patterns by dividing storage capacity by population to create a per capita storage capacity index, does not result in an accurate reflection of CW. Understanding however, that not all people use the same amount of water and that there are many water users that are not accounted for, as mentioned, is viewed as a limitation of open-access HISs.

Rainfall data required to investigate historical patterns and long-term consequences have not been readily available in the public domain, but at a substantial cost from a SAWS. Long-term data from weather stations in the vicinity of the Theewaterskloof dam that provides in excess of 50% of the CCT’s water, were not readily available in the public domain and not all measurement stations in the data set have good precipitation accounts; those that were available presented significant data gaps. Rainfall data in the public domain for the Western Cape are available via the National Department of Water and Sanitation website’s hydrological services page. This however represents the whole of the Western Cape in general terms and does not provide data explicitly applicable to the water supply available to the CCT.

6.10.1.2 Dam levels

Dam capacity updates are available on the CCT website, where it provides measurements of water stockpiled in the six major dams supplying the Metropole, in comparison with the level during the matching week of the previous year. More complete historical data are not available. As the site is updated weekly, historical data are blanked off and it is extremely challenging to near impossible to obtain the subject matter from just a previous fortnight after the site is updated. The dam capacity data in the CCT database are not consistent, making the data challenging to evaluate. Graphs of historic dam levels are accessible publicly, but historical precipitation and consumption records are not available in the public domain. It may be concluded from the results of the data search that pertinent and specific water data are not available in the public domain.

6.10.1.3 Water consumption

Snippets of Cape Town's water consumption numbers are available on the CCT open data portal. It is found to be unusable for long-term historical trend evaluation since the data only extend as far back as 2013 and data have been published at irregular intervals ever since. The CCT is unwilling to provide past water use data, but it did make available the total volume of potable water treated in megalitres. As the origins of the water calamity statistics display, the correlation between water consumed and water treated is not always clear, highlighting the need for sector-specific water use records, which are not accessible in the public domain.

The CCT has performed well to make available crucial fundamental data, and to maintain its current relevance. However, at a point in time when there is enormous and justifiable community concern about the CCT's water availability, experts, SAWS and all three tiers of government ought to make a better attempt to produce additional information and make it accessible in ways that even non-experts can comprehend.

6.10.2 Indicators

In the final analysis, the indicators used in the research are considered representative of the available data in open-access water-related databases and hydrological information systems. Overall, water-related data, although voluminous when examined in relation to relevant financial, social and environmental information, were found to be contained in data silos and icebergs. On the whole, the indicators in the DFWS risk assessment for the CCT, proposed to translate data towards defined management controls and assessment actions, are practical and strategic, maximise the value to the user, and is evidence-based. This was achieved successfully as the aims and objectives of the research questions were completely fulfilled. The DFWS indicators exposed data gaps and limitations outside the scope of this study.

Furthermore, the indicators used in the framework aid, among other benefits, with the comparison, measurement and performance measurement of the sources, stressors, habitats, and endpoints employed. The ratio scale of the indicators is easy to calculate and allows aggregation and simplification of the information and the display and communication to the end user in graphical format.

To validate the interpretation, the results and findings of the Dynamic Framework indicate that raw data should remain available, comprehensible, credible, relevant and universal. Indicators should be applicably large enough to envelop the phenomena being measured and small enough to be representative and deliver meaningful results. Indicators are required that are adequately integrated with related resources and dependency such as vegetation, land and population to accurately represent conditions in the spatial and temporal context of the research.

6.10.3 Frameworks

The DFWS is found to best represent a broad overview, outline or skeleton of interlinked items supporting a particular approach to a specific objective in comparison to comparative frameworks as discussed in Chapter 2. The framework successfully serves as a guide that can be modified as required by adding or deleting items, serving as a broad, logical, stepwise guide to establish relationships between interlinked concepts while referring to relevant information. The DFWS is found to be generic and adaptable, holistic, comprehensive, and objective- or outcome-oriented. The DFWS risk assessment is practical in its application and structured to be easily replicated and adaptable to other spatial plains.

6.10.4 Dynamic Framework for Water Security (DFWS)

It is concluded that the DFWS for the CCT efficaciously utilises indicators that relate human-water consumption to available water capacity, and that such gauges can be graphically modelled to present different types of WS. The DFWS offer a set of casual elements that define human-water consumption and available water capacity so that these gauges can be demonstrated in the framework of linked human-water structures.

6.10.5 Relative Risk Methodology (RRM)

The application of WS risk assessment by using the combination of the DFWS with RRM effectively identified the relative threats, from various sources, via various stressors identified in local habitats and projected them to desired endpoints. It can be stated that the risk assessment contributes to objectives of IWRM, is uncomplicated and require limited assumptions. The execution of the RRM methodology is not restricted to control or reference sites, nor confined to beliefs or theories about population dynamics, secondary influences, or linearity of replies.

The risk assessment permits for regard of stressors for which not much evidence is obtainable and for the consequence of potential decision making which is founded on the ranking practices. Moreover, this methodology has the capability to significantly add to the efficacy and success of water resource management and the equilibrium between the sustainable utilisation and safeguard of water resources.

6.11 Summary

The successful application and conclusion of the WS risk assessment in this research support the retrospective analysis of the CCT water crises by various authors over a broad spectrum of sectors. In general, it may be said that despite the availability of well-informed and resourced policy makers, academics and practitioners, that governance virtually failed to report on the expansion of water resources in particular and water supply overall.

As result, water governance structures have neglected to timeously coordinate and action resource and infrastructure development across different sectors and scales to the detriment and risk of the end-user. In general, water governance structures have failed to be inclusive in its relationship with the public in the availability of open-access hydrological information.

The existing modalities of WC/WDM are in conclusion limited in potential to act as a seasonal hydrological forecasting procedure and to simulate regional-scale hydrological responses in South Africa in general and the CCT specifically. The current HIS was found to be too broad in its reporting, with the dilution of climate forecast skills during the process of translating climate data into hydrological information flagged as a particular concern. A knowledge basis is lacking for operational seasonal hydrological data that enable the analysis of rain, run-off, streamflow, ground water and water re-use data, addressing aspects such as frequency and intensity of events, as well as mean conditions.

There exists a definite need for a reliable regional HIS to inform the effective and timeous management and operation of water supply, hydropower generation, and agricultural activities of the CCT economy. Such a regional HIS will also enable disaster (flood and drought) risk analysis, and inform prevention and preparedness. At this time, forecasts generated on open-access national HISs in South Africa, namely SAWS, CSIR and CSAG (and possibly others), are too broad and require a range of accessibility obstacles, which include the design and implementation of data transfer, and pre-processing and post-processing routines enabling integration of climate forecasts. This can be achieved with the design and implementation of model experiments that enable the investigation of uncertainties associated with various data processing paths, aimed at arriving at robust operational configuration. This will require involvement of all potential users of the seasonal hydrological forecast to ensure relevance of the forecasting system and project activities.

Water resource assessment in South Africa over the last 60 years has become more and more multifaceted due to rapidly increasing growth in land use, decline in water quality and the necessity to investigate the interaction between surface water and ground water. The exponential growth in computing power and the simultaneous development of appropriate tools facilitated resolving these complications, but there is a significant concern concerning the quality and monitoring of hydrological data.

Together, rainfall and river flow monitoring have demonstrated a deterioration in current years and the state with precipitation is especially significant – wherever the observation system has deteriorated from a highpoint in the 1970s to a present state where the system is as bad as it was in 1920. The expansion in native land utilisation has intensified the dilemma, owing to inadequate or non-existent monitoring. Consequently, one of the future key challenges will be to re-establish hydrological monitoring to scientific standards and will only be achievable by employment of appropriate people with the allotment of sufficient resources. Water resource management should not be allowed to be side-tracked by prevailing disputes regarding climate variation but should instead consider its impact and risks by true measurements via an expanded hydrological monitoring network.

For this reason, future studies will be well-advised to investigate water quality and the interface between surface water and subterranean water sources. The probability of climatic cycles and climate transformation must not be disregarded but should distract from the main goals. As a result, the assessment undertaken for this study have been based on imperfect data and the confidence in the results should reflect that fact. However, this is the same data that are often relied on in relatively rapid water resource analyses.

The data required to apply the WS risk assessment methods discussed are all readily available and can be applied without complex software and analytical methods. A differential adjustment to the framework could be made on the monthly flows based on local knowledge; this would involve a superior degree of hydrological knowledge and inclusive consultations with all interested and affected parties.

For this reason, it may be said that the quality of current open-access HIS data available to the public does not comply to the data integrity and differentiation required to further develop indicators to improve the WS risk assessment utilising the DFWS and RRM for the CCT.

6.12 Contribution

The DFWS proved to be a suitable fundamental framework to quantify the human influence and trade-offs on water associated ecosystems for the CCT. The framework effectively identifies, categorises, measures and models WS over extended time frames as applied from 2016-2026. As a result, the framework demonstrates the necessity of integrated indicators to provide a three-dimensional sub-space representing physical reserve accessibility, infrastructure, and economic and political alternatives.

The linked human-water system models can be applied to predict watershed directions, forecast water in/security and advise on suitable management action. Therefore, as expressed, the WS risk assessment framework as applied in this research as a combination of the DFWS and the RRM will positively contribute and assist the CCT to better plan and execute water management decisions in the prevention of a future *Day Zero*.

As expressed in the results, it may be concluded that the risk assessment in combination with the WS framework presents a robust approach to constructively add to sustainable administration of water resources. The risk assessment procedure has been successfully applied, both locally and globally, at a range of spatial and temporal scales. The risk assessment effectively identified the threats and risks to specific indicators, empowering stakeholders to consider sustainable social and ecological balance and protection of water resources. In general, the WS risk assessment can provide true transparency in and adaptability of the available alternatives for water management.

Therefore, this very flexible instrument allows for speedy interpretation of additional evidence, which will advise adaptive management and lower uncertainty related to correctness of forecasts. Stakeholders are presented with evidence-based probabilistic projections to consider water resource use alternatives. The WS risk assessment is holistic, evidence-based, transparent, adaptable and suitable for application on multiple spatial and temporal scales.

The key to future WS for the CCT is competent and adequate long-term planning to which this research can contribute significantly. Further, it is recommended that the CCT’s water supply should be made even more secure by investing in technology and resources that are less susceptible to drought and more proactive in terms of urban growth management.

Further recommendations would be to be less dependent on surface water resources, adopting a water sensitive approach to town planning and redevelopment, and the exploration of interventions to promote and actively encourage behaviour change and address inequality. The WS risk assessment can positively contribute through better engagement with other fields and disciplines; it will enable suitable social, economic, and environmental criteria to be used when deciding on practical solutions.

These recommendations can be summarised by a new paradigm that entrenches water sustainability and resilience in everyday habits of safeguarding water systems and decreasing the environmental footprint of the population.

6.13 Recommendations for further research

No universal best-practice approach to achieve cooperation and inter-agency information sharing currently exists other than executing robust integrated systems, improving collaboration among the numerous groups involved may well positively contribute. Since rivers largely cross political boundaries, water management is every so often managed in water management areas that are isolated from politicians and their electorate. A case in point is the CCT which draws water from two major rivers beyond its boundaries, each of which is managed by a different agency.

While water demands increase and water systems evolve, additional assets will be required for monitoring, data capture and modelling. Technical support integrated into political processes will enable politicians to be aware of the efficacy and validity of management data, modelling, and risks. Information must be in a format and language that empowers all interested and affected parties to act appropriately. Collaboration between hydrologists, experts from the social sciences and humanities, economics, policy and law, will enable development of water-management tools that decision makers and the public can understand and use.

Specialist practitioners additionally ought to observe and model societies’ water use patterns and behaviour. This will contribute to a better understanding of the extended timescales required for effective decisions and sustainable interventions and resist the simplistic solutions of WD/WCM by relying on the inconsistencies of climate and natural infrastructure.

6.14 Research questions answered

The objectives of the research questions were to determine the WS status of the CCT. The impact of the proposed augmentation supplies on the WS and their risks were successfully accomplished by employing the DFWS over a time period of 20 years. The WS framework effectively presents a historic overview of how the WS changed over time, with the current status of the WS as the primary objective and the predictive impact of the proposed water augmentation supplies on the WS for the CCT as secondary objective of RQ1.

The objective of RQ2 to rank the risk to the City’s WS was accomplished through applying the RRM. The sensitivity and uncertainty of the described WS to the impact of relative indicators were effectively undertaken, ranked and reported. The results in Chapter 4 identified and ranked the risk indicators according to their impact on WS and discussed the sensitivity and uncertainty of WS to these indicators.

6.14.1 Research Question 1

The primary objective of RQ1 has been successfully discharged by utilising the DFWS to determine the WS status of the CCT. The research examined and reported on the influence of the coupled human-water system by employing the proposed WS indicators. These indicators represent the Water Resources Utilisation Intensity (PW/(P+I)), the capacity of populations to invest in water-related Infrastructure and Technology (TT), and Spatial Heterogeneity (PW/CW) in water production and consumption.

The additional objective of addressing the critiques of static indices by previous WS frameworks was also successfully discharged. This was achieved by accounting for the interrelatedness of human-water structures and the varied routes by which these structures co-evolve over the chosen time period, which was accomplished by expanding the temporal time frame between 2006 and 2026. The results further recommend that human adaption to ecological transformation and expanding spatial specialisation in the contemporary world requires a more adaptable and dynamic paradigm of WS.

6.14.2 Research Question 2

The research objective of RQ2 was to further determine the risk elements associated with the WS status and the implications of the augmentation supplies on the WS of the CCT, and then to differentiating the said elements by ranking them in order of impact.

This was effectively accomplished by employing the RRM. Further to this, the results report on the sensitivity and uncertainty of the WS for the CCT by successfully identifying and ranking the risk elements threatening WS. The utilisation of the combined WS risk assessment identified population growth as the biggest risk to WS and water re-use as the best positive resource contributor to improve the WS of the CCT.

In consideration of the sensitivity and uncertainty, the probable contribution impact of all the proposed augmentation projects on the total average water potential of the CCT was considered, with the result that water re-use and ground water are deemed to present the most potential. This successfully and completely answered the research questions and fulfilled the objectives of this research project.

6.15 Reflection

The declaration of a provincial disaster by the national government in March 2018 placed the focus of everyone, including big and small enterprises, on how deeply dependent humans and the environment are on the availability of water. The CCT are facing the prospect of an uncertain water future due to climate change, increasing demands because of population growth, and delayed water supply interventions. The augmentation and diversification of water resources were mostly reactive, resulting in the drought experienced since 2015 and culminating in the threat of *Day Zero* in 2018.

I have always been interested and involved professionally in various aspects of water management, first as a research assistant at the then Institute for Water Technology at the CSIR’s branch laboratory in Bellville and then at the satellite campus in Stellenbosch. My career path then followed on to water, waste, and effluent management in the private sector. I was also privileged to contribute towards the formulation of the New Water Act in 1998 as part of the public participation phase representing agriculture.

I registered at CPUT in the 2016 academic year and struggled to find my feet regarding a supervisor and suitable topic, which in retrospect I would have made, “*Water Security Risk Assessment for Cape Town*”. It took me a year to finalise my Research Proposal, which was accepted early in 2017.

The impact of the 2015-2018 drought period led to the introduction of severe water restrictions for the City of Cape Town and larger Western Cape. The societal and economic disruption these restrictions created led me to ponder whether careful planning and a pro-active water governance approach would have been able to predict and prevent the crisis. My interest in the evolvement of the Water Security concept and the progress of ecological risk management methodology led me to believe that the successful determination of Water Security (WS) and the associated risks would inform and support short-, medium- and long-term water governance decisions.

The drought highlighted the lack of availability and consistency of water-related data in the public domain, which added a new dimension to my research in questioning the efficacy of data from open-access hydrological information systems. Water security and risk assessment literature, both historical and current, is plentiful and freely available, but no literature was found where these two approaches were applied in combination or in a spatial and temporal application such as Cape Town.

My literature review produced an exciting WS perspective by Srinivasan et al. (2017) utilising an Dynamic Framework to present indicators of water in/security via four sets of factors, namely: what water is used for, how much water is available, Infrastructure capacity, and water governance. This was achieved by considering a composite view of water security comprising the following three components: water resource utilisation, human demand or consumption, and human development. The risk assessment portion of the research was gleaned from seminal studies conducted both locally and internationally using the RRM methodology as applied to ecological risk assessments.

With water being a mobile common pool resource, achieving WS requires a flexible and dynamic approach. The impact of the drought was experienced across domestic, business, and agricultural domains with immeasurable direct short-, medium- and long-term financial implications requiring a water security risk assessment that considers all publicly available human-natural, hydrological, and financial information. This was achieved by incorporating dynamic indices across a longitudinal timeframe of 20 years. My aim for the research was assessing the WS *status quo* versus the impact of the proposed water augmentation projects of the New Water Programme, and then determining the relative risk impact of the augmentation projects to WS by identifying and ranking the related risk factors.

To achieve the outcomes envisaged by my aims set for the research, I combined the Dynamic Framework for Water Security and Relative Risk Assessment Methodology using data from open-access HISs. I found that data form open-access HIS in the public domain proved that basic, incomplete, and sometimes only undefined information on water supply in general and the CCT specifically was publicly accessible. However, beyond the basic data, I found it difficult to access and verify historical records on precipitation and dam levels. Volumetric data on water use by sector were not available from a central database, while current and historical water use data were only available from CCT reports in percentage water use per sector.

Data on the revenue and capital directly employed in water-related supply were only available in broad terms and without supporting detail. While oftentimes the data collection process was extremely unrewarding, and sometimes a total waste of time, I learned to be resilient in, and how to maintain focus on meeting my set objectives. Concurrently, I also learned when to change approaches, especially when a particular research method had proven to be limited. In hindsight, I should have changed my approach much earlier to save a lot of time. Looking back, I would have placed less emphasis on first-hand interpretation of primary data sources, which was not required for addressing my research questions concerning water usage, water availability and direct water-related financial information. I could have saved time and effort in sourcing this information from secondary sources such as official reports, books, and academic literature.

The drought phenomena produced a plethora of water-related commentaries, journal articles and research reports; the biggest challenge was what to use and what to omit. I found that with a high-pressure, full-time profession, every break I took with the research added a huge workload in keeping up with the current water-related discourse. I had to re-write the thesis a number of times to keep it relevant, hence the 4-, almost 5-year study period.

My search for relative rainfall data was particularly frustrating; open-access and free of charge precipitation information for Cape Town International Airport from January 1960 onwards was readily available; however, this information set discontinued in 2002 when the SAWS initiated a payment system to make precipitation measurements available. Moreover, this information was also of limited use for my study for the reason that precipitation at the Airport does not contribute to a water catchment area providing one of the WCWSS supply dams, but it does contribute to the recharge of the Table Mountain Group Aquifer.

Rainfall data required to investigate historical patterns and its long-term consequences have not been readily available in the public domain. Long-term data from weather stations in the vicinity of the Theewaterskloof dam that provides in excess of 50% of the CCT’s water, were not readily available in the public domain and not all measurement stations in the data set have good precipitation accounts; those that were available presented significant data gaps.

It may be said that the current methodology to determine water use patterns by dividing storage capacity by population to create a per capita storage capacity index does not result in an accurate reflection of water consumed. Understanding however, that not all people use the same amount of water and that there are many water users that are not accounted for, as mentioned, is viewed as a limitation of open-access HISs.

Water consumption records based on dam capacity data in the CCT database are not consistent, making the data challenging to evaluate. Graphs of historic dam levels are accessible publicly, but historical precipitation and consumption records are not available in the public domain. It may be concluded from the results of the data search that pertinent and specific water data sets are not available in the public domain.

Snippets of Cape Town's water consumption numbers available on the CCT's open data portal were found to be unusable for long-term historical trend evaluation since the data only extend as far back as 2013 and data have been published at irregular intervals ever since. The CCT was unwilling to provide past water use data, but it did make available the total volume of potable water treated in megalitres. As the origins of the water calamity statistics display, the correlation between water consumed and water treated is not always clear, highlighting the need for sector-specific water use records, which are not accessible in the public domain.

On the whole, I found the indicators in the DFWS risk assessment for the CCT to translate data successfully towards defined management controls and assessment actions; they are practical and strategic, maximising the value to the user and are evidence-based. I achieved the aims of the research questions successfully with the objectives completely fulfilled.

Furthermore, the indicators used in the framework were found to aid, among other benefits, with the comparison, measurement and performance measurement of the sources, stressors, habitats, and endpoints employed. The ratio scale of the indicators is easy to calculate and allows aggregation and simplification of the information and the display and communication to the end user in graphical format.

In the application of the DFWS in this research, I determined it to best represent a broad overview, outline or skeleton of interlinked items supporting a particular approach to a specific objective in comparison with comparative frameworks as discussed in Chapter 2. The framework successfully serves as a guide that can be modified as required by adding or deleting items, serving as a broad, logical, stepwise guide to establish relationships between interlinked concepts while referring to relevant information. The DFWS was also found to be generic and adaptable, holistic, and comprehensive and objective or outcome-oriented. The DFWS risk assessment is practical in its application and structured to be easily replicated and adaptable to other spatial plains.

I can confirm the claim of the creators that the DFWS applied for the CCT efficaciously utilises indicators that relate human-water consumption to available water capacity, and that such gauges can be graphically modelled to present different types of WS. The DFWS offers a set of casual elements that define human-water consumption and available water capacity so that these gauges can be demonstrated in the framework of linked human-water structures.

I executed the application of the WS risk assessment by using the combination of the DFWS with RRM, effectively identifying the relative threats from various sources via various stressors identified in local habitats, and projected them to desired endpoints. I can confidently state that the risk assessment contributes to objectives of IWRM, and that it is uncomplicated and requires limited assumptions. The execution of the RRM methodology was by far the more satisfying part of the research and it was not restricted to control or reference sites, nor confined to beliefs or theories about population dynamics, secondary influences, or linearity of replies. In retrospect, I would have liked to integrate the DFWS and the RRM with more specialised indicators as mentioned in the discussion of the results and findings.

The risk assessment permits for regard of stressors for which not much evidence is obtainable and for the consequence of potential decision making, which is founded on the ranking practices. Moreover, this methodology has the capability to significantly add to the efficacy and success of water resource management and the equilibrium between the sustainable utilisation and safeguard of water resources.

The successful application and conclusion of the WS risk assessment in this research support the retrospective analysis of the CCT water crisis by various authors over a broad spectrum of sectors. In general, it may be said that despite the availability of well-informed and resourced policy makers, academics and practitioners, that governance virtually failed to report on the expansion of water resources in particular and water supply overall.

As result, water governance structures have neglected to timeously coordinate and action resource and infrastructure development across different sectors and scales to the detriment and risk of the end-user. In general, water governance structures have failed to be inclusive in its relationship with the public in the availability of open-access hydrological information.

The existing modalities of WC/WDM are in conclusion limited in its potential to act as a seasonal hydrological forecasting procedure and to simulate regional-scale hydrological responses in South Africa in general and the CCT specifically. The current HIS was found to be too broad in its reporting, with the dilution of climate forecast skills during the process of translating climate data into hydrological information flagged as a particular concern. A knowledge basis is lacking for operational seasonal hydrological data that enable the analysis of rain, run-off, streamflow, ground water and water re-use data, addressing aspects such as frequency and intensity of events, as well as mean condition.

There exists a definite need for a reliable regional HIS to inform the effective and timeous management and operation of water supply, hydropower generation, and agricultural activities of the CCT economy. Such a regional HIS will also enable disaster (flood and drought) risk analysis, and inform prevention and preparedness. At this time, forecasts generated on open-access national HISs in South Africa, namely SAWS, CSIR and CSAG (and possibly others), are too broad and require a range of accessibility obstacles, which include the design and implementation of data transfer, and pre-processing and post-processing routines enabling integration of climate forecasts. This can be achieved with the design and implementation of model experiments allowing investigation of uncertainties associated with various data processing paths, aimed at arriving at robust operational configuration. This will require involvement of all potential users of the seasonal hydrological forecast to ensure relevance of the forecasting system and project activities.

Water resource assessment in South Africa over the last 60 years has become more and more multifaceted due to rapidly increasing growth in land use, decline in water quality, and the necessity to investigate the interaction between surface water and ground water. The exponential growth in computing power and the simultaneous development of appropriate tools facilitated resolving these complications, but there is a significant concern concerning the quality and monitoring of hydrological data.

Together, rainfall and river flow monitoring have demonstrated a deterioration in current years and the state with precipitation is especially significant, wherever the observation system has deteriorated from a highpoint in the 1970s to a present state where the system is as bad as it was in 1920. The expansion in native land utilisation has intensified the dilemma, owing to inadequate or non-existent monitoring. Consequently, one of the future key challenges will be to re-establish hydrological monitoring to scientific standards and will only be achievable by employing appropriate people with the allotment of sufficient resources. Water resource management should not be allowed to be side-tracked by prevailing disputes regarding climate variation but should instead consider its impact and risks by true measurements via an expanded hydrological monitoring network.

For this reason, future studies will be well advised to investigate water quality and the interface between surface water and subterranean water sources. The probability of climatic cycles and climate transformation must not be disregarded but should not distract from the main goals. As a result, the assessment undertaken for this study has been based on imperfect data and the confidence in the results should reflect that fact. However, this is the same data that are often relied on in relatively rapid water resource analyses.

The data required to apply the WS risk assessment methods discussed are all readily available and can be applied without complex software and analytical methods. A differential adjustment to the framework could be made on the monthly flows based on local knowledge; this would involve a superior degree of hydrological knowledge and inclusive consultations with all interested and affected parties.

For this reason, it may be said that the quality of current open-access HIS data available to the public does not comply with the data integrity and differentiation required to further develop indicators to improve the WS risk assessment utilising the DFWS and RRM for the CCT.

The DFWS proved to be a suitable fundamental framework to quantify the human influence and trade-offs on water-associated ecosystems for the CCT. The framework effectively identifies, categorize, measure and model WS over extended timeframes as applied between 2016 and 2026. As a result, the framework demonstrates the necessity of integrated indicators to provide a three-dimensional sub-space representing physical reserve accessibility, infrastructure, economic and political alternatives.

The linked human-water systems models can be applied to predict watershed directions, forecast water in/security, and advise suitable management action. Therefore as expressed the WS risk assessment framework as applied in this research as a combination of the DFWS and the RRM, will positively contribute and assist the CCT to better plan and execute water management decision in the prevention of a future *Day Zero*.

As expressed in the results, it may be concluded that the risk assessment in combination with the WS framework presents a robust approach to constructively add to sustainable administration of water resources. The risk assessment procedure has been successfully applied, both locally and globally, at a range of spatial and temporal scales. The risk assessment effectively identified the threats and risks to specific indicators, empowering stakeholders to consider sustainable social and ecological balance and protection of water resources. In general, the WS risk assessment can provide true transparency in and adaptability of the available alternatives for water management.

Therefore, this very flexible instrument allows for speedy interpretation of additional evidence, which will advise adaptive management and lower uncertainty related to correctness of forecasts. Stakeholders are presented with evidence-based probabilistic projections to consider water resource use alternatives. The WS risk assessment is holistic, evidence-based, transparent, adaptable and suitable for application on multiple spatial and temporal scales.

The key to future WS for the CCT is competent and adequate long-term planning to which this research can contribute significantly. Further, it is recommended that the CCT’s water supply should be made even more secure by investing in technology and resources that are less susceptible to drought and more proactive in terms of urban growth management.

Further recommendations would be to be less dependent on surface water resources, adopting a water sensitive approach to town planning and redevelopment, and the exploration of interventions to promote and actively encourage behaviour change and address inequality. The WS risk assessment can positively contribute through better engagement with other fields and disciplines; it will enable suitable social, economic, and environmental criteria to be used when deciding on practical solutions.

These recommendations can be summarised by a new paradigm that entrenches water sustainability and resilience in everyday habits of safeguarding water systems and decreasing the environmental footprint of the population.

Since rivers largely cross political boundaries, water management is every so often managed in water management areas that are isolated from politicians and their electorate. A case in point is the CCT which draws water from two major rivers beyond its boundaries, each of which is managed by a different agency.

While water demands increase and water systems evolve, additional assets will be required for monitoring, data capture and modelling. Technical support integrated into political processes will enable politicians to be aware of the efficacy and validity of management data, modelling, and risks. Information must be in a format and language that empowers all interested and affected parties to act appropriately. Collaboration between hydrologists, experts from the social sciences and humanities, economics, policy and law, will enable development of water-management tools that decision makers and the public can understand and use.

Specialist practitioners additionally ought to observe and model societies' water use patterns and behaviour. This will contribute to a better understanding of the extended timescales required for effective decisions and sustainable interventions and resist the simplistic solutions of WD/WCM by relying on the inconsistencies of climate and natural infrastructure.

Some of the more long-term benefits I derived from this study include a better self-awareness, a willingness to allow my perspective to be influenced by alternative paradigms, the discernment of methodical triangulation of data, and the language of academic writing.

In conclusion, I have to confess that time management and consistency of the research process suffered because of incomplete planning and procrastination. This resulted in re-writing of some sections of the thesis a number of times as new literature became available at critical junctures of the process, which if excluded would have detracted from the quality of the work.

REFERENCES

FAO *see* Food and Agricultural Organisation of the United Nations.

OECD *see* Organisation for Economic Co-operation and Development.

RSA see Republic of South Africa.

SADC *see* South African Development Community.

Stats SA *see* Statistics South Africa.

UNESCO *see* United Nations Educational, Scientific and Cultural Organisation.

UNISDR *see* Unites Nations Office for Disaster Risk Reduction.

USEPA see United States Environmental Protection Agency.

WHO/UNICEF *see* World Health Organisation and United Nations Children's Fund.

WIAG see WHYCOS International Advisory Group.

WRI *see* World Resources Institute.

WWAP *see* United Nations World Water Assessment Programme.

Alavi, M. & Carlson, P. 1992. A review of MIS research and disciplinary development. *Journal of Management Information Systems,* 8(1):45-62.

Albrecht, T.R., Crootof, A. & Scott, C.A. 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, 13(4):1-26. 10.1088/1748-9326/aaa9c6.

Allain, S., Ndong, G.O., Lardy, R. & Leenhardt, D. 2018. Integrated assessment of four strategies for solving water imbalance in an agricultural landscape. *Agronomy for sustainable development*, 38(6):1-12.

Al-Saadi, H. 2014. *Demystifying ontology and epistemology in research methods,* Sheffield: University of Sheffield.

Avinash, N.V. 1980. *Theory of International Trade: A dual, general equilibrium approach*. Cambridge University Press, 2.

Ayre, K. & Landis, W. 2012. A Bayesian approach to landscape ecological risk assessment applied to the Upper Garnde Ronde Watershed, Orgeon. *Human and Ecological Risk Assessment: An International Journal,* 18(5):946-970.

Bailey, A. & Pitman, W. 2016. *Water Resources of South Africa, 2012 Study (WRC2012).* Water Research Commission.

Bakker, K. 2012. Water: Political, biopolitical, material. *Social Studies of Science,* 42(4):616-623.

Barnard, M. 2017. Vingers nou gewys oor kanale in W-Kaap. *Die Burger*. Aug 4:10.

Barnard, M. 2018. Watertariewe drasties verhoog. *Die Burger*. Jan 20:4.

Barnes, J. 2016. Rifts or bridges? Ruptures and continuities in human-environment interactions. *RCC Perspectives: Transformations in Environment and Society,* 2(1):41-46.

Batchelor, C. 2007. *Water governance literature assessment*. Report contributing to the scoping exercise managed by IIED to help develop a DFID research programme on water ecosystems and poverty reduction under climate change. G02523. International Institute for Environment and Development.

Beck, H.E., Van Dijk, A.I., De Roo, A., Miralles, D.G., McVicar, T.R., Schellekens, J. & Bruijnzeel, L.A. 2016. Global-scale regionalisation of hydrologic model parameters. *Water Resources Research*, 52(5):3599-3622.

Bell, E., Bryman, A. & Harley, B. 2018. *Business research methods*. 5th ed. Oxford University Press.

Bhat, A. 2019. *Research design: Definition, characteristics and types.* [Online]. Available at: https://www.questionpro.com/blog/research-design/ [Accessed: 14 September 2019].

Blaikie, N. 2010. *Designing social research: The logic of anticipation*. 2nd ed. UK: Polity Press. ISBN: 978-0-745-69936-3.

Bogardi, J., Spring, U.O. & Brauch, H.G. 2016. Water security: Past, present and future of a controversial concept. In: Pahl-Wostl, C. (ed.), *Water security.* Massachusetts: Edward Elgar, 38.

Bohatch, T. 2017. *What's causing Cape Town's water crisis? Population growth, drought and climate change threaten the city's water supply*. GroundUp. [Online]. Available at: https://www.groundup.org.za/article/whats-causing-cape-towns-water-crisis/ [Accessed: 10 May 2017].

Boonzaaier, D. 2018. Wes-Kaap: Verliese weens droogte styg. *Rapport Sake.* Mar 4:3.

Bourblanc, M. & Blanchon, D. 2018. Political ecologies of water in South Africa: A literature review. *WIREs Water,* 6(5):1-14.

Brandt, K. 2018. Day Zero brought forward, CT officials prepare for worst. *Eyewitness News (EWN)*. Jan. 23.

Breytenbach, J. 2017. Waterheffing: Kapenaars maak stem dik. *Die Burger.* Sep 22:8.

Brown, A. & Matlock, M. 2011. *A review of water scarcity indices and methodologies.* Arkansas: Sustainability Consortium.

Bryman, A. 2012. *Social research methods.* 4th ed. New York :Oxford University Press.

Burton, G.A., Chapman, P.M. & Smith, E.P. 2002. Weight-of-evidence approaches for assessing ecosystem impairment. *Human and Ecological Risk Assessment*, 8(7):1657-1673.

Cameron, R. & Katzschner, T. 2016. Every last drop: the role of spatial planning in enhancing integrated urban water management in the City of Cape Town. *South African Geographical Journal*, 99(2):1-21. doi:10.1080/03736245.2016.1231622.

Carter, N.H., Andrés, V., Hull, V. & McConnell, W.J. 2014. Coupled human and natural systems approach to wildlife research and conservation. *Ecology and Society,* 19(3):43.

Chaves, H. 2014. Assessing water security with appropriate indicators: Challenges and recommendations. *Proceedings.* The GWP Workshop: Assessing Water Security with Appropriate Indicators, 1-113. Global Water Partnership.

Chaves, H. & Alipaz, S. 2007. An integrated indicator for Basin hydrology, environment, life, and policy: The Watershed Sustainability Index. *Water Resource Management,* 21:883-895. https://doi.org/10.1007/s11269-006-9107-2.

Chen, J.C. & Landis, W.G. 2005. Using the Relative Risk Model for a regional-scale ecological risk assessment of the Squalicum Creek watershed. In: Landis, W.G. (ed.), *Regional-scale ecological risk assessment: Using the Relative Risk Model*. Boca Raton, USA: CRS Press, 195-230.

Chevalier, M. & Chase, B.M. 2016. Determining the drivers of long-term aridity variability: A Southern African case study. *Journal of Quaternary Science*, 31(2):143-151.

City of Cape Town. 2016/17. *Integrated Annual Report*. [Online]. Available at: https://resource.capetown.gov.za/documentcentre/Documents/City%20research%20reports%20and%20review/Annual%20Report%202016_17.pdf. [Accessed: 16 September 2018].

City of Cape Town. 2017a. *Think water: Our shared water future*. [Online]. Available at: https://coct.co/water-dashboard/ [Accessed: 2 November 2018].

City of Cape Town. 2017b. *Reconciliation strategy for the Western Cape water supply system.* Department of Water & Sanitation. [Online]. Available at: http://www.dwa.gov.za/Projects/RS_WC_WSS/ [Accessed: 30 June 2019].

City of Cape Town. 2018a. *Water Outlook 2018 Report: Revision 27 – Updated September 2018.* Department of Water and Sanitation, City of Cape Town.

City of Cape Town. 2018b. *Water Outlook 2018 Report: Revision 30.* Department of Water & Sanitation, City of Cape Town.

City of Cape Town. 2019a. *Cape Town Water Strategy: Our shared water future.* Draft for comment. Version 1.6. January 2018. City of Cape Town.

City of Cape Town. 2019b. *City of Cape Town open data portal.* [Online]. Available at: https://web1.capetown.gov.za/web1/OpenDataPortal/ [Accessed: 21 September 2019].

City of Cape Town. 2019c. *Water resilience profile: City water resilience assessment: Cape Town.* [Online]. Available at: https://www.resilienceshift.org/wp-content/uploads/2020/01/Cape_Town_WaterResilienceProfile_FINAL.pdf [Accessed: 22 November 2019].

City of Cape Town. 2020. *Our shared water future: Cape Town's water strategy*. [Online]. Available at: https://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Cape%20Town%20Water%20Strategy.pdf [Accessed: 20 February 2020].

Claassen, M. 2013. Integrated water resource management in South Africa. *International Journal of Water Governance*, 1(3-4):323-338.

Claassen, M., Strydom, W.F., Murray, K. & Jooste, S. 2001. *Ecological risk assessment guidelines*. Pretoria: Water Research Commission.

Climate-Data.org. 2019. *Cape Town climate (South Africa).* [Online]. Available at: https://en.climate-data.org/africa/south-africa/western-cape/cape-town-788/ [Accessed: 21 September 2019].

Cole, N.L. 2019. *Understanding purposive sampling.* Chicago: ThoughtCo.

Colnar, A.M. & Landis, W. 2007. Conceptual model development for invasive species and a regional risk assessment case study: The European Green Crab, Carcinus Maenas, at Cherry Point, Washington, USA. *Human and Ecological Risk Assessment: An International Journal,* 13(1):120-155.

Cook, C. & Bakker, K. 2012. Water security: Debating an emerging paradigm. *Global Environmental Change*, 22(1):94-102.

Cook, C. & Bakker, K. 2016. Water Security: Critical analysis of emerging trends and definitions. In: C. Pahl-Wostl, (ed,), *Water Security.* Massachusetts: Edgar Elgar, 19.

Crossman, A. 2019. *Understanding purposive sampling: An overview of the method and its applications.* [Online]. Available at: https://www.thoughtco.com/purposive-sampling-3026727 [Accessed: 14 September 2019].

Cullis, J.D., Horn, A., Rossouw, N., Fisher-Jeffes, L., Kunneke, M.M. & Hoffman, W. 2019. Urbanisation, climate change and its impact on water quality and economic risks in a water scarce and rapidly urbanising catchment: Case study of the Berg River Catchment. *H2Open Journal*, 2(1):146-167.

Dadson, S., Hall, J.W., Garrick, D., Sadoff, C., Grey, D. & Whittington, D. 2017. Water security, risk, and economic growth: Insights from a dynamical systems model. *Water Resources Research*, 53(8):6425-6438.

Davies, B. & Day, J. 1998. *Vanishing waters.* University of Cape Town Press, 313-315, 339-340.

De Assis, W.D., Ribeiro, M.M.R. & Da Silva, S.R. 2020. Multi-level governance application to a shared river basin. *Brazilian Journal of Water Research*, 25. Epub. https://doi.org/10.1590/2318-0331.252020190164.

De Kock, A. 2018. Kapenaars sink boorgate dat dit klap. *Die Burger.* Dec 9:11.

De Lange, W., Wise, R.M., Forsyth, G.G. & Nahman, A. 2010. Integrating socio-economic and biophysical data to support water allocations within river basins: An example from the Inkomati Water Management Area in South Africa. *Environmental Modelling & Software,* 25(1):43-50. https://doi.org/10.1016/j.envsoft.2009.06.011.

Denzin, N.K. & Lincoln, Y.S. (eds). 2005. *The Sage handbook of qualitative research.* 3rd ed. Thousand Oaks, California, USA: Sage.

Department of Water Affairs. 2010. *Strategic assessment of water re-use potential to augment the Western Cape water supply system.* Pretoria, RSA: Department of Water Affairs.

Department of Water Affairs. 2012. *Proposed National Water Resource Strategy 2 (NWRS 2): Summary: Managing water for an equitable and sustainable future.* [Online]. Available at: https://www.gov.za/sites/default/files/gcis_document/201409/finalwater.pdf [Accessed: 1 August 2020].

Department of Water and Sanitation. 2018. *National Water and Sanitation Master Plan: Volume 2: Plan to Action Version 2: Ready for the future and ahead of the curve.* [Online]. Available at: https://www.dws.gov.za/National%20Water%20and%20Sanitation%20Master%20Plan/Documents/Volume2%20(Printed%20version%20).pdf [Accessed: 1 August 2020].

Department of Water and Sanitation. 2019. *Department of Water and Sanitation 2019/20 Annual Performance Plan; Human Settlements Budget: Committee Report; Legacy reports.* [Online]. Available at: https://pmg.org.za/committee-meeting/28510/ [Accessed: 1 August 2020].

Donohew, Z. 2009. Property rights and western United States water markets. *Australian Journal of Agricultural and Resource Economics*, 53(1):85-103.

Du Toit, D., Pollard, S. & Pejan, R. 2010. A Rights approach to environmental flows: What does it offer. Centre for Environmental Rights. Unpublished.

Dudgeon, D. 2014. Threats to freshwater biodiversity in a changing world. *Global Environmental Change,* 1:243-253.

Dudovskiy, J. 2019. *inductive approach (inductive reasoning).* Business Research Methodology. [Online]. Available at: https://research-methodology.net/research-methodology/research-approach/inductive-approach-2/ [Accessed: 17 June 2020].

DWA Groundwater Dictionary. 2019. *Hydrological year.* [Online]. Available at: http://www.dwa.gov.za/Groundwater/Groundwater_Dictionary/index.html?introduction_hydrological_year.htm [Accessed: 21 September 2019].

El-Gafy, I. 2018. The water poverty index as an assistant tool for drawing strategies of the Egyptian water sector. *Ain Shams Engineering Journal,* 9(1):173-186.

Endo, A., Tsurita, I., Burnett, K. & Orencio, P. 2017. A review of the current state of research on the water, energy, and food nexus. *Journal of Hydrology: Regional Studies,* 11(1):20-30.

Enqvist, J. & Ziervogel, G. 2019. Water governance and justice in Cape Town: An overview. *WIREs water*, 26(5):1-15.

Essop, P. 2018. Metro maak nie sy inwoners bang, sê hoë. *Die Burger.* Feb 8:10.

Esty, D.C., Levy, M., Srebotnjak, T. & De Sherbinin, A. 2005. *Environmental sustainability index: Benchmarking national environmental stewardship.* New Haven: Yale Center for Environmental Law & Policy, 47-60.

European Commission. 2005. *Developing strategies for regulating and managing water resources and demand in water deficient regions: Methodological approach and case studies*. WaterStrategyMan Project, Contract No. EVK1-CT-2001-00098. [Online]. Available at: http://environ.chemeng.ntua.gr/wsm/Uploads/Deliverables/Final/Deliverable_21.5.pdf [Accessed: 4 August 2020].

Falkenmark, M. 1989. The massive water scarcity now threatening Africa: Why isn't it being addressed? *AMBIO,* 18(2):112-118.

Falkenmark, M. 2001. The greatest water problem: The inability to link environmental security, water security and food security. *International Journal of Water Resources Development*, 17(4):539-554.

Falkenmark, M. & Lundqvist, J. 1998. Towards water security: Political determination and human adaption crucial. *Natural Resources Forum,* 22(1):37-51.

Falkenmark, M. & Rockström, J. 2006. The new blue and green water paradigm: Breaking new ground for water resource planning and management. *Journal of Water Resources Planning and Management* 132(3:)129-132.

Ferraro, P., Sanchirico, J. & Smith, M. 2018. Causal interference in coupled human and natural systems. *Proceedings of the National Academy of Sciences USA,* 116(12):5311-5318.

Fiege, K. 2019. *HOW IT'S DONE!* Humboldt-Universität, Berlin. doi:10.18452/20031.

Fischhendler, I. & Nathan, D. 2016. The social construction of water security discourses: Preliminary evidence and policy implications from the Middle East. In: Pahl-Wostl, C., Bhadurim A. & Gupta, J. (eds.), *Handbook on water security*. Edward Elgar. doi:https://doi.org/10.4337/9781782548010.

Fisher-Jeffes, L., Armitage, N. & Carden, K. 2017. The viability of domestic rainwater harvesting in the residential areas of the Liesbeek River Catchment, Cape Town. *Water SA,* 43(1):81-90.

Flower, P. 2017. *Cape Town water resilience*. Presentation. Water and Sanitation Department, 23 June. [Online]. Available at: http://acceleratecapetown.co.za/wp/wp-content/uploads/2017/06/Cape-Town-Water-Resilience-Sarah-Rushmere-CoCT.pdf [Accessed: 16 August 2020].

Flynn, J. 2016. *A business process reengineering framework using the AHP to select an traceability technology for spare parts management in capital-intensive industries.* Master's thesis, Stellenbosch University.

Food and Agricultural Organisation of the United Nations. 2020. *AQUASTAT: Counting every drop.* [Online]. Available at: http://www.fao.org/3/i4203e/i4203e.pdf [Accessed: 17 September 2020].

Funke, N., Nortje, K., Meissner, R. & Steyn, M. & Ntombela, C. 2019. Understanding water security at local government level in South Africa. In: Meissner, R., Funke, N., Nortje, K. & Steyn, M. (eds.), *An analysis of international and South African discourses and perspectives on water security. Cham:* Palgrave Pivot, 45-71.

Gabriel, Y., Gray, D.E. & Goregaokar, H. 2013. Job loss and its aftermath among managers and professionals: Wounded, fragmented and flexible. *Work, Employment and Society*, 27(1):56-72.

Gain, A., Guipponi, C. & Wada, Y. 2016. Measuring global water security towards sustainable development goals. *Environmental Research Letters,* 11(12):1-14.

Galaitsi, S.E., Russell, R., Bishara, A., Durant, J.L., Bogle, J. & Huber-Lee, A. 2016. Intermittent domestic water supply: A critical review and analysis of causal-consequential pathways. *Water*, 8(7):274.

Gallier, R.D. 1991. Choosing appropriate information systems research approaches: A revised taxonomy. In: Nissen, H.-E., Klein, H.K. & Hirschheim, R. (eds.), *Information systems research: Contemporary approaches & emergent traditions*. Amsterdam¸ North-Holland, 327-345.

Gallopin, G. 1997. Indicators and their use: Information for decision making. In: Moldan, B. & Billharz, S. (eds.), *Sustainability Indicators, report on the project on indicators of sustainable development.* Chichester: Wiley, 13-27.

Gareau, B. & Crow, B. 2006. Ken Conca, governing water: Contentious transnational politics and global institution building. *International Environmental Agreements: Politic, Law and Economics,* 6(3):317-320.

GAWSIS. 2020. *Station Information System.* [Online]. Available at: https://gawsis.meteoswiss.ch/GAWSIS/#/. [Accessed: 31 July 2020].

Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M. & Waha, K. 2011. Global water availability and requirements for future food production. *Journal of Hydrometeorology*, 12(5):885-899.

Gleick, P.H. 1990. Global climatic change and international security. *Colorado Journal of International Environmental Law and Policy*, 1(1):41-56.

Gleick, P.H. 2018. Sustainability. *PNAS,* 115(36):8863-8871.

Gleick, P.H. & Cain, N. 2005. The global water crises. *Science and Technology,* 21(4):1-4.

Gleick, P.H., Chalecki, E.L. & Wong, A. 2002. *Measuring water well-being: Water indicators and indices*. Washington, DC: Island Press, 87-112.

Global Water Partnership. 2000. Towards water security: A framework for action. Stockholm, Sweden and London, United Kingdom: GWP. ISBN: 91-630-9202-6.

Göktürk, E. 2009. *What is "paradigm"?* Department of Informatics, University of Oslo, Norway

Grasham, C., Korzenevica, M. & Charles, K. 2019. On considering climate resilience in urban water security: A review of the vulnerability of the urban poor in sub-Saharan Africa. *WIREs Water,* 6(1):1-11.

GreenCape. 2018. *Water: 2018 Market Intelligence Report*. [Online]. Available at: https://www.greencape.co.za/assets/Uploads/GreenCape-Water-MIR-FINAL-20180405.pdf [Accessed: 23 September 2020].

Grey, D. & Sadoff, C. 2007. Sink or swim? Water security for growth and development. *Water Policy,* 9(1):545-571.

Gunda, T., Hess, D., Hornberger, G. & Worland, S. 2019. Water security in practice: The quantity-quality-society nexus. *Water Security,* 6(1):1-6.

Gupta, J., Dellapenna, J.W. & Van den Heuvel, M. 2016. Water sovereignty and security, high politics and hard power: The dangers of borrowing discourses! In: *Handbook on water security*. Cheltenham: Edward Elgar, 120-136.

Habitat Conservation Trust Fund. (2003) *Mission creek sustainable watershed indicators workbook*. British Columbia: 22.

Hall, J. & Borgomeo, E. 2013. Risk-based principles for defining and managing water security. *Philosophical Transactions of the Royal Society,* 371(1):1-22.

Hammond, M.J., Chen, A.S., Djordjević, S., Butler, D. & Mark, O. 2015. Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12(1):14-29.

Harrington, C. 2013. *Fluid identities: Toward a critical security of water*. Electronic Thesis and Dissertation Repository. 1716. https://ir.lib.uwo.ca/etd/1716.

Hay, D., Breen, C. & Nkhata, B. 2014. Water security: A complex, messy and wicked business. *Water Wheel*, 13(5):34-36.

Hay, L.E. & McCabe, G.J. 2010. Hydrologic effects of climate change in the Yukon River Basin. *Climatic Change*, 100(3):509-523.

Hayes, E.H. & Landis, W.G. 2004. Regional ecological risk assessment of a near shore marine environment: Cherry Point, WA. *Human and Ecological Risk Assessment*, 10(2):299-325.

Heaps, C., Kemp-Benedict, E. & Raskin, P. 1998. *Conventional worlds: Technical description of bending the curve scenarios.* Polestar Series Report No. 9. Stockholm Environment Institute.

Hering, J. & Ingold, K. 2012. Water resources management: What should be Integrated? *Water Management,* 336(6086):1234-1235.

Hirschheim, R. 1985. *Information systems epistemology: A historical perspective.* London School of Economics.

Hoekstra, A.Y. 2008. The water footprint of food. In: Förare, J. (ed.), *Water for food*. The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, 49-61.

Hoekstra, A.Y., Buurman, J. & Van Ginkel, K. 2018. Urban water security: A review. *Environmental Research Letters,* 13(5):1-18.

Hoekstra, A.Y. & Mekonnen, M.M. 2011. The water footprint of humanity. *Proceedings of the Natural Academy Sciences,* 109(9):3232-3237.

Hoff, H. 2011. Understanding the nexus. *Background paper.* The Bonn 2011 Conference: The Water, Energy and Food Security Nexus, Stockholm Environment Institute, Stockholm, Bonn. DiVA.

Howlett, M.P. & Cuenca, J.S. 2017. The use of indicators in environmental policy appraisal: Lessons from the design and evolution of water security policy measures. *Journal of Environmental Policy & Planning*, 19(2):229-243.

HydroNet. 2020. *South African Weather Service: Satellite image*. [Online]. Available at: https://www.weathersa.co.za/home/satelliteimg [Accessed: 4 October 2020].

Isaacs, L. 2018. #WaterCrisis: 1990 article shows Day Zero plans should’ve began years ago. IOL. [Online]. Available at: https://www.iol.co.za/capetimes/news/watercrisis-1990-article-shows-day-zero-plans-shouldve-began-years-ago-13044464 [Accessed: 24 June 2019].

Ismail, A. 2018. State ignored water alarm bells for 47 years. *Cape Argus.* Jan 25:12.

Jack, C., Wolski, P., Steynor, A. & Lennard, C. 2016. *Climate change projections for the City of Cape Town: An update based on the most recent science,* Cape Town: CSAG UCT.

Jacobs, S., Martín-López, B., Barton, D.N., Dunford, R., Harrison, P.A., Kelemen, E., Saarikoski, H. et al. 2018. The means determine the end–pursuing integrated valuation in practice. *Ecosystem Services*, 29:515-528.

Jaeger, W.K., Amos, A., Conklin, D.R., Langpap, C., Moore, K. & Plantinga, A.J. 2019. Scope and limitations of drought management within complex human–natural systems. *Nature Sustainability*, 2(8):710-717.

Jensen, O. & Wu, H. 2018. Urban water security indicators: Development and plot. *Environmental Science and Policy,* 83(1):33-455.

Jepson, W., Budds, J., Eichelberger, L., Harris, L., Norman, E., O’Reillya, K., Pearson, A. et al. 2017. Advancing human capabilities for water security: A relational approach. *Water Security,* 1:46-52. doi:10.1016/j.wasec.2017.07.001.

Keskinen, M., Guillaume, J.H., Kattelus, M., Porkka, M., Räsänen, T.A. & Varis, O. 2016. River basins // The water-energy-food nexus and the transboundary context: Insights from Large Asian Rivers. *Water*, 8:193.

Kleinberg-Levin, D.M. 1988. *The opening of vision: Nihilism and the postmodern situation.* Routledge, Taylor & Francis.

Koopman, M. & De Buys, A. 2017. *What do long-term data reveal about Cape Town’s water shortage?* Cape Town: NRF South African Environmental Observation Network.

Kretzmann, S. & Joseph, R. 2020. *Coca-Cola and Cape Town's sweetheart Day Zero deal.* Cape Town: Bizcommunity.

Kuhn, T.S. 1962. *The structure of scientific revolutions.* University of Chicago Press: Chicago.

Kuhn, T.S. 1977. Objectivity, value judgment, and theory choice. In the essential tension: Selected studies in scientific tradition and change. In: *The essential tension*. Chicago: University of Chicago Press, 320-339. https://doi.org/10.7208/9780226217239-014.

Kumar, P. 2011. Typology of hydrologic predictability. *Water Resources Research,* 47*(*22):1-9.

Lall, S., Henderson, J. & Venables, A. 2017. *Africa's cities opening doors to the world.* Washington: World Bank.

Landis, W.G. & Thomas, J.F. 2009. Regional risk assessment as a part of the long-term receiving water study. *Integrated Environmental Assessment and Management: An International Journal*, 5(2):234-247.

Landis, W.G. and Wiegers, J.A. 1997. Design considerations and a suggested approach for regional and comparative ecological risk assessment. *Human and Ecological Risk Assessment*, 3(3):287-297.

Landis, W.G. and Wiegers, J.K. 2005. Introduction to the regional risk assessment using the Relative Risk Model. In: Landis, W.G. (ed.), *Regional-scale ecological risk assessment using the Relative Risk Model.* Boca Raton (FL): CRC, 11-36.

Landis, W.G. & Wiegers, J. 2007. Ten years of Relative Risk Model and regional-scale ecological risk assessments. *Human Ecological Risk Assessment,* 13:25-38.

Landis, W.G., Luxon, M. & Bodensteiner, L.R. 2000. Design of a relative risk model regional-scale risk assessment with confirmational sampling for the Willamette and McKenzie Rivers, Oregon. In: *Environmental toxicology and risk assessment: Recent achievements in environmental fate and transport: Ninth Volume*. ASTM International.

Landis, W.G., Markiewicz, A.J., Ayre, K.K., Johns, A.F., Harris, M.J., Stinson, J.M. & Summers, H.M. 2017. A general risk-based adaptive management scheme incorporating the Bayesian Network Relative Risk Model with the South River, Virginia, as case study. *Integrated Environmental Assessment and Management*, 13(1):115-126.

Lawrence, P.R., Meigh, J. & Sullivan, C. 2002. *The Water Poverty Index: An international comparison*. Keele, Staffordshire, UK: Department of Economics, Keele University.

Lehtonen, M. 2015. Indicators: Tools for informing, monitoring or controlling? In: Jordan, A.J. & Turnpenny, J.R. (eds.), *The tools of policy formulation: Actors, capacities, venues and effects. New horizons in public policy*. Cheltenham, UK and Northampton, MA, USA: Edward Elgar, 76-99. ISBN: 9781783477036.

Li, X., Su, X. & Wei, Y. 2019. Multistage integrated water security assessment in a typical region of Northwestern China. *Journal of Cleaner Production*, 220:732-744.

Liersch, S., Fournet, S., Koch, H., Djibo, A.G., Reinhardt, J., Kortlandt, J., Van Weert, F. et al. 2019. Water resources planning in the Upper Niger River basin: Are there gaps between water demand and supply? *Journal of Hydrology: Regional Studies*, 21:176-194. https://doi.org/10.1016/j.ejrh.2018.12.006.

Lindhe, A. 2008. *Integrated and probabilistic risk analysis of drinking water systems*. Thesis, Chalmers University of Technology, Göteborg, Sweden.

Lindhe, A. 2010. *Risk assessment and decision support for managing drinking water systems*. Doctoral Thesis, Chalmers University of Technology.

Link, P.M., Scheffran, J. & Ide, T. 2016. Conflict and cooperation in the water-security nexus: A global comparative analysis of river basins under climate change. *Wiley Interdisciplinary Reviews: Water*, 3(4):495-515.

Liu, J., Folberth, C., Yang, H., Röckström, J., Abbaspour, K. & Zehnder, A.J. 2013. A global and spatially explicit assessment of climate change impacts on crop production and consumptive water use. *PLoS One*, 8(2):e57750.

Liu, J., Liu, Q. & Yang, H. 2016. Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. *Ecological indicators*, 60:434-441.

Liu, J., Scanlon, B.R., Zhuang, J. & Varis, O. 2020. Food-energy-water nexus for multi-scale sustainable development. *Resources, Conservation & Recycling,* 154:104565.

Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N. et al. 2017. Water scarcity assessments in the past, present, and future. *Earth's Future*, 5(6):545-559.

Lotz-Sisitka, H., Ali, M.B., Mphepo, G., Chaves, M., Macintyre, T., Pesanayi, T., Wals, A. 2016. Co-designing research on transgressive learning in times of climate change. *Current Opinion in Environmental Sustainability*, 20:50-55.

Luker, E. & Rodina, L. 2017. *The future of drought management for Cape Town: Summary for policy makers.* Vancouver: University of British Columbia.

Mahlanza, L., Ziervogel, G. & Scott, D. 2016. Water, rights and poverty: An environmental justice approach to analysing water management devices in Cape Town. *Urban Forum,* 27(1):363-382.

Malaza, N. & Maduba, A.I. 2019. Challenges of integrated water resources management in the Western Cape Province, South Africa. *Journal of Water Resources and Ocean Science,* 8(2):9-20.

Mannan, M., Al-Ansari, T., Mackey, H.R. & Al-Ghamdi, S.G. 2018. Quantifying the energy, water and food nexus: A review of the latest developments based on life-cycle assessment. *Journal of Cleaner Production*, 193:300-314.

Marais, C., Van Wilgen, B.W. & Stevens, D. 2004. The clearing of invasive alien plants in South Africa: A preliminary assessment of costs and progress: Working for water. *South African Journal of Science*, 100(1):97-103.

Mariño, M. 2017. *Cape Town Water Crises 2017 analysis from international experience*. [Online]. Available at: http://resource,capetown,gov,za/documentcentre/Documents/Cityresearchreportsandreview/2017CapeTownWaterCrisesAnalysisReport.pdf [Accessed: 14 April 2019].

Marques, É.T., Gunkel, G. & Sobral, M.C. 2019. Management of tropical river basins and reservoirs under water stress: Experiences from Northeast Brazil. *Environments*, 6(6):62.

Marttunen, M., Mustajoki, J., Sojamo, S., Ahopelto, L. & Keskinen, M. 2019. A framework for assessing water security and the water–energy–food nexus—The case of Finland. *Sustainability*, 11(10):2900.

May, A. 2018. City's sights on Day Zero. *Cape Argus.* Jan 29:1.

McCraine, S., Anderson, C., Weber, C. & Shaw, M.R. 2019. The nature of risk: A framework for understanding nature-related risk to business. World Wildlife Fund (WWF). [Online]. Available at: https://c402277.ssl.cf1.rackcdn.com/publications/1255/files/original/WWF_Nature_of_Risk.FINAL2.pdf?1568216828 [Accessed: 25 February 2020].

McNabb, D. 2019. *Global pathways to water sustainability.* ebook ed. s.l.: Springer.

Meigh, J., McKenzie, A. & Sene, K. 1999. A grid-based approach to water scarcity estimates for Eastern and Southern Africa. *Water Resources Management,* 13(1):85-115.

Meissner, R. & Jacobs, I. 2016. Theorising complex water governance in Africa: The case of the proposed Epupa Dam on the Kunene River. *International Environmental Agreements: Politics, Law and Economics*, 16(1):21-48.

Meissner, R., Funke, N., Nortje, K., Jacobs-Mata, I., Moyo, E., Steyn, M., Shadung, J. et al. 2018a. Water security at local government level in South Africa: A qualitative interview-based analysis. *The Lancet Planetary Health*, 2*:*S17.

Meissner, R., Steyn, M., Moyoa, E., Shadunga, J., Masanganea, W., Nohayia, N. & Jacobs-Mataa, I. 2018b. South African local government perceptions of the state of water security. *Environmental Science & Policy,* 87:112-127.

Mekonnen, M.M. & Hoekstra, A.Y. 2010. *The green, blue and grey water footprint of farm animals and animal products, Volume 1: Main Report.* Value of water Research Report Series No. 48*.* Delft: UNESCO-IHE Institute for Water Education.

Mekonnen, M.M. & Hoekstra, A.Y. 2016. Four billion people facing severe water scarcity. *Science Advances,* 2(2):1-6.

Meyer, W. 2018. Rampbestuur van vandag operasioneel. *Die Burger.* Jan 29:4.

Mitchell, G. 1996. Problems and fundamentals of sustainable development indicators. *Sustainable Development*, 4(1):1-11.

Midgley, G.F., Chapman, R.A., Hewitson, B., Johnston, P., De Wit, M., Ziervogel, G., Mukheibir, P. et al. 2005. *A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the Western Cape*. CSIR Report No. ENV-S-C 2005-073, Stellenbosch.

Mills, G., Hamukoma, N. & Doyle, N. 2019. *Cape Town: A tale of transitions*. Johannesburg, South Africa: The Brenthurst Foundation.

Molle, F. 2008. Nirvana concepts, narratives and policy models: Insights from the water sector. *Water Alternatives,* 1(1):131-156.

Molle, F. & Mollinga, P. 2003. Water poverty indicators: Conceptual problems and policy issues. *Water Policy,* 5(5-6):529-544. doi:10.2166/wp.2003.0034.

Moraes, R., Landis, W.G. & Molander, S. 2002. Regional risk assessment of a Brazilian rain forest reserve. *Human and Ecological Risk Assessment*, 8(7):1779-1803.

Movik, S., Mehta, L., Van Koppen, B. & Denby, K. 2016. Emergence, interpretations and translations of IRWM in South Africa. *Water Alternatives,* 9(3):456-472.

Mukheibir, P. & Ziervogel, G., 2006. *Framework for adaptation to climate change in the City of Cape Town*. Climate Systems Analysis Group, University of Cape Town (CSAG).

Muller, M. 2014*. Water security: Towards a values based approach*. Technical Report. World Economic Forum – Global Agenda Council on Water Security.

Muller, M. 2017. Understanding the origins of Cape Town's water crises: Water engineering. *Civil Engineering*, 1(6):11-16.

Muller, M. 2018. Cape Town's drought: Don't blame climate change. *Nature,* 559(7713):174-176.

Muller, M. 2019. South Africa's real water crisis: Not understanding what's needed. *Mail & Guardian.* 7 Nov.

Muller, M., Schreiner, B., Smith, L., Van Koppen, B., Sally, H., Aliber, M., Cousins, B. et al. 2009. *Water security in South Africa*. Development Planning Division. Working Paper Series, 12. DBSA: Midrand.

Murray, K. & Claassen, M. 1999. Interpretation and evaluation of the US Environmental Protection Agency ecological risk assessment guidelines. *Water SA*, (4):513-518.

Nagendra, H., Bai, X., Brondizio, E. & Lwasa, S. 2018. The urban south and the predicament of global sustainability. *Nature Sustainability,* 1(1):341-349.

Narain, V., Khan, M.S.A., Sada, R., Singh, S. & Prakash, A. 2013. Urbanisation, peri-urban water (in) security and human well-being: A perspective from four South Asian cities. *Water international*, 38(7):930-940.

Nel, C. 2018. Wes-Kaap se krieket seisoen word deur droogte uitgeboul. *Die Burger.* Feb 2:4.

Newkirk II, V.R. 2018. *Cape Town is an omen: Climate change is going to revolutionise politics in Cities across the world.* [Online]. Available at: https://www.theatlantic.com/science/archive/2018/09/cape-south-south-africa-water-crisis/569317/ [Accessed: 4 August 2019].

News24. 2018. Panic and blame as Cape Town braces for water shut-off. 28 Jan. [Online]. Available at: https://www.news24.com/SouthAfrica/News/panic-and-blame-as-cape-town-braces-for-water-shut-off-20180128. [Accessed: 11 August 2019].

Nienaber, M. 2018. Droogte tot nasionale ramp verklaar. *Die Burger.* Feb 14:9.

Nienaber, S. 2017. Gearing green business. *Water & Sanitation Africa*, 12(4):9-11.

Norman, E.S., Dunn, G., Bakker, K., Allen, D.M. & De Albuquerque, R.C. 2013. Water security assessment: Integrating governance and freshwater indicators. *Water Resources Management*, 27(2):535-551.

Obery, A.M. & Landis, W.G. 2002. A regional multiple stressor risk assessment of the Codorus Creek watershed applying the relative risk model. *Human and Ecological Risk Assessment: An International Journal*, 8(2):405-428.

O’Brien, C.G. 2012. *Regional-scale risk assessment methodology using the relative risk model as a management tool for aquatic ecosystems in South Africa*. Doctoral Thesis, University of Johannesburg.

O’Brien, G.C. & Wepener, V. 2012. Regional-scale risk assessment methodology using the Relative Risk Model (RRM) for surface freshwater aquatic ecosystems in South Africa. *Water SA*, 38(2):153-166.

O'Brien, G.C., Dickens, C., Hines, E., Wepener, V., Stassen, R., Quayle, L., Fouchy, K. et al. 2018. A regional-scale ecological risk framework for environmental flow evaluations. *Hydrology and Earth System Sciences*, 22(2):957-975.

Office of the High Commissioner of Human Rights. 2000. *United Nations Millennium Declaration: General Assembly Resolution 55/2 of 8 September 2000*. [Online]. Available at: https://www.ohchr.org/EN/ProfessionalInterest/Pages/Millennium.aspx [Accessed: 24 August 2020].

Okedi, J. 2019. *The prospects for stormwater harvesting in Cape Town, South Africa using the Zeekoe Catchment as a case study*. PhD Thesis, University of Cape Town. http://hdl.handle.net/11427/30453.

Ololade, O.O., Esterhuyse, S. & Levine, A.D. 2017. The water-energy-food nexus from a South African perspective. In: *Water-Energy-FoodNexus: Principles and practices.* John Wiley & Sons, 129.

Olsen, M.E., Lodwick, D.G. & Dunlap, R.E. 1992. Viewing the world ecologically. *Bulletin of Science, Technology & Society*, 13(4): 245-246. https://doi.org/10.1177/027046769301300491.

Organisation for Economic Co-operation and Development. 2001. *OECD environmental indicators 2001: Towards sustainable development*. OECD.

Organisation for Economic Co-operation and Development. 2018. *Implementing the OECD principles on water governance: Indicator framework and evolving practices*. Paris: OECD. http://dx.doi.org/10.1787/9789264292659-en.

Otto, F.E., Wolski, P., Lehner, F., Tebaldi, C., Van Oldenborgh, G.J., Hogesteeger, S., Singh, R. et al. 2018. Anthropogenic influence on the drivers of the Western Cape drought 2015-2017. *Environmental Research Letters*, 13(12):124010.

Padowski, J.C., Gorelick, S.M., Thompson, B.H., Rozelle, S. & Fendorf, S. 2015. Assessment of human–natural system characteristics influencing global freshwater supply vulnerability. *Environmental Research Letters*, 10(10):104014.

Pahl-Wostl, C., Bhaduri, A. & Gupta, J. 2016. *Handbook on water security.* Edward Elgar.

Palmer, M., Bernhardt, E., Chornesky, E., Collins, S., Dobson, A., Duke, C., Gold, B. et al. 2004. Ecology for a crowded planet. *Science,* 304(5675): 1251-1252. doi:10.1126/science.1095780.

Parks, R., Mclaren, M., Toumi, R. & Rivett, U. 2019. *Experiences and lessons in managing water from Cape Town,* London: Imperial College Grantham Institute.

Parliamentary Monitoring Group. 2018. *Water and Sanitation & Trans Caledon Tunnel Authority deviations & expansions: Hearing with Minister.* 6 June. PMG. [Online]. Available at: https://pmg.org.za/committee-meeting/26601/ [Accessed: 24 August 2020].

Patrick, M.J., Elsawah, S., Burgher, I. & Jakeman, A.J. 2016. Australian water security: A water–food–environment–energy nexus perspective. In: Claudia Pahl-Wostl, C., Bhaduri, A. & Gupta, J. (eds.), *Handbook on water security*. Edward Elgar.

Pengelly, C., Seyler, H., Fordyce, N., Van Vuuren, P.J., Van Der Walt, M., Van Zyl, H. & Kinghorn, J. 2017. *Managing water as a constraint to development with decision-support tools that promote integrated planning: The case of the Berg Water Management area.* Water Research Commission.

Pires, A., Morato, J., Peixoto, H., Botero, V., Zuluaga, L. & Figueroa, A. 2017. Sustainability assessment of indicators for integrated water resources management. *Science of the Total Environment*, 578:139-147.

Pitt, C. 2018. *City of Cape Town relaxes water restrictions, tariffs to Level 5.* News24. 10 Sep. [Online]. Available at: https://www.news24.com/news24/SouthAfrica/News/city-of-cape-town-relaxes-water-restrictions-tariffs-to-level-5-20180910. [Accessed: 10 September 2018].

Pohl, B., Carius, A., Conca, K., Dabelko, G., Kramer, A., Michel, D., Schmeier, S. et al. 2014. *The rise of hydro-diplomacy: Strengthening foreign policy for transboundary waters.* Berlin: adelphi.

Poplak, R. 2018. What’s actually behind Cape Town’s water crisis: Blame austerity-obsessed technocrats, irresponsible development, and wilful ignorance. *The Atlantic.* Feb 15:15.

Raskin, P. 1997. *Water Futures: Assessment of long-range patterns and problems. Comprehensive assessment of the freshwater resources of the world.* The Stockholm Environmental Institute, Stockholm, Sweden.

Rawlins, J. 2019. Political economy of water reallocation in South Africa: Insights from the Western Cape water crisis. *Water Security*, 6*:*100029.

Reed, M. & Bruyneel, S. 2010. Rescaling environmental governance, rethinking the state: A three-dimensional review. *Progress in Human Geography,* 34(5):646-653.

Republic of South Africa. 1998. National Water Act No. 36 of 1998. *Government Gazette,* 398(19182): Oct.10.

Research and Markets Report. 2019. *Global Environmental Sustainability Index 2019: Rank 97 Markets – Which in 2018 Represented 89.1% of the World's Population and 97.2% of Global GDP.* Dublin: Globe Newswire.

Rockström, J., Steffen, W. & Foley, J. 2009. A safe operating space for humanity. *Nature,* 461(1):472-45.

Rodina, L. & Findlater, K.M. 2018. *What can other cities learn about water shortages from Day Zero?* The Conversation. [Online]. Available at: https://theconversation.com/what-can-other-cities-learn-about-water-shortages-from-day-zero-98996 [Accessed: 31 January 2019].

Rohli, R.V., Joyner, T.A., Reynolds, S.J., Shaw, C. & Vázquez, J.R. 2015. Globally extended Köppen–Geiger climate classification and temporal shifts in terrestrial climatic types. *Physical Geography*, 36(2):142-157. https://doi.org/10.1080/02723646.2015.1016382.

Rushforth, R. & Ruddell, B. 2016. The vulnerability and resilience of a city's water footprint: The case of Flaggstaff, Arizona, USA. *Water Resources Research,* 52(1):2698-2714.

Saal, P. 2018. Cape Town's 'day zero' for water is pushed back to April 16. *Business Day.* Jan 30.

Sadoff, C.W., Hall, J.W., Grey, D., Aerts, J.C.J.H., Ait-Kati, M., Brown, C., Cox, A. et al. 2015. *Securing water, sustaining growth.* Report of the GWP/OECD Task Force on water security and sustainable growth. Oxford, UK: University of Oxford. https://hdl.handle.net/10568/82685.

Saunders, M.N., Lewis, P. & Thornhill, A. 2012. *Research methods for business students.* 5th ed. Harlow: Prentice Hill.

Saunders, M.N., Lewis, P., Thornhill, A. & Bristow, A. 2019. Understanding research philosophy and approaches to theory development. In: *Research methods for business students*. Pearson Education.

Savage, C. 1991. Middle east water. *Asian Affairs*, *22*(1):3-10.

Savenije, H.H.G. 2000. Water scarcity indicators: The deception of the numbers. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 25(3):199-204.

Savenije, H.H.G. & Van der Zaag, P. 2002. Water as an economic good and demand management paradigms with pitfalls. *Water International*, 27(1):98-104.

Schiermeier, Q. 2018. Droughts, heat waves and floods: How to tell when climate change is to blame. *Nature,* 560(1):20-22.

Schimpf, C. & Cude, C. 2020. A systematic literature review on water insecurity from an Oregon Public Health perspective. *International Journal of Environmental Research and Public Health*, 17(3):1122.

Schoeman, L. & Marais, J. 2018. Wynkarweier nou straks waterboer. *Die Burger.* Jan 30:4.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Äijälä, M. et al. 2018. Impact on short-lived climate forcers increases projected warming due to deforestation. *Nature Communications*, 9(1):1-9.

Seckler, D., Amarasinghe, U., Molden, D., De Silva, R. & Barker, R. 1998. *World water demand and supply, 1990 to 2025: Scenarios and issues*. Colombo, Sri Lanka: International Irrigation Management Institute (IIMI). doi:http://dx.doi.org/10.3910/2009.019.

Shalamzari, M.J. & Zhang, W. 2018. Assessing water scarcity using the Water Poverty Index (WPI) in Golestan province of Iran. *Water*, 10(8):1079.

Sharma, S. & Vairavamoorthy, K. 2009. Urban water demand management: prospects and challenges for the developing countries. *Water and Environment,* 23(3):210-218.

Sheppard, E. & McMaster, R. 2004. Introduction: Scale and geographic inquiry. In: E. Sheppard, E. & McMaster, R. (eds.), *Scale and geographic inquiry: Nature, society, and Method.* Blackwell, 1-22.

Siebrits, R., Winter, K. & Jacobs, I. 2014. Water research paradigm shifts in South Africa. *South African Journal of Science,* 110(5/6):1-9.

Simpson, G. & Jewitt, G. 2019. The development of the water-energy-food nexus as a framework for achieving resource security: A review. *Frontiers in Environmental Science,* 7(8):1-9.

Simpson, N.P., Shearing, C.D. & Dupont, B. 2019. Climate gating: A case study of emerging responses to Anthropocene risks. *Climate Risk Management*, 26:1-10. https://doi.org/10.1016/j.crm.2019.100196.

Sinclair-Smith, K. & Winter, K. 2018. Water demand management in Cape Town: Managing Water security in a changing climate. In: Scott, D., Davies, H & New, M. (eds.), *Mainstreaming climate change in urban development: Lessons for Cape Town.* Cape Town: Juta, 352.

Sivapalan, M. & Blöschl, G. 2015. Time scale interactions and the coevolution of humans and water. *Water Resources Research*, 51(9):6988-7022.

Smith, L. 2004. The murky waters of the second wave of neoliberalism: Corporatisation as a service delivery model in Cape Town. *Geoforum,* 35(3):375-393.

Snape, D. & Spencer, L. 2003. *The foundations of qualitative research.* Manchester: Manchester Metropolitan University.

Somlyódy, L. & Varis, O. 2006. Freshwater under pressure. *International Review for Environmental Strategies*, 6(2):181-204.

South African Development Community. 2016. SADC regional situation update on El Niño-induced drought. *SADC News Bulletin.* May 15:1.

South African Weather Service. 2017. Scientific meteorological and climatological news from the South African Weather Service: August 2017. WEATHERSMART News. [Online]. Available at: https://www.weathersa.co.za/Documents/Corporate/WeatherSmartNewsAugust2017.pdf [Accessed: 21 October 2020].

Srinivasan, V., Konar, M. & Sivapalan, M. 2017. A dynamic framework for water security. *Water Security,* 1(1):1-22.

Srinivasan, V., Seto, K., Emerson, R. & Gorelick, S., 2013. The impact of urbanisation on water vulnerability: A coupled human-environment system approach for Chennai, India. *Global Environmental Change,* 23(1):229-239.

Statistics South Africa. 2011. *Annual report 2011/12*. Pretoria: Stats SA.

Statistics South Africa. 2012. Stats SA Library Cataloguing-in-Publication (CIP) data. *Bulletin of Statistics*, 46(2). Pretoria, Statistics South Africa.

Statistics South Africa. 2017. Business bleeds jobs for the third consecutive quarter. [Online]. Available at: http://www.statssa.gov.za/?p=10825 [Accessed: 14 January 2020].

Steyn, M., Meissner, R., Nortje, K., Funke, N. & Petersen, C. 2019. Water security and South Africa. In Meissner, R., Funke, N., Nortje, K. & Steyn, M. (eds.), *Understanding water security at local government level in South Africa*. Cham: Palgrave Pivot. doi:10.1007/978-3-030-02517-5.

Stosch, K.C., Quilliam, R.S., Bunnefeld, N. & Oliver, D.M. 2017. Managing multiple catchment demands for sustainable water use and ecosystem service provision. *Water*, 9(9):677.

Stockholm International Water Institute. 2020. Manual 1: Principles and practices of integrated water resources management workplace-based professional training. SIWI. [Online]. Available at: https://www.siwi.org/wp-content/uploads/2020/06/IWRM-Training-Manual-1_final.pdf [Accessed: 17 December 2020].

Streek, B. 1990. City will run out of water 'in 17 years'. *Cape Times.* April 26.

Suhardiman, D. & Giordano, M. 2012. Process-focused analysis in transboundary water governance research. *International Environmental Agreements: Politics, Law and economics,* 12(1):299-308.

Sullivan, C. 2002. Calculating a Water Poverty Index. *World Development,* 30(7):1195-1210.

Sullivan, C., Meigh, J. & Ciacomello, A. 2003. The Water Poverty Index: Development and application at the community scale. *Natural Resource Forum,* 27(3):189-199.

Sun, F., Staddon, C. & Chen, M. 2016a. Developing and applying water security metrics in China: Experience and challenges. *Current Opinion in Environmental Sustainability*, 21:29-36.

Sun, S., Wang, Y., Liu, J., Cai, H., Wu, P., Geng, Q. & Xu, L. 2016b. Sustainability assessment of regional water resources under the DPSIR framework. *Journal of Hydrology*, 532:140-148.

Suter II, G.W. 1993. A critique of ecosystem health concepts and indices. *Environmental Toxicology and Chemistry: An International Journal*, 12(9):1533-1539. https://doi.org/10.1002/etc.5620120903.

Suter II, G.W. 2001. Applicability of indicator monitoring to ecological risk assessment. *Ecological indicators*, 1(2):101-112. https://doi.org/10.1016/S1470-160X(01)00011-5.

Suter, G., Cormier, S. & Barron, M. 2017. A weight of evidence framework for environmental assessments: Inferring qualities. *Integrated Environmental Assessment and Management*, 13(6):1038-1044. https://doi.org/10.1002/ieam.1954.

Swana, U.U., Feleni, U., Malefetse, T.J., Mamba, B.B., Schmitz, P. & Nkambule, T.T. 2020. The status and quantification of de facto water reuse in South Africa–a review. *Water Practice & Technology*, 15(2):225-247.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F. et al. 2009. Growing-season rainfall and scenarios of future change in southeast Africa: implications for cultivating maize. *Climate Research*, 40(2-3):147-161.

Taing, L., Chang, C., Pan, S. & Armitage, N. 2019. Towards a water secure future: Reflections on Cape Town's Day Zero crises. *Urban Water Journal,* 16(7):530-536.

Teng, Y., Zuo, R., Xiong, Y., Wu, J., Zhai, Y. & Su, J. 2019. Risk assessment framework for nitrate contamination in groundwater for regional management. *Science of The Total Environment*, 697:134102.

Theron, N. & Brits, E. 2018. Ons kán dag Zero vryspring as… *Die Burger.* March 2:1.

Tindall, J.A. & Campbell, A.A. 2010. Water security – National and global issues. *AGU Fall Meeting Abstracts,* H14F-01. December. https://doi.org/10.3133/fs20103106.

Toale, J. & Molfetas, M. 2019. *Cape Town's drought & water scarcity.* Cape Town: Impact Human.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N. et al. 2003. A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences*, 100(14):8074-8079.

Turton, A. 2015. Sitting on the horns of a dilemma: Water as a strategic resource in South Africa. *South African Institute of Race Relations,* 6(22):1-26.

Umraw, A. 2018. *#WaterCrises: Drought or national government failure?* Cape Town: Huffington Post.

United Nations Global Compact. 2020. *SDG Compass. Clean Water and Sanitation.* [Online]. Available at: https://sdgcompass.org/wp-content/uploads/2016/04/Goal_6.pdf. [Accessed: 15 September 2020].

United Nations. 2015a. *Integrating the three dimensions of sustainable development: A framework and tools.* [Online]. Available at: https://www.unescap.org/sites/default/files/Integrating%20the%20three%20dimensions%20of%20sustainable%20development%20A%20framework.pdf [Accessed: 28 February 2020].

United Nations. 2015b. *The Millennium Development Goals Report 2015.* [Online]. Available at: https://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf [Accessed: 28 February 2020].

United Nations Educational, Scientific and Cultural Organisation. 2014. *The United Nations World Water Development Report 2014*. World Water Assessment Programme. ISBN: 978-92-3-104259-1. ePub: 978-92-3-904259-3.

United Nations World Water Assessment Programme. 2014. *The United Nations World Water Development Report 2014: Water and energy*. Paris: UNESCO.

United Nations World Water Assessment Programme. 2016. *The United Nations World Water Development Report 2016: Water and jobs.* Paris: UNESCO.

United Nations World Water Assessment Programme. 2019. *The United Nations World Water Development Report 2019: Leaving no one behind*. Paris, UNESCO.

Unites Nations Office for Disaster Risk Reduction. 2017. *UNISDR Strategic Framework 2016-2021.* [Online]. Available at: https://www.preventionweb.net/files/51557_unisdrstrategicframework20162021pri.pdf [Accessed: 28 February 2020].

United States Environmental Protection Agency. 1992. *Guidelines for exposure assessment.* EPA/600/Z-92/001. Washington, DC: USEPA Risk Assessment Forum.

United States *Environmental Protection Agency. 2002. Index of Watershed Indicators: An overview.* US Environmental Protection Agency Office of Wetlands, Oceans, and Watersheds.

United States Environmental Protection Agency. 2019. Risk assessment: Environmental Quality Index (EQI). [Online]. Available at: https://www.epa.gov/risk [Accessed: 28 February 2020].

University of Cape Town. 2019. *Ethics in research – Faculty of Commerce,* Cape Town: University of Cape Town, Faculty of Commerce, Igniting knowledge and opportunity. [Online]. Available at: http://www.commerce.uct.ac.za/com/Ethics-in-Research [Accessed: 7 September 2019].

UN-Water. 2016. UN-Water Annual Report 2016. [Online]. Available at: https://www.unwater.org/publications/un-water-annual-report-2016/ [Accessed: 28 February 2020].

Van Beek, E. & Arriens, W. 2014. *Water security: Putting the concept into practice.* Stockholm: Global Water Partnership Technical Committee.

Van Wyk, E., Breen, C.M., Roux, D.J., Rogers, K.H., Sherwill, T. & Van Wilgen, B.W. 2006. The Ecological Reserve: towards a common understanding for river management in South Africa. *Water SA*, 32(3):403-409.

Visser, W.P. 2018. A perfect storm: The ramifications of Cape Town's drought crisis. *The Journal for Transdisciplinary Research in Southern Africa,* 14(1):1-10.

Vogel, C. & Olivier, D. 2019. Re-imagining the potential of effective drought responses in South Africa. *Regional Environmental Change*, 19(6):1561-1570.

Vogel, C., Scott, D., Culwick, C.E. & Sutherland, C. 2016. Environmental problem-solving in South Africa: Harnessing creative imaginaries to address “wicked” Challenges and opportunities. *South African Geographical Journal,* 98(3):515-530.

Vollmer, D., Regan, H. & Andelman, S. 2016. Assessing the sustainability of freshwater systems: A critical review of composite indicators. *Ambio,* 45(1):765-780.

Vollmer, D., Shaad, K., Souter, N.J., Farrell, T., Dudgeon, D., Sullivan, C.A., Fauconnier, I. et al. 2018. Integrating the social, hydrological and ecological dimensions of freshwater health: The Freshwater Health Index. *Science of the Total Environment*, 627:304-313.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S. et al. 2010. Global threats to human water security and river biodiversity. *Nature*, 467(7315):555-561.

Vose, D. 2008. *Risk analysis: A quantitative guide*. John Wiley & Sons.

Wagener, T., Sivapalan, M., Troch, P. & McGlynn, B. 2010. The future of hydrology: An evolving science for a changing world. *Water Resources Research,* 46: 1-10.

Walker, R., Landis, W. & Brown, P. 2001. Developing a regional ecological risk assessment: A case study of a Tasmanian agricultural catchment. *Human and Ecological Risk Assessment*, 7(2):417-439.

Water Research Commission. 1990. *Annual Report: Water Research Commission*. Pretoria. [Online]. Available at: http://www.wrc.org.za/wp-content/uploads/mdocs/Annual%20Report%201990.pdf [Accessed: 31 July 2019].

Wellington, J. 2015. *Educational research: Contemporary issues and practical approaches.* 2nd ed. London: Bloomsbury Academic.

Werner, B. & McNamara, D. 2007. Dynamics of coupled human-landscape systems. *Geomorphology,* 91(3):393-407.

Western Cape Government. 2012. *Western Cape sustainable water management plan: Part 1: The water plan.* [Online]. Available at: https://www.greencape.co.za/assets/Water-Sector-Desk-Content/WC-DEAP-DWS-Western-Cape-sustainable-water-management-plan-2012.pdf [Accessed: January 2018].

Western Cape Government. 2019. *Western Cape Government: Overview.* [Online]. Available at: https://www.westerncape.gov.za/your_gov/70 [Accessed: 14 March 2019].

WHYCOS International Advisory Group. 2011. *9th WIAG Meeting: Final Report.* [Online]. Available at: https://library.wmo.int/index.php?lvl=notice_display&id=8750#.YEfRQ2ij-DI [Accessed: 26 February 2020].

Wiegers, J.K., Feder, H.M., Mortensen, L.S., Shaw, D.G., Wilson, V.J. & Landis, W.G. 1998. A regional multiple-stressor rank-based ecological risk assessment for the fjord of Port Valdez, Alaska. *Human and Ecological Risk Assessment*, 4(5):1125-1173.

Wilkinson, P. 2000. City profile: Cape Town. *Cities*, 17(3):195-205.

Winter, K. 2017. *What's driving Cape Town's water insecurity, and what can be done about it*. The Conversation: Africa. [Online]. Available at: https://theconversation.com/whats-driving-cape-towns-water-insecurity-and-what-can-be-done-about-it-81845 [Accessed: 21 September 2020].

Winter, K. 2018. The value of storm water. *Our Future Cities.* May 16:1.

Winter, K. 2019. *'Progressive' new water strategy for Cape Town*. University of Cape Town's (UCT) Future Water Institute.

Wolski, P. 2018. *Facts are few, opinions plenty... on drought severity again.* CSAG. [Online]. Available at: http://www.csag.uct.ac.za/2018/01/22/facts-are-few-opinions-plenty-on-drought-severity-again/ [Accessed: 4 October 2020].

Wolski, P., Hewitson, B. & Jack, C. 2017. *Why Cape Town's drought was so hard to forecast*. The Conversation. [Online]. Available at: https://theconversation.com/why-cape-towns-drought-was-so-hard-to-forecast-84735 [Accessed: 4 October 2020].

Woodhouse, P. & Muller, M. 2017. Water governance – A historical perspective on current debates. *World Development*, 92, 225-241.

World Economic Forum. 2011. *Global risks 2011.* 6th ed. An initiative of the Risk Response Network. ISBN: 92-95044-47-9, 978-92-95044-47-0 REF: 050111.

World Health Organisation and United Nations Children's Fund. 2000. *Global Water Supply and Sanitation Assessment 2000 Report*. WHO/UNICEF. [Online]. Available at: https://www.who.int/water_sanitation_health/monitoring/jmp2000.pdf [Accessed: 26 February 2020].

World Health Organisation and United Nations Children's Fund. 2015. *Progress on sanitation and drinking water: 2015 update and MDG assessment.* WHO/UNICEF. [Online]. Available at: https://www.who.int/water_sanitation_health/publications/jmp-2015-update/en/ [[Accessed: 26 February 2020].

World Health Organisation and United Nations Children's Fund. 2017. *Joint Monitoring Programme 2017 Report.* WHO/UNICEF. [Online]. Available at: https://www.unwater.org/new-publication-whounicef-joint-monitoring-programme-2017-report/ [Accessed: 26 February 2020].

World Health Organisation and United Nations Children's Fund. 2019. *Progress on household drinking water, sanitation and hygiene 2000-2017: Special focus on inequalities.* WHO/UNICEF. ISBN: 978-92-415-1623-5. [Online]. Available at: https://www.who.int/water_sanitation_health/publications/jmp-report-2019/en/ [Accessed: 26 February 2020].

World Meteorological Organisation. 2012. WMO statement on the status of the global climate in 2011. WMO-No. 1085. ISBN: 978-92-63-11085-5.

World Meteorological Organisation. 2018. *World weather information service.* South African Weather Service. [Online]. Available at: https://worldweather.wmo.int/en/country.html?countryCode=35 [Accessed: 14 April 2019].

World Meteorological Organisation. 2019. WMO Statement on the State of the global climate in 2018. WMO-No. 1233. ISBN: 978-92-63-11233-0.

World Resources Institute. 2000. *World Resources 2000-2001. People and ecosystems: The fraying web of life.* United Nations Development Programme, United Nations Environment Programme, World Bank and World Resources Institute. [Online]. Available at: https://www.wri.org/publication/world-resources-2000-2001[Accessed: 27 February 2020].

World Wildlife Fund. 2016. *Water facts & futures: Rethinking South Africa’s water future.* Stellenbosch: WWF.

World Wildlife Fund. 2017. *WWF-SA 2017, scenarios for the future of water in South Africa*. Cape Town, South Africa: WWF-SA. [Online]. Available at: http://awsassets.wwf.org.za/downloads/wwf_scenarios_for_the_future_of_water_in_south_africa.pdf [Accessed: 23 September 2020].

Wurtz, M., Angeliaume, A., Herrera, M.T.A., Blot, F., Paegelow, M. & Reyes, V.M. 2019. A spatial application of the water poverty index (WPI) in the State of Chihuahua, Mexico. *Water Policy*, 21(1):147-161.

Yuan, L., He, W., Liao, Z., Degefu, D.M., An, M., Zhang, Z. & Wu, X. 2019. Allocating water in the Mekong river basin during the dry season. *Water*, 11(2):400.

Zeng, Z., Liu, J. & Savenije, H.H. 2013. A simple approach to assess water scarcity integrating water quantity and quality. *Ecological Indicators*, 34:441-449.

Zeitoun, M., Lankford, B., Krueger, T., Forsyth, T., Carter, R., Hoekstra, A.Y., Taylor, R. et al. 2016. Reductionist and integrative research approaches to complex water security policy challenges. *Global Environmental Change*, 39:143-154.

Ziervogel, G. 2019. *Unpacking the Cape Town drought: Lessons learned,* Cape Town: African Centre for Cities.

Ziervogel, G., Pelling, M. & Cartwright, A. 2017. Inserting rights and justice into urban resilience: A focus on everyday risk. *Environment and Urbanisation,* 29(1):123-138.