WATER DEMAND MANAGEMENT IN THE UPPER ORANGE RIVER BASIN, SOUTH AFRICA

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Declaration

I declare that the work contained in this thesis is my original writing. Sources referred to in the creation of this work have been appropriately acknowledged by explicit references. Other assistance received has been acknowledged. I have not knowingly copied and used the words or ideas of others without such acknowledgement. I further more grant that copyright of this thesis in favour of North-West University (Mafikeng Campus).

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Thesis has been submitted with the approval as a university promoter and I certify that the requirements for the applicable PhD degree rules and regulations have been fulfilled.

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Lobina G. Palamuleni (PhD)

Dedication

This work is dedicated to my wives Limpho Patricia 'Maphole and Tlaleng Rachel 'Matshepang, my children - Mofuli Kish, Thato Augustina, Lits'itso Ernest, Relebohile Priscilla, Morareli Gabriel, Tebello Joyce; Phole Simon, Lesedi, Karabo, Tshepang Yvonne, the Mahasa Family, relatives and friends.

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Abstract

This study introduces a new framework called Water Accounting Plus (WA+) that is designed to provide explicit spatial information on water depletion and net withdrawal processes in complex river basins. The study is based on the supposition that water scarcity and growing competition for water among different sectors requires proper water management strategies and decision processes. Environmental and demographic pressures have indeed led to the current rise in importance of Water Demand Management (WDM) and the associated focus on efficiency and sustainability in the management of water resources. Water must be conveyed to where it is needed, in the right quantity, at the required pressure, and at the right time using the fewest resources. Thus, there is need for a clear understanding of the basin hydrological processes, manageable and unmanageable water flows, the interaction with land use and opportunities that mitigate the negative effects of water depletion on society. Currently, water professionals do not have a common framework that links depletion to user groups of water and their benefits. This, together with an absence of a standard hydrological and water management summary, causes confusion and leads to wrong decisions. In addition, the non-availability of water flow data contributes to a further non-existence of an operational water accounting systems for river basins in place. As a result, the introduction WA+ considers the influence of land use and landscape evapotranspiration on the water. WA+ presents four sheets: (i) a resource base sheet, (ii) an evapotranspiration sheet, (iii) a productivity sheet, and (iv) a withdrawal sheet, with each sheet encompassing a set of indicators that summarise the overall water resources situation. The study also shows that the impact of external (e.g. climate change) and internal influences (e.g. infrastructure building) can be estimated by evaluating the changes in these WA+ indicators. Furthermore, satellite measurements are presented as significant in the acquisition of a vast amount of required data but not a precondition for implementing WA+ framework. The study concludes that data from hydrological models and water allocation models can also be used as inputs to WA+.

Definition of Concepts

- **Adaptive strategies to climate change**: these are approaches aimed at increasing the irrigation efficiency, applying irrigation deficit stress, and delaying the planting date (Ashofteh *et al.* 2016; Wang *et al.* 2016b).
- **Available water** is the exploitable water minus reserved outflows and non-utilisable outflow. It represents the water that is available for use at the domain (Karimi *et al.* 2013: 2470).
- **Basin-level water accounting [Consumed Fraction/Depleted Fraction (CF)]:** This is portion of system inflow that is consumed (Simons *et al.* 2015: 565).
- **Basin-level water accounting [Recoverable Fraction (RF)]:** The portion of water withdrawals that is not consumed and can be recovered for reuse downstream (Simons *et al.* 2015: 565).
- **Blue water** refers to surface and groundwater that is found in aquifers, rivers and other water bodies (Zhao *et al.* 2016; Kauffman *et al.* 2014 and Orlowsky *et al.* 2014).
- **Conserved land use** relates to the environmentally sensitive land uses and natural ecosystem that is set aside for protection from human-related activities and even the sea (Karimi *et al.* 2013: 2470).
- **Degree of return flow reuse:** The fraction of drainage water that is reused in the catchment (Simons *et al.* 2015: 565).
- **Diffuse irrigation** is irrigation, usually in the form of run-of-river irrigation, which is not supported by releases from large dams. This leads to efficient and consumptive use of water. The attainment of irrigation efficiency is particularly important and can be achieved through the use of more efficient technologies such as sprinkler and drip irrigation that result in lower overall return flows (DWAF 2004: 2 – 7; Lozano *et al.* 2016; Meixner *et al.* 2016).
- **Downstreamness,** a concept introduced by van Oel *et al.* (2009), relates to the function in a river basin that is based on the area of its upstream catchment. Downstreamness is valuable in raising awareness of the spatial context of water supply to a location, and in evaluating a certain location on the basis of its upstream commitments (Simons *et al.* 2015: 567). Functions in the basin, such as water availability or water use, are also defined as the downstreamness-weighted integral of that function divided by its regular integral.

- **Eco-hydrology** focuses on the interaction between plants and the hydrological process, and describes ecological patterns and eco-hydrological mechanisms (Yang *et al.* 2014: 8). Eco-hydrology determines the interaction between the ecosystem and water (Rinaldi *et al.* 2016; Savenije *et al.* 2014).
- **Economic value of water** relates to methods that are acceptable with the international community, which are used to calculate the quantification of benefits and services, and rarely consider the natural value of water (Turner *et al.* 2016; Díaz-Delgado 2014: 72).
- **Environmental conditions**: These are the currently warmer and drier conditions due to climate change, which will further aggravate the water crisis in many regions of the world that are already facing water shortages due to economic and population growth. Increased water demand might increase conflicts between different water uses and affect the in-stream needs for retaining ecosystem sustainability (Wang *et al.* 2016b: 84).
- **Epilimnion**: It is a surface layer or the top-most layer in a thermally stratified lake that occurs above the deeper hypolimnion. It is warmer and typically has a higher pH and higher dissolved oxygen concentration than the hypolimnion (Dargahi *et al.* 2017; Qiu *et al.* 2017).
- **Exploitable water** represents water available in reservoirs, rivers, lakes and groundwater that is for utilised, utilisable, non-utilisable and reserved outflows (Karimi *et al.* 2013: 2470).
- **Grey water footprint** refers to the volume of water that is required to assimilate polluted water. It reflects the intensity of water pollution caused by water use for human activities (Liu *et al.* 2017).
- **Gross inflow** is the total amount of water, including precipitation plus any inflow from surface or ground water sources, which flows into the domain, (Karimi *et al.* 2013: 2470).
- **Green water** refers to water held in (unsaturated) soil above the groundwater table that is available for evaporation and transpiration (Zhao *et al.* 2016; Kauffman *et al.* 2014; Orlowsky *et al.* 2014).
- **Integrated Water Resources Management** is a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital eco-systems and the environment (Meyer 2013; DWA 2012e).
- **Irrigation water** consists of water which is artificially applied to land for agricultural purposes (UNDS 2012: 51).

- **Landscape Evapotranspiration (ET)** is the water that evapotranspires directly from the natural water cycle without artificial supply (Karimi *et al.* 2013: 2470).
- **Linear regression of water reuse to scale [withdrawals per ha]:** This is the amount of water that is reused per additional unit of surface area (Simons *et al.* 2015: 565).
- **Managed water use** represents landscape elements that receive withdrawals from utilised flows (Karimi *et al.* 2013: 2470).
- **Modelling**: This provides the capability to evaluate and test management measures under varied hydrological conditions in order to identify possible undesirable outcomes prior to the implementation of such measures (Sahin *et al.* 2016; Wang *et al.* 2016b). Modelling plays the role of a "laboratory" where proposed management measures and schemes are first tried out and proven at a small cost before they are implemented in the real world. Modelling also fills missing gaps in a water resources system that has no recorded data by simulating components that are known to exist but for which actual recorded data are not available (i.e. a sub-system where the streamflow is not measured). Modelling in support of water resource analysis offers the potential to observe the full picture and interdependencies, even if the model remains an approximation and cannot be absolutely accurate in predicting the future behaviour of an actual water resource system (Carboni *et al.* 2016; Kotir *et al.* 2016; Shabani *et al.* 2016; Wanjiru *et al.* 2016; Yang *et al.* 2016b).
- **Modified land use** relates to the replacement of the original vegetation aimed at an increased utilisation of land resources (Karimi *et al.* 2013: 2470).
- **Net inflow** is the gross inflow after correction of storage change (ΔS) and represents water available for landscape ET and exploitable water (Karimi *et al.* 2013: 2470).
- **Non-use values of water:** These are the (1) Bequest value – the value of nature left for the benefit of future generations; and (2) Existence value – the intrinsic value of water and water ecosystems as well as biodiversity, such as the value people place simply on knowing that a wild river exists, even if they never visit it (UNDS 2012: 123).
- **Precipitation sheds** provide direct insight into the effect of a particular region's land use change or increased water consumption on the precipitation downwind (Savenije *et al.* 2014: 324; Keys *et al.* 2012).
- **Predictive model** is a robust demand-forecasting model, which provides an accurate estimation of water demand and thus assists managers in designing a more environmentally sustainable water distribution systems that enable an efficient management of available

water resources. The use of a predictive model together with a water demand management strategy can help managers overcome operational problems (e.g. low pressure during peak demands) and issues related to asset management (e.g. non-replacement of assets or replacement by lower capacity assets reaching the end of their economic life) (Carboni *et al.* 2016; Kotir *et al.* 2016; Shabani *et al.* 2016: 100; Wanjiru *et al.* 2016: Yang *et al.* 2016b).

- **Reserved outflow** is the water that has to be reserved to meet the committed outflow, navigational flows and environmental flow (Karimi *et al.* 2013: 2470).
- **Return Flow Ratio** is the amount of upstream non-consumed water divided by the available surface water (Simons *et al.* 2015: 566).
- **Reuse dependency:** The fraction of the water supply for reuse areas which is actually covered by drainage re-use (Simons *et al.* 2015: 565).
- **Socio-hydrology** is defined as the co-evolution of human-natural coupled systems. It is not possible to predict water cycle dynamics over decadal or longer time periods without considering interactions and feedbacks among natural and human components of the water system (Gober and Wheater 2014: 1419). Socio-hydrology is a use-inspired scientific discipline with a focus on the understanding, interpretation, and scenario development of the flows and stocks in the human-modified water cycle at multiple scales, with explicit inclusion of the two-way feedbacks between human and water systems (Blair and Buytaert 2016; Dang *et al.* 2016; Sivapalan *et al.* 2014). The aim of socio-hydrology is to uncover the dynamic cross-scale interactions and feedbacks between the human and natural processes that may result in the challenges of water sustainability in the Anthropocene.
- **System of Environmental-Economic Accounting for Water (SEEAW)**: The SEEAW has been developed by the UNSD in conjunction with the London Group on Environmental Accounting (UNSD 2012). Its main objective has been to standardise concepts related to water accounting and provide a conceptual framework for organising economic and hydrological information. As a result, water accounts generally, and the SEEAW in particular, are a useful tool in the decision-making process regarding the allocation of water resources and improvement of water efficiency. SEEAW framework considers the flows between the environment and the economy. The inland water resource system, which comprises of surface water, groundwater and soil water in relation to the economy, is represented by abstractions, imports, exports and returns of the most relevant economic agents. These agents include households; the industry involved in the collection, treatment

and discharge of sewage; the industry involved in the collection, treatment and supply of water to households; industries and the rest of the world; and other industries which use water in their production process. The SEEAW tables related to water resources are organised in flow accounts or asset accounts according to whether they represent the water flows in physical units within the economy and between environment and the economy, or whether they measure stocks at the beginning and at the end of the accounting period (Pedro-Monzonís *et al.* 2016: 2).

- **Systems dynamic model**, also outlined in Chapter 6, integrates supply, demand and financial dimensions (Sahin *et al.* 2016).
- **Uniform rationing** allocates water in proportion to each observed irrigated area x (Salanié and Zaporozhets 2016: 11).
- **Use values of water:** These are the (1) Direct use values related to the direct use of water resources for consumptive uses, such as input to agriculture, manufacturing and domestic use, and non-consumptive uses, such as generating hydroelectric power, recreation, navigation and cultural activities; (2) Indirect use values pertaining to the indirect environmental services provided by water, such as waste assimilation, habitat and biodiversity protection and hydrologic function; and (3) Option value, which is the value of maintaining the option for direct or indirect use of water in the future (UNDS 2012: 123).
- **Utilisable outflow** is the water available for resources development (Karimi *et al.* 2013: 2470).
- **Utilised flow** is the portion of available water that is depleted during use (Karimi *et al.* 2013: 2470).
- **Utilised land use** represents a low to moderate resource utilisation, such as savannah, woodland and mixed pastures (Karimi *et al.* 2013: 2470).
- **Virtual water** describes the amount of water required to generate a product (Ouertani 2016; Liu *et al.* 2014). The concept of virtual water added a new dimension to international trade and provided a completely new way of thinking about water resources management and water scarcity (Bajzelj *et al.* 2016; Birkenholtz 2016; Tamea *et al.* 2016). In other words, an inflow of virtual water through a variety of imported products reduces the pressure on domestic water resources with an outflow of virtual water through exporting finished products resulting in water loss from a regional perspective and thereby adding to the pressure on the amounts of local water systems (Sun *et al.* 2016; Zhuo *et al.* 2016a; Cazcarro *et al.* 2014; Orlowsky *et al.* 2014; Tamea *et al.* 2014). Virtual water transfer is

indicated in the fact that populations of most nations consume products of both domestic and foreign origin and in the process importing the products together with the water which is expended abroad for their production (Orlowsky *et al.* 2014).

- **Water accounting** is the only approach that integrates economic accounts with accounts for water supply and use in a framework that supports quantitative analysis. As a result, water accounting is considered here as making a unique contribution to integrated water resources management (IWRM). Water managers often have access to information about water use by broad groups of end-users, but such data cannot be easily used for economic analysis because the classification of end-users rarely corresponds with the classification of economic activities used for the national accounts. The water accounts, in contrast to other water databases, links water data, such as supply, use, resources, discharge of pollutants and assets, directly to economic accounts. They achieve this by sharing structures, definitions and classifications with the 2008 System of National Accounts (SNA), as exemplified in the way water suppliers and end-users are classified by the same system used for the economic accounts, the International Standard Industrial Classification of All Economic Activities (ISIC) (UNDS 2012: 138).
- **Water consumption** accounts for the share of the extracted water which is lost from the ecosystem either by incorporation into a product or lost through physical processes such as evapotranspiration. In the literature, "water consumption" (extraction minus return flows) is also called "consumptive use" (Lutter *et al.* 2016: 172; EEA 2014).
- **Water demand management** focuses on the efficient and effective use of water that seeks to reduce demand while ensuring optimal use of water resources. This means that water must be conveyed to where it is needed, in the right quantity, at the required pressure, and at the right time using less resources. This can be achieved by the use of Modern Artificial Intelligence (MAI) techniques (Ponte *et al.* 2016: 168).
- **Water footprint** is a comprehensive measure of freshwater consumption that connects water use to a certain place, management system, time, and type of water resource (Zhuo *et al.* 2016b; Hoekstra 2011; Hoekstra *et al.* 2011). It is distinct from the common measure of water use and water withdrawals because a water footprint only accounts for consumptive water use, which is water that becomes unavailable for local reuse in the short term due to evaporation, incorporation into products, or a substantial quality decline (Beltrán 2016, Morera *et al.* 2016; Cazcarro *et al.* 2014; Dourte *et al.* 2014). The water footprint (WF) metric is considered as an indicator of the impact of water use by

agricultural production systems on freshwater resources (Herath *et al.* 2014: 111; Vanham 2016: 302).

- **Water management strategies** can be divided into three broad classes, supply side management, demand side management and business-as-usual management (Wang *et al.* 2016b: 84). Water supply management, which is the most traditional approach to water resources management, focuses on increasing the amount of available water in order to keep pace with increases in water demand and ensure the adequate availability of quality water. The supply-side approaches include: changing the structures, operating rules and institutional arrangements; increasing flood defences; building weirs and locks to facilitate navigation; and modifying or expanding infrastructure for water collection and distribution. Water demand management (WDM) refers to any technical, economic, administrative, financial or social approaches that reduce the quantity or quality of water required to accomplish a specific task (Wang *et al.* 2016b: 84). Finally, the business-as-usual management approach refers to managing water resources without considering possible future circumstances that may have a negative impact on these resources. The business-as-usual approach to water management is not suitable in the context of climate change, as it is very certain that fresh water will be scarcer in the future. It has been projected that 4.8 billion people, or more than half of the world's population, and approximately half of global grain production will be at risk due to water stress by 2050 if status quo or business-as-usual management is practised (Wang *et al.* 2016b: 84).
- **Water Reuse Index** measures the number of times water is withdrawn consecutively during its passage downstream (Simons *et al.* 2015: 565).
- **Water Saving Efficiency (WSE)** is defined as the ratio between the increase in river discharge and the reduction in on-farm irrigation water application that caused this increase in inflow (Simons *et al.* 2015: 567).
- **Water use** accounts for the actual quantities of fresh water extracted from water sources such as groundwater bodies or diverted from a river or lake. Water which is used can be returned to the same water body, although it may be shifted in time or location, and its quality may be changed (Lutter *et al.* 2016: 172; EEA 2014).

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CHAPTER 1

GENERAL INTRODUCTION

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1. Adaptive Water Management

The recognised central guiding principles in the protection, management, use, conservation, development and control of water resources are sustainability, efficiency and equity (Kotir *et al.* 2017; Woodhouse and Muller 2017; Rasmussen *et al.* 2017; Bajzelj *et al.* 2016; DWA 2012a). Inherent to these guiding principles is the management of water quality. South Africa is considered as a water scarce country (Tamea *et al.* 2016, Meyer 2013) as a result, the Department of Water Affairs and Forestry (DWAF) has declared that water resources must be shared equitably and managed judiciously by all water users in an utmost discretion manner. Water demand is on a rapid increase due to urbanisation and economic progress, a condition that is leading to water scarcity in various regions in the world (Wang 2014) such that South Africa opted to introduce an 'integrated water resource management' (IWRM) program (Jorgenson *et al.* 2016, Overton *et al.* 2014 and Meyer 2013). Therefore, South Africa has created organisations such as decentralised catchment management agencies (CMAs) and river basin organisations (Reijerkerk *et al.* 2012) in an effort to manage the country's water resources in a coordinated way.

The inception of the IWRM in 1992 has witnessed the decision-makers, planners and stakeholders emphasising, in their interactions, on water management practices that are based on the understanding of the IWRM process (Shah and Van Koppen 2016, Savenije *et al.* 2014). This encouraged ordinary people to communicate more about water than how the hydrological system works. In addition, water researchers have gradually focused their work on eco-hydrology and socio-hydrology in order to understand better the dynamics of development and co-evolution (Savenije *et al.* 2014, Elshafei *et al.* 2014, Gober and Wheater 2014, Ribeiro Neto *et al.* 2014, Sivapalan *et al.* 2014). Eco-hydrology is simple to understand as it does not change rapidly compared to socio-hydrology which has various complex feedback mechanisms. This complexity in socio-hydrology arises from the adaptive capacity of human beings in adjusting the environment to their wishes. A comparison between ecosystems and humans shows that humans are more mobile, much capable of changing their environment by using rapid communication, able to set up of institutions, highly developed to use adaptive technology and implement innovative interventions in engineering, and able to establish viable economic incentives (Savenije *et al.* 2014). This will enhance the management of the country's water resources in a coordinated way.

Nationally, the Orange-Senqu River basin and its largest and most important tributary, the Vaal River, is of paramount importance to South Africa. South Africa's industrial areas, which include the Greater Pretoria and Johannesburg areas are supplied with water that is drawn from the Vaal River. The industrial areas drawing water from the Vaal River produce more than 80% of the South Africa's electricity requirements – more than 50% of all the electricity generated in Africa – and more than 50% of its wealth (DWA 2012a). The Vaal River water supplies water to some of the largest Platinum and Gold mines in the Gauteng, the North West and the Free State provinces of South Africa. The river also supplies water to various South African coal mines, which are among some of the largest mines in the world. Thus the Orange-Senqu River basin has a direct effect on at least six of South Africa's nine provinces, hence some of the most ambitious and largest water projects undertaken in Africa are located in the basin (DWA 2012a, DWAF 2011).

The importance of large river systems emerged in the early 1990s due to a multitude of interacting and complex factors that contributed to an increased pressure on freshwater resources. Various research applications placed a requirement on water resources or hydrological information from a global to a regional focus. Chief among the focus was the need to: estimate future climate and global environmental change effects that relate to water supply, droughts, floods, or generation of hydro-electricity; analyse global biogeochemical cycles, nutrient and carbon budgets; manage international freshwater resources sustainably; urgently estimate possible limitations in global food production caused by the constrained water availability; conserve and systematically plan freshwater biodiversity; and to advance the assessment of regional health risks caused by water quality issues or water-borne diseases (Breen and Minnes 2013, Lehner and Grill 2013).

Finally, the issue of water demand management, which addresses the actual requirements for water and not the demand for water (Bijl *et al.* 2016), is prominent in the discourses on water management in relation to climate change. Water demand management ensures further reduction in water use, leads to reduced water losses through the water distribution network, prevents water pollution and disposal of wastewater in nature, promotes efficient use of available water resources, advocates for prudent future planning on new water resources and finally leads to the establishment of the cost of real, affordable and acceptable water supply. Therefore, water demand management can be implemented together with public awareness programmes at schools and via the media as part of a consolidated program. It is indeed important that the general public be made aware of the associated problems and how the water shortage crisis can be overcame (Almeida and Dias 2016; Subramanian and Siromony 2014).

1.1 Research Problem

Sustainable environmental use and management are now regarded as the cornerstones of economic and social development and thus, the protection and wise use of ecosystems and biomes should be the parameters of social and economic development (Jorgenson *et al.* 2016; McIlwee *et al.* 2013). The measures that enable the greening of the economy are also important to a country's development. As such, developing countries can 'leap frog' the carbon intensive age and develop renewable energy options in order to achieve their future socio-economic development. The ultimate causes of pressures on human and ecological receptors are often very hard to attribute.

Freshwater ecological systems are determined by water demand, hydrology, water quality, morphology and other physical factors (Tibebe *et al.* 2016; McGonigle *et al.* 2012). These complex interacting factors can confound efforts that lead to an understanding of both the causes of the decline of ecological status in a given basin and that of the prediction of the likely effectiveness of a set of policies, or the likely operational timeframes within which they are likely to be effective. Until now, there is sufficient evidence supporting the cost-effectiveness of measures intended to tackle and address some of the world's water scarcity. A major knowledge gap, therefore, confronts policy-makers at the catchment scale to design sound, effective and well targeted interventions. Thus, water demand, a combination of source apportionment techniques, iterative modelling studies and tracer experiments all need to be investigated further (Haque *et al.* 2014, McGonigle *et al.* 2012).

The science of managing water resources and hydrology have held central roles in human and economic development throughout history (Savenije *et al.* 2014). These roles have often been obscured or marginalised. Nonetheless, water resources engineering and management and the knowledge of hydrology have transformed the landscape as well as the very hydrology operating within catchments. It is only recently that experts started to investigate and place more research focus on several emerging concepts such as integrated water resources management (IWRM), eco-hydrology and socio-hydrology. Recent developments in the last 25 years have arrived at a stage at which a more systemic understanding of scale interdependencies is achieved. This has led to the sustainable governance of water systems, using new concepts such as virtual water transfers, water footprints, precipitation sheds, and water value flow (Beltrán *et al.* 2016; Chaffin and Gunderson 2016, Knüppe *et al.* 2016, Savenije *et al.* 2014).

To date, several studies (see Dai *et al.* 2016; Pedro-Monzonís *et al.* 2016b; Ponte *et al.* 2016; Valencia *et al.* 2016; Xiao and Hu 2016; Xiao *et al.* 2016; Xiao-jun *et al.* 2014) of water demand management have tended to emphasise available water from a systems approach focusing on other geographical areas with little research attention on the upper Orange River basin.

1.2 Research Aim and Objectives

1.2.1 Research Purpose

The purpose of the study is to determine water demand management practices in the study area given that water resources in the mountain areas are increasingly under pressure, with serious implications for both the mountain and lowland areas (Pelser and Letsela 2012). The Maloti Drakensberg Transfrontier Project (MDTP) is a predominantly rural mountain area shared by Lesotho and South Africa thus prompting intensive measures to account for this shared water resource. This mountainous area is a source of water supply for two main rivers, the Orange-Senqu River and the Tugela River, resulting in Lesotho being regarded as 'the sponge of Southern Africa' or the 'water factory of Southern Africa' (Pelser and Letsela 2012: 48).

It should be underscored further that the provision of water by the MDTP area aquatic ecosystems is a major ecosystem service that has both national and regional significance (Matthews 2015). One of the management priorities for South Africa as a whole is to wisely manage its scarce water resources, and this requires a catchment-level approach (Borrego-

Marín *et al.* 2016). The Drakensberg escarpment and Lesotho highlands form a vital watershed that feeds South Africa with water (Jacobs 2012, Nkheloane *et al.* 2012). It is in this light that this research is carried out.

1.2.2 Specific Objectives

The specific objectives of the study were:

1) To identify water users in the study area.
2) To identify actual allocation of water needs by DWAF – Republic of South Africa (RSA), Lesotho Highlands Development Authority (LHDA) and Department of Water Affairs (DWA) – Lesotho.
3) To perform water accounting on the study area's different users for the period 1994 to 2014.
4) To assess the state of equity in water allocation.
5) To develop a suitable water demand management model.

1.2.3 Hypotheses

Three research hypotheses are advanced for this study. These are outlined below.

1. There exists a standardised water allocation system in the study area.

2. Municipal authorities in different areas use the same method to allocate water in the study area.

3. The different users' water allocations are characterised by unacceptable levels of inconsistencies.

There are several null hypotheses suggested for this study:

H_{01}: There are differences in the methods of identifying different water users in the study area.

H_{02}: There are differences in the methods of allocating water in different municipal areas.

H_{03}: There are differences in determining water accounting for different water users.

1.3 Significance of the Study

The natural environment of the study area is defined by various significant features, which include sensitive biodiversity, important high altitude wetlands that supply water to rivers that serve the lowlands, protected areas and national parks, and informal protected areas. Policy-makers are instrumental in the development, implementation and refinement of policy on how to tackle water demand and to understand the main sources and impacts of water in setting the 2030 Agenda, Paris Climate Accord 'Twin Plans for Transformative Progress'. This should be done within the context of a likely socio-economic and environmental change, assist in identifying the most effective mitigation interventions, and facilitate ways to influence water management areas (WMAs) and users to take the policies up. Finally, the policy-makers should also perform effective modelling and monitoring approaches, a primary requirement for the tracking of progress.

The significance of the study lies in its quest to determine water demand levels that are acceptable for designated uses such as irrigation, drinking water, industries, swimming, and aquatic life. This is important for the following reasons as this has a bearing on: human health, the survival of aquatic life, the continued existence of industrial or agricultural use; and defining the state of water-supply criteria. It is also expected that the study will expand our understanding of the behaviour of the Orange-Senqu River basin system's components and their interconnections in a systemic and time-compressed manner, thus contributing towards an improved and effective management of water resources.

1.4 The Study Area

In terms of area and extent, the primary focus of the research activities stretches across South Africa's Free State, Eastern and Northern Cape provinces and Lesotho. It includes the Maloti Drakensberg Trans-frontier Conservation and Development Area (MDTFCA), which is one of the six Trans-frontier Conservation Areas on the borders of South Africa and its neighbouring state, Lesotho (Afromontane Research Unit 2013). The primary study area is the Upper Orange WMA comprising of Lesotho and the upper Orange-Senqu River (Figure 1). This area is located between Latitudes (28^{0} 0' 0'' and 32^{0} 0' 0'' S) and Longitudes (24^{0} 0' 0'' and 30^{0} 0' 0'' E).

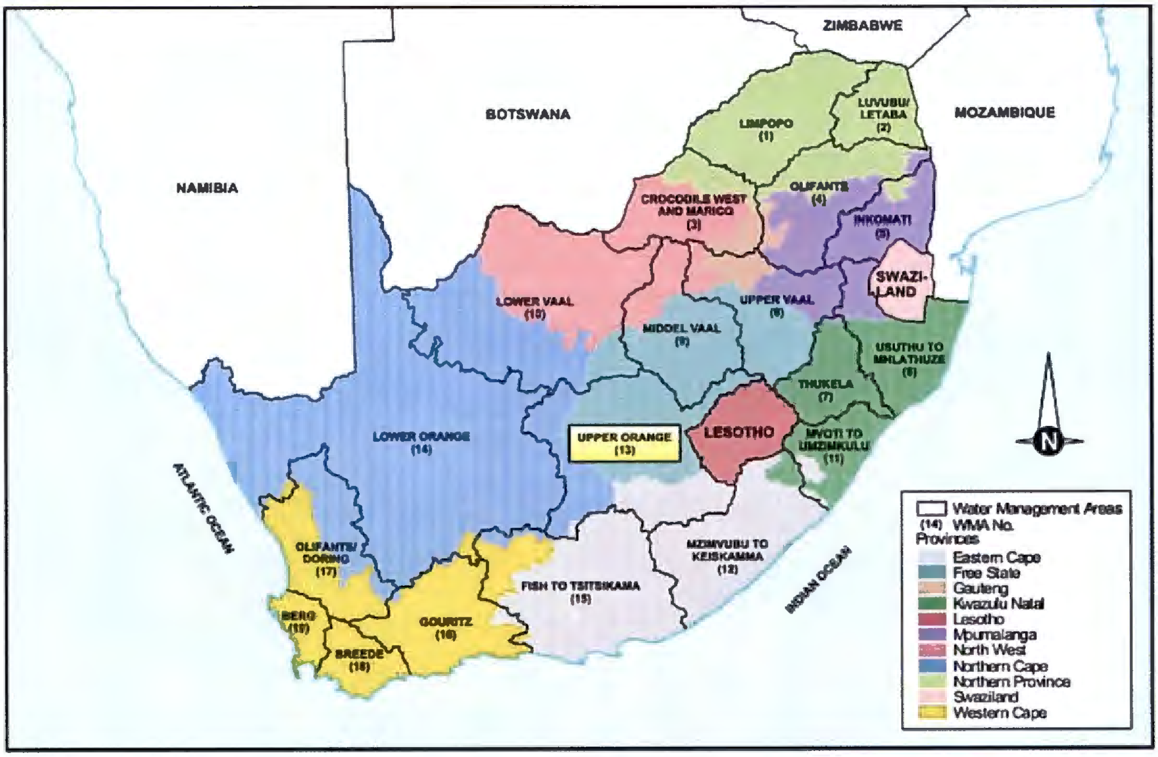

Figure 1: Location of Upper Orange River

(DWAF 2004: 1-1)

1.5 Basic Ethical Principles in Research

The four principles of ethics include autonomy (respect for the person- a notion of human dignity), beneficence (benefit to the research participant), non – malfeasance (absence of harm to the research participant) and justice (notably distributive justice-equal distribution of risks and benefits between communities) (MRC 2002). Research participants from different institutions were informed about the purpose of the study and their rights in the context of the relevant principles. The fourth principle, concerning justice, did not arise in this kind of research. Nonetheless, the consent to participate in the study was sought and participants were informed that participation was voluntary. However, participants were encouraged to participate in the study. The safety, rights and dignity of the participants were of primary concern and all information gained from them was kept strictly confidential.

Responses from respondents were strictly for research purposes, the identity of respondents and their personal details remained confidential. Participants were also informed that they were free to withdraw at any time, had their rights explained to them and that the proposal was presented to and approved by the Northwest University Ethics Committee. Finally, the results of evaluation indicated that a formal Ethics Form was dully filled in and the accompanying permission documentation attached and a clearance was given. (Appendix 1).

1.6 Summary

This chapter introduced and discussed water demand management and Adaptive Water Management based on Climate Change and Water Security. Key issues including the problem statement, research aim, objectives, hypotheses to be tested and significance of the study, were also discussed in this chapter. Basic ethical considerations and a concluding summary were also outlined.

The next chapter presents the literature review whilst placing much focus on the water demand management principles and models. It draws on advances made and experiences obtained from diverse geographical areas, including those which have similar geographical settings such as the study area itself. It also addresses the knowledge gap obtained from literature that prompted this study to be undertaken.

CHAPTER 2

REVIEW OF WATER DEMAND AND HYDROLOGICAL MODELS

2. Introduction

This chapter addresses the dynamics of the hydrological cycle that are directly changed by humans through the construction of dams for water storage and water withdrawals intended for irrigation, industrial or domestic purposes. Water demand and supply are expected to be additionally affected by climate change. The chapter also reviews some commonly used hydrological models together with a literature on water demand. It also considers the analyses of climate change and direct human impacts on the terrestrial water cycle using a multi-model approach. The chapter also focuses on reservoir simulation models used in South Africa and goes on to place more emphasis on the two commonly used Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM). Finally, the chapter identifies the knowledge gaps that this research addresses with regards to water withdrawals and dams and the larger impact of human interventions on the hydrological cycle in the study area.

2.1 Hydrological Models

The increased demand for water witnessed in many parts of the world arises from population growth, innovations in agriculture that led to expanded irrigation areas, and economic development that raises water scarcity (Foster *et al.* 2017; Chen *et al.* 2016a; b; Shiva 2016). As a result, many rivers become dry for substantial periods of the year before they reach the sea (De Graaf *et al.* 2014; Haddeland *et al.* 2014). Moreover, water unavailability has become severe in many parts of the world due to climate change (Dube *et al.* 2016; Hanasaki *et al.* 2013). Hence, regions with frequent water stress and large river basins use inter-river water transfers as a remedial resource measure to meet water demands.

Water transfers in most of these water stressed regions exceed natural flows, thereby negatively affecting stream flow, ecosystems, and local water demands (Chen *et al.* 2016b; Husain *et al.* 2016; Fader *et al.* 2016; Quan *et al.* 2016 and Rey *et al.* 2016). Previous model studies that focused on global-scale water consumption and its effects had to deal with the reality that there existed little to no information on the attribution of water demand to surface water and groundwater abstraction. Available studies have provided different assumptions about this attribution. Models were only limited to those that explicitly accounted for human water abstractions (Khan *et al.* 2017; Pryor *et al.* 2017; Kim *et al.* 2016; De Graaf *et al.* 2014).

Several researchers (Karlsson *et al.* 2016; Mizukami *et al.* 2016; Sikder *et al.* 2016; Varela-Ortega *et al.* 2016) report numerous similarities between the simulations of hydrology and its associated processes as they relate to several water cycle components of the general circulation models (GCMs) and stand-alone hydrological models. The observations are that the models are different, especially with respect to how they describe the processes, operational time scales, approaches to parameter estimation, and how input data and outputs are determined spatially (Sikder *et al.* 2016; Haddeland *et al.* 2011). When applied at a basin scale or a catchment scale, the stand-alone models usually need many parameters that require calibration or estimation to provide good results regionally. Examples of models from this category include Hydrological Simulation Program-Fortran (HSPF) (Bicknell *et al.* 1997), Soil and Water Assessment Tool (SWAT) (Neitsch *et al.* 2002) and Hydrologiska Byråns Vattenbalansavdelning (HBV) (Lindström *et al.* 1997).

The application of these models is restricted to small regions only although some can be used globally (Khalid *et al.* 2016; Liao *et al.* 2016). It is often impractical to apply these models owing to lack of information (Efstratiadis 2014). An absence of flow routing means that the simulation of vegetation interfaces, atmospheric energy balance and soil at finer scales (often – hours) in Land Surface Schemes (LSSs) becomes dependent on the fact that LSS is both a GCM and a hydrological model (Yang *et al.* 2016a). Models such as the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson *et al.* 1986) and the Community Land Model (CLM3.5) (Oleson *et al.* 2008) fall into this category due to their good performance (Giorgi 2014). The other models are the Joint UK Land Environment Simulator (JULES) (Sood and Smakhtin 2015) and Simple Biosphere Model (SiB) (Sellers *et al.* 1986).

The actual Global Hydrological Models (GHMs) (Sood and Smakhtin 2015; Haddeland *et al.* 2011) place emphasis on lateral transfer of water and water resources. Some studies (Widén-Nilsson *et al.* 2007; Döll *et al.* 2003; Vörösmarty *et al.* 1989), however, showed that few parameters could be calibrated at climatic region, eco-region scale or large river basins. For instance, it is noted that with the WBM-WTM (Vörösmarty *et al.* 1998) only a tuning effect is introduced and it cannot be calibrated. On the contrary, the WaterGAP model combines both processes of tuning and calibration. Calibration against river discharge should be done. The basins that tend to overestimate or underestimate flows are then subjected to tuning by adjusting two factors - discharge correction and runoff (Döll *et al.* 2003). The resolution of available global climate input data is referred to as the GHMs' spatial resolution. The use of GHMs emerged in the 1990s but the constant evolution in this field has produced increased activity (Döll *et al.* 2008; Lawford *et al.* 2004). The availability of finer global spatial data sets has prompted all GHMs to become more complex and resolute and thus becoming more functional. Voß *et al.* (2008) and Döll *et al.* (2008) note that model sensitivity, due to available data types, now makes it possible to determine model uncertainty and couple GHMs with other models.

The availability of global data from satellites for use in GHMs has triggered the rapid development of GHMs (McMillan *et al.* 2016; Tang *et al.* 2009). Most GHMs are used mainly for global-scale studies though they are at times used for catchment-scale applications because they are valuable and abundant in numbers and can be applied in the estimation of global water resources (Schmied *et al.* 2016; Veldkamp *et al.* 2016). GHMs augment information received through ground-based observed data that is linked with the statistical analysis of the hydrological components, all of which are prone to a lot of uncertainty (Rodda 1995). A linkage of GHMs with other models reveals more functionalities, such as biodiversity, climate change, crop growth, ecology, energy balance describing global economy, trade, land-use change and other water resources issues, in models (McMillan *et al.* 2016; Alcamo 2009; Islam *et al.* 2007; Vörösmarty *et al.* 2000).

2.2 Global Hydrological Models

There exists various hydrological models that are applied to hydrology and other various resource applications and only a few will be reviewed herein. Vörösmarty *et al.* (1989) pioneered the Water Balance Model (WBM) which was adjoined to the Water Transport Model (WTM) and resulted in more GHMs being developed. The WBM simulates spatially and temporally varying components of the hydrological cycle and multi constituent water quality variables (Trambauer *et al.* 2013). Trambauer *et al.* (2013) also indicate that WBM meteorological inputs include temperature, precipitation and potential evaporation, with more complex configurations requiring vapour pressure, solar radiation, wind, daily maximum and minimum temperature (see also Engeland *et al.* 2016). Using a linear reservoir model, predictions at grid level relating to overland flow, evapotranspiration (ET) and soil moisture (SM) and WTM routing the runoff generated can be sufficiently simulated in WBM (Vörösmarty *et al.* 1989). The availability of water can be determined from the knowledge of the type of vegetation and soil at finer resolution as water is controlled by the field capacity (FC) (Campos *et al.* 2016; Volkmann *et al.* 2016).

The parameters in a WBM-WTM model are few and usually the model employs a snow-ball effect until a dynamic steady state is attained for various precipitation types. It computes water release from large reservoirs as a function of inflow to the reservoir, current storage, mean annual inflow, and maximum capacity (Trambauer *et al.* 2013). Over the years, there has been modification of this model to WBMplus class to cater for irrigation and reservoirs, the permafrost effect (HydroDynamic Model (HDTM 1.0) and Pan-arctic Water Balance Model (PWBM)) and treating soil moisture routinely (HDTM 1.0). The parameter values in WBM are priori- assigned and with no calibration.

The development of the Macro-Probability Distribution Model (Macro-PDM) in 1998 (Arnell 1999) resulted in the observation of river discharge simulation as both direct runoff and delayed runoff. Just as in WBM, similar classification of vegetation is determined but the soil moisture at field capacity is assumed mathematically and determined within sub-divisions below the grid level to account for variations. In a grid cell, the relationship between potential evapotranspiration (PET) and ET is linearly proportional to the average soil moisture. It was observed that six out of thirteen model parameters are globally uniform. In addition, the Max-Planck Institute (MPI), in 1998, developed the Max Planck Institute – Hydrology Model (MPI-HM) that coupled the European Centre Hamburg Model (ECHAM) GCM to a hydrological discharge (HD) model (Hagemann and Dümenil 1998). This made it suitable to model potential irrigation water consumption (Haddeland *et al.* 2014). The model partitions vegetation at finer resolutions on the basis of vegetation maps introduced by Matthews (1983) since vegetation flourishes under ambient water content in the root zone. The groundwater flow is explained as a single reservoir while the river discharge and overland flow are considered as a sequence of linear reservoirs.

The Global Water Availability Assessment (GWAVA) model (Meigh *et al.* 1999), which was also developed in order to study water scarcity issues, also uses probability distribution in the simulation of soil moisture storage. It is driven by rainfall and evaporation.

Model outputs include simulated monthly flows and a cell-by-cell comparison of water availability (Trambauer *et al.* 2013). This model treats irrigation schemes and industrial water use, population and livestock watering as a basis for water demand. Four simplified land cover categories, which are bare soil, bushes, grass and trees, are used in this model. Groundwater is determined through density and pumping tests of wells in each grid. The status of the aquifer is obtained through a determination of recharge and associated groundwater kinematics. Furthermore, soil is treated as a single layer in all the models mentioned above.

The Variable Infiltration Capacity (VIC) model, developed in 2001, is a hybrid of physically based and conceptual components (Nijssen *et al.* 2001). Soil is treated as two layers that include sub-grid variability in land surface vegetation, precipitation and capacity of soil moisture storage. Since it is a multipurpose water reservoir scheme (Haddeland *et al.* 2014), it can be a simple water balance model or an energy and water balance model. The VIC model considers thirteen land covers and these include the bare soil layer and the top vegetation cover. Simulation of snow is done as a single layer energy and mass balance model. The river routing model is used separately. This model, which is popularly used in Africa, has been applied in the US to identify regional-scale droughts and associated severity, aerial and temporal extent under historic and projected future climate (Trambauer *et al.* 2013).

The Land Dynamics (LaD) model (Milly and Shmakin 2002) is a simple balance model for large-scale land continental water and energy. The model was developed from the enhancement of an older version water and energy balance model developed by Manabe (1969). This was through the addition of groundwater storage, terrestrial sensible heat storage and stomata resistance. The state of grid cells is assessed in accordance to the degree of glaciation. Input data include incoming shortwave and counter-radiation, surface pressure, total precipitation, humidity, and near-surface atmospheric temperature and wind speed. The model does not include precipitation interception processes (Trambauer *et al.* 2013). Nonetheless, all forms of water storage are incorporated in the model including the necessary conditions for generating runoff.

The PCRaster GLOBal Water Balance (PCR-GLOBWB) model (van Beek and Bierkens 2008), developed in 2004, is a grid-based leaky bucket type of model coded in a dynamic modelling language that is part of the GIS PCRaster, which contributes to the river discharge in the forms of overland flow, sub-surface flow and groundwater flow. There are three categories of surface vegetation – irrigated, rain-fed and natural – under classification as short (obtaining moisture from the top-most soil layer) or tall vegetation (obtaining moisture from the bottom-most layer). Evapotranspiration is determined as transpiration and direct evaporation exiting soil that is bare. Haddeland *et al.* (2014) acknowledge that that this model is suited for potential water abstractions and consumption for domestic and industrial purposes.

The Water – Global Analysis and Prognosis (WaterGAP) model (Alcamo *et al.* 2003; Döll *et al.* 2003) has two main components: a Global Hydrology Model (including overland flow, groundwater recharge and river discharge) and a Global Water Use Model (including withdrawal and consumptive water use; domestic, industry, irrigation and livestock (Haddeland *et al.* 2014; Trambauer *et al.* 2013). One shortcoming noted by Trambauer *et al.* (2013) is that the WaterGAP model cannot be used in highly developed river basins that have transfers, large artificial storages and irrigation schemes, or river basins where discharge is influenced by man-made reservoirs. Hence, the model cannot be simulated well on developed basins.

The Lund-Potsdam-Jena (LPJ) and the Lund-Potsdam-Jena managed Land (LPJmL) models (Bondeau *et al.* 2007) are two German-developed GHMs. Both cater for multipurpose reservoir water schemes and offer reasonable modelling of potential and actual irrigation water withdrawals and consumption (Haddeland *et al.* 2014). While water demand simulation is done in the WaterGAP model, simulations for vegetation and crops are done in the LPJ and the LPJmL models in more detail. The WaterGAP model consists of two components – the GHM per se and the global water use model. Human water consumption (i.e. domestic, irrigation use, industrial, thermal power production and livestock watering) is incorporated in the global water use model (Malsy *et al.* 2014; Flörke *et al.* 2013; Aus der Beek *et al.* 2010). The GHM model involves the calculation of the vertical and lateral water balance in each grid and treats soil as a single layer. Surface and sub-surface flow are transported as a fast process, and the base flow is transported as a slow process. The explanation pertaining to the lateral movement of overland flow is achieved by a set of multiple storages that represent streams, lakes (both global and/or local), reservoirs and wetlands.

The development of LPJmL model, however, was achieved through the addition of a hydrology module onto the dynamic global vegetation model (DGVM). Photosynthesis, plant respiration, evapotranspiration and the carbon cycle are done under the vegetation routine simulation of the model. The model is capable of simulating up to twelve crop types and nine natural plant types (both irrigated and rain-fed). The model assumes a mixture of both natural vegetation and types of crops within each grid. The model facilitates the dynamic generation of the vegetation inputs in order to achieve the calculation of the water balance for each using a river routing module (Rost *et al.* 2008). Water that is consumed in evapotranspiration is categorised into the productive (promoting transpiration in plants) and non-productive (relating to interception losses and direct evaporation). The two 'buckets' represent the soil storage.

The Water and Snow balance Modelling system (WASMOD-M) (Widén-Nilsson *et al.* 2007), which originates from WASMOD (Xu 2002), utilises few and usually four to six calibrating parameters. Simulation in WASMOD-M is done at monthly time steps for each grid and can separate overland flow into fast and slow processes. The simulation routine in each grid can account for rain, accumulation of snow, snowmelt and evapotranspiration. The parameters are, however, regionalised in order to simplify model application. Of all the six parameters in the model, calibration is possible on five and one is stationary (Widén-Nilsson 2007).

The H08 model (Hanasaki *et al.* 2008 a; b) is a two-purpose reservoir scheme that deals with both irrigation and non-irrigation systems in more integrated and detailed way (Haddeland *et al.* 2014). The model consists of six modules - river routing, land surface hydrology, environmental flow requirements, reservoir operation, crop growth and anthropogenic water withdrawal. The calculation of both the energy and hydrology balance is done in the land surface hydrological module. It utilises the leaky-bucket concept to simulate the soil moisture (Hanasaki *et al.* 2008a).

The Total Runoff Integrating Pathways (TRIP) model (Oki and Sud 1998) uses the river routing module. TRIP encompasses a network of integrated pathways that provide information on lateral water movement over land. The heat unit theory is used in the crop routine of the model, (Barnard 1948; Phillips 1950) and it is based on the Soil and Water Integrated Model (SWIM) (Krysanova *et al.* 1998). The SWIM itself is based on SWAT and MATSALU which are a comprehensive GIS-based tools for hydrological and water quality modelling in mesoscale watersheds (from 100 to 10,000 km^2) (Trambauer *et al.* 2013). The heat unit theory, however, provides an explanation regarding each and every plant's possession of its own ambient temperature range that enables the plant to achieve maximised growth. SWIM, a river basin model, was developed by the Potsdam Institute for Climate Impact Research (PIK) to accomplish simulation of hydrology, sediments, carbon movement and nutrients, plant growth and yield. Nineteen types of crops were investigated and large water storage dams (for volumes in excess of 10^9 m^3) were used.

The ISBA-TRIP model (Alkama *et al.* 2010) was developed from a combination of two models; the modified Land Surface model established by Noilhan and Planton (1989) and the overland flow pathway network, TRIP, also established by Oki and Sud (1998). ISBA is a relatively simple LSM that uses the force-restore method to calculate the time evolution of the surface energy and water budgets (Noilhan and Planton 1989). It includes a comprehensive sub-grid hydrology to account for the heterogeneity of precipitation, topography and vegetation in each grid cell. A representation of the soil is done by three layers, while a simulation of daily discharge is routed in TRIP by ISBA into river discharge.

2.3 Comparison of Model Features

A grid format is a prescribing feature in all GHMs. The spatial resolution in most GHMs is 0.5 degrees, except at the Equator, where it is slightly above 3,100 km^2 per grid cell. The available global meteorological data and computational resources are used to determine the grid format and resolution that could be employed, thus making the gridded format convenient in the manipulation of input data (e.g. gridded format are made available as remote sensing (RS) data). The advent of faster computers and availability of input data that is of a spatially finer resolution has encouraged the development of a higher resolution GHMs. The new generation of GHMs include a five minute version of WaterGAP, namely WaterGAP3, six minute version of PCR-GLOBWB (i.e., PCR-GLOBWB 2.0) and 2010 version of WBMplus that performs simulations at a range of resolutions determined by the underlying gridded network (45", 90", 3', 5', 6', 15') (Sood and Smakhtin 2015).

The available input data is normally made up of a monthly time step, but most of the GHMs have a one-day temporal resolution. Historical 20^{th} century data need downscaling into daily temporal scale since it is available at monthly temporal resolution. Advancements in meteorological reanalysis data have enabled the use of more inputs in the models. The development of the fourth generation of ECMWF reanalysis (ERA) daily data sets from 1979 to date resulted in some GHMs' using ERA data (Wada *et al.* 2010), and in studies to perform intercomparison between models (Weedon *et al.* 2011).

An explicit consideration of reservoir storage is done in the five models, WBMplus, WaterGAP, PCR-GLOBWB, LPJmL and H08. Only PCR-GLOBWB is incapable of irrigation-directed simulation. Some models treat several soil layers as a single storage unit (Macro-PDM, MPI-HM, WASMOD-M, H08 and WaterGAP), while others consider multiple storage layers (LaD – five layers, ISBA-TRIP – three layers, PCR-GLOBWB - two layers, LPJmL – two layers, VIC – two layers). Only LPJmL and H08 models can explicitly simulate crop growth. Although all the models have capabilities to deal with meteorological data changes such as the climate change induced vagaries in precipitation and the changes in ET due to variations temperature, only the models that have crop growth and/or vegetation models have the abilities to handle changes in plant physiology due to increase in temperature and to changes in CO_2 concentration. As a result of this, LPJmL and H08 are well suitable for evaluating climate change impact scenarios on crop yield and hence on hydrology. The simulation of natural vegetation (also agriculture) in LPJmL and the proportion of different vegetation classes in each grid are based on relative importance in terms of water, space, light and other environmental factors (Gerten 2013).

Spatial data remains an essential necessity in modelling. Land coverage is one of the most important element of the necessary spatial data as it plays a decisive role in hydrological modelling. However, only models such as the WaterGAP, LaD, LPJmL and VIC have a higher potential to allow a detailed determination of land-use classification. Other models exhibit simple classifications, for example WBM-WTM categorises land-use into the three classes grassland, shrubland and forest, while the 2010 version, WBMplus, categorises land-use into multiple classes and is capable of handling four categories (Wisser *et al.* 2010). Thirty-two of the vegetation classes from the Terrestrial Ecosystem Model can be simulated in the WBMplus model (Melillo *et al.* 1993). The capabilities of the 2010 version of WBM include directly handling numerous classes of vegetation-related parameters as input from external sources and in making simulations using the different parameter combinations possible (Sood and Smakhtin 2015). Macro-PDM utilises only grassland and forest categories for land use while the PCR-GLOBWB is able to handle the three categories: irrigated crops, rain-fed crops and natural vegetation with further emphasis placed on vegetation height (i.e. in the simulation of ET from different soil profile layers) (Sood and Smakhtin 2015).

The different models offer different determinations of energy balance, soil stratification and sub-grid effects. About half of the models (LaD, H08, ISBA-TRIP, MPI-HM, PCR-

GLOBWB, VIC) under review herein have their own energy balance modules. A grid, in some models the WaterGAP and the PCR-GLOBWB, is considered as a homogenous spatial entity as they relate to data on climate parameters, infiltration and vegetation, while others account for sub-grid effects in an attempt to explain variable heterogeneity in each grid cell (VIC, ISBA-TRIP). Some models, such as the ISBA-TRIP, treat root-zone depth as one of the soil layer heights while other models have a stationary depth of the first layer (PCR-GLOBWB – 0.3 m, LPJmL – 0.5 m) (Sood and Smakhtin 2015).

The main output in all the models is river discharge which results from apportioning precipitation into evapotranspiration, soil moisture, fast and slow flow (although the terms used may be different, e.g., overland flow, lateral flow and base flow). The WaterGAP, LPJmL, VIC and H08 also consider the water requirements of several crops because all these models have a detailed land-use classification. All models provide output at grid level (mostly 0.5-degree resolution). These model outputs are compounded to basin scale on the grounds that all are within river basin boundary (Sood and Smakhtin 2015). Of these models, none utilises direct incremental drainage sub-basin discretisation.

The GHMs are not necessarily developed for hydrology alone. There are other reasons behind their development, with LPJmL for example being a dual purpose model that has the vegetation and the hydrological model components. The ISBA-TRIP, LaD and VIC are hydrology models but also incorporate a component of energy balance, while the H08 model can also be used to determine energy balance and crop growth. The WaterGAP and WBM_{plus} are meant only for irrigation purposes, while the GWAVA also focuses on water use. It should be noted that WBM_{plus} is ideally suited for potential irrigation water withdrawals and consumption only (Haddeland *et al.* 2014). The utilisation of any PET equation in a hydrological model may not be regarded as an energy balance since the framework of the model already has an energy balance built into it. Nonetheless, the incorporation of land-use changes in all models reviewed is lacking (Agarwal *et al.* 2002), while the impact of financial implications on hydrology in the GHMs is not considered.

2.4 Trends in GHMs Development

There is a globally-connected effort lead by the Global Water System Project (GWSP) and the Integrated Project Water and Global Change (WATCH) seeking to bring together all stakeholders related to the development of GHMs so that they can participate in an intercomparison project of models. Seven different GHMs were offered climate related inputs, and their outputs were compared at varying spatial scales of major river basins. During this exercise, it was noted that little agreement existed between models on global water projections. For instance, the range of predicted global overland flow from different models was approximately 45% of the mean simulated overland flow (Haddeland *et al.* 2011). Similarly, Gudmundsson *et al.* (2012) applied nine large-scale water cycle models in Europe and found huge disparities in model accuracies that included high variations in the low overland flow percentile.

There is an initiative on a four-yearly basis currently been undertaken - Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). Several GHMs, including MacPDM, WBM, VIC, MPI-HM, H08, WaterGAP and PCR-GLOBWB, along with other global impact models, are part of this project, where new climatic and socioeconomic scenarios developed as part of IPCC's Fifth Assessment Report, are used as forcing, and their possible impact on different sectors (such as agriculture, ecosystems, health, infrastructure and water) are being evaluated (Sood and Smakhtin 2015).

2.4.1 Focusing on Model Uncertainties

Models represent real-world systems, with modelling focussing and aiming at ensuring the minimum model uncertainty through parameterisation in the most parsimonious manner (Efstratiadis 2014). According to the WATCH study (Voß *et al.* 2008), simulation of total annual flow between the models provided a small deviation with a coefficient of variation (CV) of about 0.09, while larger deviations were observed for colder (polar, with the exception of Antarctica - CV of about 1.0) and drier regions (Continental Africa and Australasia - CV of about 0.41). Although there was a generally similar total flow, there were very huge variations in the soil moisture (CV - 0.33) and evaporation results (CV - 0.27) and these results warranted more detailed insight into model structural differences. Simulation in some models indicated a likely increase in total global freshwater flow for the period 2071 to 2100, and a reduction shown in other models (Voß *et al.* 2008) ranging from -40 to +30%. On the overall, there was high uncertainty in the processes that are intermediate as shown in that study. Wada *et al.* (2013) utilise seven GHMs for the assessment of the impact of climate change on future irrigation water demand. The conclusion that was observed was that high uncertainty is due to GHMs rather than to GCMs (Sood and Smakhtin 2015).

Currently, most uncertainties in GHMs have been inadequately emphasised or analysed. Mostly validation of model outputs of GHMs is done through an inter-comparison of the results with the output of other GHMs. There could be many uncertainties in hydrological modelling but the common four types are: those related to the structure of the model, inputs, parameters (or values) and outputs. The uncertainties associated with the GHM WaterGAP were analysed by Palmer *et al.* (2008). It was concluded that, basing on this and other analyses (such as Döll *et al.* 2014, Müller *et al.* 2014, Sood and Smakhtin 2015), there were higher uncertainties due to inputs than the parameter uncertainties. Using performance of the model calibration as an indicator, the studies found that total uncertainty in river discharge averaged 43% in large river basins, 32% in lower and 25% in higher. In another study, Widén-Nilsson (2007) compared the WASMOD-M and five other global models with the results from all the models indicating a high volume error (i.e. error in the river discharge), although the regions of high error were inconsistent. The volume error ranged from 50 to 65 % in most cases. Biemans *et al.* (2009), in their prediction of river discharge at global scale, found out that precipitation uncertainty had a multiplier effect. The results indicated uncertainty in the precipitation data at an average of 30% and yet when used as an input with the GHM, LPJmL it showed an uncertainty in river discharge at an average of 90%.

Several studies (Dimitriadis *et al.* 2016; Tsendbazar *et al.* 2016; Müller *et al.* 2014; Kauffeldt *et al.* 2013; Mulligan 2013; McMillan *et al.* 2012; Döll and Siebert 2002 and Arnell 1999) have attributed the evident high uncertainty in model inputs to data scarcity or inconsistent input data. Data scarcity correlates well with the level of regional development where developing regions experience greater data scarcity (Katiraie-Boroujerdy *et al.* 2016; Schuol and Abbaspour 2006), and gaps caused by missing data, weak observational infrastructure and lack of desire to share data. In addition, the low-quality data that is often flawed and disinformative (Kauffeldt *et al.* 2013) often provides a falsified sensation of data that could be considered rich. This leads to increased model uncertainty (Sampson *et al.* 2016; Wang *et al.* 2016b).

All GHMs (other than WaterGAP) are subjected to tuning when they convert flow from the grids into river discharges with the validation following the observed data from generally large-gauged rivers (Sood and Smakhtin 2015). This can be exemplified in the way the PCRaster Global Water Balance model (PCRGLOBWB) utilises annual river discharge time series from 99 large river basins, the MPI-HM 35 river basins for validation, Macro-PDM 31 large river basins, and the LaD, VIC, WaterGAP (needs calibration) (Sood and Smakhtin 2015). This annual river discharge time series is for H08, GWAVA, WASMOD-M and ISBA-TRIP 26, 33, 37, 82, 96, 663 and 724 river basins respectively (Sood and Smakhtin 2015). It should however be stated that the number of river basins used is variable for the calibration/validation of the same model depending on the study, with 724 calibration stations made for WaterGAP as used by Döll *et al.* (2003) and 1,235 stations used for the same model by Hunger and Döll (2008).

It is clear that limited tuning/calibration may introduce uncertainty in model outputs. There could also be inherent inaccuracies due to direct river discharge measurements and the modification of most large rivers features, a high priority nowadays, (Döll *et al.* 2009). This makes for a compelling case to include river alterations and water withdrawals in future modelling activities in GHMs (van Beek *et al.* 2011). In addition, a tremendous decrease in the number of river-gauging stations has been observed worldwide from the early 1990s, such that current gauging network now monitor river discharge only from an approximately 50% of the land mass (Fekete and Vörösmarty 2007; Fekete *et al.* 2002).

2.4.2 Integrating with Remote Sensing

Data collection is expedited by the use of Remote Sensing (RS) (Barrett *et al.* 2016; Tayyebi and Jenerette 2016; Sood and Smakhtin 2015). Advancements in RS technologies can effectively minimise uncertainties related to inputs and observations (Baraskar *et al.* 2016; Politi *et al.* 2016). The anticipated use of GHMs is dependent on the advancements in RS technologies and the availability of RS data to the general public. Many GHMs already utilise digital elevation models (DEMs), solar radiation and land use input data that is derived through satellites. It is arguably more accurate to use ground-based than satellite-based measurements but it may also be very impracticable to have this ground-based data for all points on the globe.

The use of satellite data for calibration seems to be the source of the future influence in hydrological modelling and acquisition as this data has increased in the last decade. Global soil moisture maps are now available since the launch of European Space Agency's (ESA) Soil

Moisture and Ocean Salinity (SMOS) satellite in November, 2009. Large microwaves (Lband) are used to determine brightness temperature from which the calculation of surface soil moisture can be done. Validation of the data is done using a wide array of measurements that are ground-based (International Soil Moisture Network) and implemented by the Global Energy and Water Cycle Experiment (GEWEX) in conjunction with the Group on Earth Observations (GEO) and the Committee on Earth Observation Satellites (CEOS) and ESA. It seems likely that active and passive microwave technologies will result in the attainment of composite systems (Das *et al.* 2011).

A combined radiometer and synthetic aperture radar operating at L-band (1.20 - 1.41 GHz) was released by the National Aeronautics and Space Administration (NASA) in 2014 (Neeck 2015). Although there are limitations evidenced with respect to the measurement of soil moisture at increased depth, the application of the RS soil moisture is a pre-requisite for calculating the dynamics of soil moisture in a model. It has now become easy to obtain satellite-derived evapotranspiration products such as the Moderate-resolution Imaging Spectroradiometer (MODIS) product, MOD 16. A modified ordinary Penman–Monteith equation served as a basis for the development of MOD16 (Mu *et al.* 2007). Satellite-based data has been under investigations in order to determine ET and enhance further calibration in a model for a 46,000 km^2 basin in southern India (Immerzeel and Droogers 2008). In these efforts, Surface Energy Balance Algorithm for Land (SEBAL) was used to determine ET from satellite-acquired data thus making the whole exercise complicated and parameter-sensitive. This indicates that a more accurate and direct ET estimates can be used in calibrating GHMs (Sood and Smakhtin 2015).

Several satellite-based products, such as the Leaf Area Index (LAI), are now being used to determine vegetation characteristics (Garrigues *et al.* 2008). Products including MOD15 from MODIS, a twofold database at 1km resolution of ecosystems and land surface parameters for meteorological applications (ECOCLIMAP-II/Africa), Global Land Products for Carbon Model Assimilation (GLOBCARBON) and an algorithm derived from SPOT/VEGETATION sensors with a 10-day temporal sampling and 1/112° (about 1km at Equator) ground sampling distance, were used in a Plate Carrée projection for the period 1999- 2007 (CYCLOPES) and these described the consistent temporal profiles over most vegetation types. Since the Gravity Recovery and Climate Experiment (GRACE) satellite launch, focus was on the measurement of terrestrial storage (see Li *et al.* 2016c; Zhou *et al* 2016; Döll *et al.* 2014; Ramillien *et al.*

2014; Alkama *et al.* 2010; Tang *et al.* 2010; Syed *et al.* 2009; Strassberg *et al.* 2009) and could be coupled onto hydrology (Werth *et al.* 2009). It should however be noted that the spatial and temporal resolution in GRACE is very coarse and may be prone to uncertainties. GRACE makes observations on atmospheric mass changes, storage forms of surface waters, soil and on groundwater. At a particular point in time, only four components can be measured in GRACE during the satellite's pass over. Continental water storage snapshots are determined on an infrequent basis in GRACE (estimated at 10 days) and its spatial resolution is approximately 200 km (i.e., 2 x 2 degrees at the Equator) (Sood and Smakhtin 2015).

It is therefore, clear that GRACE has higher uncertainties than the uncertainties in GHMs regarding smaller river basins (Alkama *et al.* 2010). Furthermore, the development of GRACE or related technologies could minimise such uncertainties. The launch of the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission in 2009 began the provision of data related to earth's gravity at 100-km resolution and assists in addressing this GRACE coarse resolution issue.

2.4.3 Improving Precipitation Inputs

The performance of any hydrological model is dependent on the quality and scale of available input data, especially that on precipitation. Traditional (rain-gauge) precipitation data remains limited worldwide. Radar technology, which is an improvement over rain-gauge data can now be used, however it still has limitations due to range and obstructions. An uninterrupted, global meteorological data collection can nonetheless be provided by satellites and in that way improve the primary input to hydrological models. Both the geostationary satellites that observe visible (VIS) and infra-red (IR) radiation, and the Low Earth Orbiting (LEO) satellites that use Microwave (MW) technology, provide precipitation information. They have their distinct strengths and weaknesses (Kidd *et al.* 2009). The availability of higher resolution VIS and IR data means that the derived precipitation is always dependent on the relationship between cloud top temperature and rainfall, i.e., 'cold-cloud duration' methods (Kidd *et al.* 2009). However, the estimated precipitations are determined as indirect measurements thus making them erroneous. Passive MW technology addresses these issues but their existing spatio-temporal resolution is still a determining factor in their effective use in hydrological modelling. Calibration of passive MW techniques still needs to be done to determine precipitation (Sood and Smakhtin 2015).

Various efforts seeking to produce precipitation data sets that are more reliable have been made in order to augment the capabilities of the geostationary and LEO satellites (Kuligowski 2002). Satellite-derived precipitation data in hydrological modelling is still at the pioneering stage and thus hindering advances in the outputs of GHMs in comparison to radar- or ground-based precipitation data (Tobin and Bennett 2009). As a result, the manipulation of meteorological reanalysis data may close the existing long-term historical rainfall data gap. Li *et al.* (2013) computed hydrological output in southern African river basins by enforcing a regional hydrological model with rainfall obtained from two different sources – reanalysis of ERA-40 and satellite-based Tropical Rainfall Measuring Mission (TRMM). The results of this analysis show that river discharge simulations indicated better results when modelling was forced with rainfall (after bias correction) from reanalysis as compared to rainfall that was satellite-derived. It is my contention that satellite-derived precipitation and hydrological models offer a reliable application as indicated in this study.

2.4.4 Improving Spatial Resolution

Wood *et al.* (2011) argue that the too high uncertainties in GHMs and too coarse spatial resolutions used in GHMs - 50-km grids (considering 0.5° grids) undermine the effective simulation of the hydrological cycle. This is followed by a further proposal for the development of future GHMs at '*hyperresolution*' scale (i.e. 100-m at continental level and 1-km globally) though there could be limitations associated with acquiring such enormous computing power. Gosling *et al.* (2011; 2010) utilised Campus Grid to perform model simulation on multiple GCMs with climate change data. A reduction in computation time of 9 hours from 750 hours on a single-processor personal computer was achieved. The ready availability of high resolution RS data in the last decade has made it relatively feasible for GHMs to be used to address many local issues even at basin-specific levels. The increasing complexity and resolution of GHMs may lead to the demand for more spatially diverse observational data at the ground level (which is already a big problem). This is confirmed by Sood and Smakhtin (2015), in consideration of this complexity, who question whether the ultimate intention of increasing spatial resolution is to address local water resources problems in the applications of GHMs.

Modelling at finer spatial resolution may assist GHMs to model at the small basin scale (instead of the grids) (Sood and Smakhtin 2015). This can be applied in South Africa, where evaluation and monitoring of water resources is done on a 'quaternary' sub-basin scale because there is a very detailed system of basin delineation. Quaternary sub-basins are incremental drainage subdivisions, 'flowing' one into another and covering the entire country. Approximately 2,000 of these sub-basins, with an average area of 60 km^2 regions that have high humidity and 2,000 km^2 regions that have high aridity, exist. As a result, the water management problems can be addressed at finer subdivisions - the "quineries". In another example, India performs large scale assessments on as many as 19 major drainage areas that are not so detailed subdivisions. The areas that possess these drainage areas vary from 22,000 to 860,000 km^2 (Sabarmati River Basin) and (Ganga River Basin) respectively (Amarasinghe *et al.* 2005). In addition, the USA has the whole country's detailed catchment delineation done to six levels in the form of the Watershed Boundary Dataset that is freely available. These six levels' classification is sub-watersheds (level 5), watersheds (level 4), sub-basins (level 3), basins (level 2), sub-regions (level 1) and regions (level 0). An average drainage area is approximately 160 km^2 at the sixth-level drainage delineation criterion. Hence, such finer resolution river basin delineations only exist in few countries but the aim is to account for the water management problems at the much refined subdivisions scale. Nonetheless, as noted by Sood and Smakhtin (2015) a closer integration of such models to the country-specific national drainage divisions could be advantageous.

Massive strides are made in South Africa to employ models for hydrology and water resources planning with the water resources being modelled at river basin level. Gosling *et al.* (2011) note that river basin-scale hydrological models (CHMs) usually simulate water resource impacts that are based on a more explicit representation of river basin water resources than that available from GHMs. This has culminated in an improvement of various models with several others being developed (ORASECOM 2007).

Two models from a wide array of models at the disposal of both the South African government and private sector are discussed here. The models discussed here are the water resources systems models which comprise the water resources yield model (WRYM) and the water resources planning model (WRPM). Both models were developed by the Department of Water Affairs and Forestry to assist planners in the assessment and management of the country's water resources (Lombaard *et al.* 2015). The WRYM and the WRPM are both network-based water resource models used to analyse complex water systems under various operating and growth scenarios. Both models are used by the department for detailed river basin analysis throughout South Africa. The models are, nevertheless, updated from time to time in response to the changing analysis needs. As a recent development, a user interface WRYM - IMS has been made to improve data management and output viewing facilities. This improves the model efficiency and decreases set-up time and costs. The new interface also provides users with expanded possibilities for access and data handling.

2.5 Water Reuse in River Basins with Multiple Users

Unravelling the water users' proper interaction in a river basin is an essential requirement towards a sound management of water resources, particularly in a context where there is need to save water in the face of increasing water scarcity. It is imperative for a thorough exploration of processes associated with water reuse in a river basin. This should be compounded by a further comprehensive review of existing methods to form a direct or indirect description of both consumed and non-consumed water, recoverable flow and/or water reuse (see Figure 2).

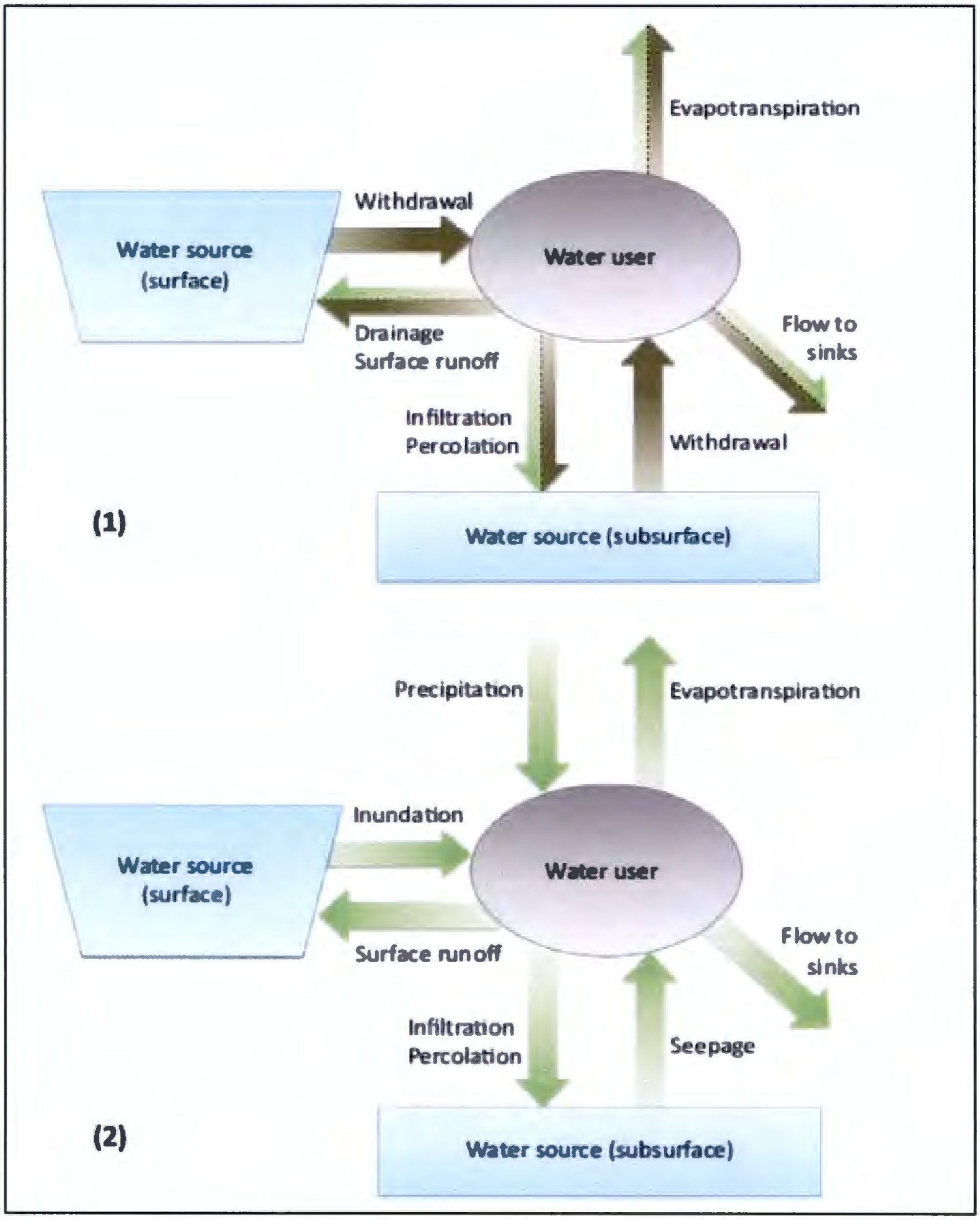

Figure 2: Typical hydrological flows associated with water users dependent on (1) natural inflow and (2) water withdrawal. Green arrows indicate flows governed by natural processes; brown arrows indicate anthropogenic flows (managed by humans).

(Simons *et al.* 2016: 560)

Based on Simons *et al.* (2015: 565), the description of the basic categorisation of flow processes for comparing consumed and non-consumed water uses the following equations:

$$Q_w = Q_c + Q_{nc} \quad (1)$$

$$Q_{nc} = Q_r + Q_{nr} \tag{2}$$

where Q_w is surface water or ground water abstraction, Q_c is consumed water, Q_r is recoverable water, Q_{nc} is non-consumed water, and Q_{nr} is non-recoverable water.

From Eqns. (1) and (2), it may be indicated that the hydrological fractions that follow are:

$$CF = Q_c/Q_w \tag{3}$$

$$NCF = Q_{nc}/Q_w \tag{4}$$

$$RF = Q_r/Q_w \tag{5}$$

$$NRF = Q_{nr}/Q_w \tag{6}$$

where CF is the Consumed Fraction, RF is the Recoverable Fraction, NCF is the Non-Consumed Fraction and NRF is the Non-Recoverable Fraction.

On the basis of the recoverable fractions of users upstream, it is possible to account for the recoverable flow that arrives at certain locations in an interconnected water users' cascade. The hypothetical equation that follows for a system is derived from Q_{nc} in the reuse, with three different RF amounts that are present in the system:

$$Q_r = ((Q_{w_{init}} * RF_x)^{nx} * (Q_{w_{init}} * RF_y)^{ny} * (Q_{w_{init}} * RF_z)^{nz})/Q_{w_{init}}^{\Sigma n-1} \tag{7}$$

where $Q_{w_{init}}$ is the first user's water abstraction in the cascade, RF_x, RF_y and RF_z are different amounts of the recoverable fraction, nx, ny and nz are the number of users in the system with RF_x, RF_y and RF_z respectively, and R_n is the amount of times water is used by subsequent individual water users prior to reaching at the calculation point location. Solving Equation 7 recoverable flow at user C is Q_r = ((100 ⁄ 0.6)1 ⁄ (100 ⁄ 0.5)1)/100(2-1) = 30. The concept of Eqn. (7) can be subjected to adjustment for different RF values in a cascade. In the case of all water users' RF values, or in the water recycling case, the equation can now be:

$$Q_r = (Q_{w_{init}} * RF)^n/Q_{w_{init}}^{\Sigma n-1} \tag{8}$$

or

$$Q_r = Q_{w_{init}} * RF^n \quad (9)$$

Based on a $Q_{w_{init}}$ of 100 units leads to the exploration of how Eqns. 7 - 9 dictate that Q_r decreases with an increase in the number of withdrawals along a flow path. For purposes of demonstration, the system is simplified to consist of single RF users. A selection of four scenarios (0.3, 0.5, 0.75 and 0.9) represents different types of water users. An RF of 0.9 typically represents an industrial water user where most abstractions return back into the hydrological system. An RF of 0.75 is a plausible value for domestic abstractions, as not all households are connected to a sewage system and water is consumed by people and animals for respiration. An RF of 0.5 ideally represents the irrigation sector, and an RF of 0.25 could be negligible greenhouses return flows (sometimes even 0 when all water is recycled internally). It can be demonstrated that after 5 - 6 reuse cycles, hardly any recoverable water will remain in a succession of water users with an RF of 0.5 or lower.

To put the portion of recoverable water into perspective of total non-consumed water, Q_r is meaningfully expressed as a fraction of Q_{nc} by:

$$RE = Q_r / Q_{nc} \quad (10)$$

$$RE = RF/NCF \quad (11)$$

with RE being termed Recycling Efficiency and Return Flow Efficiency. It is proposed that the term Reuse Efficiency for RE be used. An RE of 1 indicates that $RF = NCF$ and all water that is non-consumed can be recovered downstream. A high amount for RE is a desirable situation, irrespective of whether the water user is chiefly non-consumptive or consumptive.

Owing to the meaningful differences in processes which dictate transport of recoverable water through, to ground water and against surface water, an important qualification is necessary between $Q_{r_{sw}}$and $Q_{r_{gw}}$ term. Or, in fractions:

$$RF_{sw} = Q_{r_{sw}}/Q_r \quad (12)$$

and

$$RF_{gw} = Q_{r_{gw}}/Q_r \quad (13)$$

where $Q_{r_{sw}}$ and $Q_{r_{gw}}$ are the portions of recoverable water that contribute to surface water and ground water recharge respectively, RF_{gw} is the fraction of recoverable water contributing to ground water recharge, while RF_{sw} is the fraction of recoverable water feeding into surface water. High values for RF_{gw} are indicative of a more complex reuse system and increased uncertainty of the time scale associated with recharge, transport and downstream recovery.

Even when the focus is on deliberate abstractions only, discharge of return flow can be by both natural and anthropogenic pathways. Knowledge about whether recoverable flow is governed by artificial or natural processes provides a detailed opinion on the opportunities for the management of this flow spatio-temporally. The description of this differentiation could be:

$$Q_r = Q_{r_n} + Q_{r_a} \quad (14)$$

$$RF_a = Q_{r_a}/Q_r \quad (15)$$

$$RF_n = Q_{r_n}/Q_r \quad (16)$$

where Q_{r_n} is representative of the natural processes' flow discharged such as unmanaged surface runoff, percolation, infiltration, and Q_{r_a} is the anthropogenic flow dictated by man-made infrastructure that includes sewerage, drains and canals. RF_n and RF_a are the natural and anthropogenic fractions respectively. A high RF_a amount warrants more direct opportunities for management interventions.

An evaluation of reuses of surface water and ground water that is based on reuse water measurements at surface and underground via check dams has to be done separately. Surface water reuse can be observed to increase proportionally with 4.6 x 10^6 m^3 per 1000 ha, with the farmers that pump for either supplemental or complete irrigation which leads to an increment of (re)use of water via pumping by 1.3 x 10^6 m^3 per 1000 ha.

In a simple formula expression:

$$y_{sw} = Q_{w_{sw\_ha}} * \chi + B_{sw} \quad (17)$$

$$y_{gw} = Q_{w_{gw\_ha}} * \chi + B_{gw} \quad (18)$$

where y_{sw} and y_{gw} are the reused surface water and ground water volumes respectively, $Q_{w_{sw\_ha}}$ constitutes use of water via dams per ha, $Q_{w_{gw\_ha}}$ is representative of ground water abstractions per ha, and B a residual term close to 0. All ground water abstractions are envisaged as reuse since percolation occurs at a faster rate than ground water abstractions.

At a location (x, y), the term Water Reuse Index (WRI) is calculated on dividing the aggregate of upstream water (agricultural, domestic and industrial) abstractions $Q_{w_{upstream}}$ by the annual surface (mean) and subsurface runoff $(Q_{x,y})$ at that particular site. This was adopted by the United Nations in their World Water Development Reports (2012, 2009, 2006 and 2003) and the SEEAW water accounting framework (UN 2012):

$$WRI_{x.y} = \sum Q_{w_{upstream}} / Q_{x,y} \quad (19)$$

The term Return Flow Ratio is computed for a river basin, user, or site, as the amount of upstream non-consumed water on dividing by the surface water (available). In generalised terms, RFR is defined as:

$$RFR_{x.y} = \sum Q_{nc_{upstream}} / Q_{sw\_x,y} \quad (20)$$

where $Q_{nc_{upstream}}$ is non-consumed water (upstream) and $Q_{sw\_x,y}$ is surface runoff at the site, user or river basin being considered. Note that if ground water can be ignored, the difference between Eqns. (20) and (16) is the accumulated consumptive use.

The degree of return flow reuse indicates the fraction of recoverable water being reused in the river basin. For specific irrigated conditions with clearly defined source and reuse schemes, and both an internal and external drain that collect drainage water that is potentially reused, it is defined as follows:

$$DRR = \left(\chi_D Q_{P,D} + \chi_D \chi_E Q_{P,E}\right) / D_{CS} \quad (21)$$

where χ_D is the mixing ratio between surface drainage from a source scheme and total inflow into a drain, χ_E is the mixing ratio of river basin drainage water with external water sources, $Q_{P,D}$ and $Q_{P,E}$ are the volumes of pumping by internal and external reuse stations respectively, and D_{CS} is surface drainage from the source scheme.

A generalised water reuse system can be applied to the conceptual model, irrespective of type of downstream water use ("reuse scheme"), upstream water use (the "source scheme"), or pathway between them ("drain"). A sequence of mixing ratios is always inclusive in the case of a series of multiple reuses. Acknowledgement of presence of different destinations of the recoverable flow is allowed for in the concept, and further allows for a distinction between sources of water as follows:

$$DRR = \left(\chi_{sw} * Q_{w_{sw\_downstream}} + \chi_{sw} * Q_{w_{gw\_downstream}}\right)/Q_{nc} \quad (22)$$

where χ_{sw} is the mixing ratio of non-consumed water from a user with surface water, $Q_{w_{sw\_downstream}}$ is surface water withdrawal downstream, χ_{gw} is the mixing ratio of non-consumed water with ground water, $Q_{w_{gw\_downstream}}$ is ground water withdrawal downstream, and Q_{nc} is the non-consumed water from the user under consideration.

The fraction of gross inflow to a water user that is dependent on reuse of upstream non-consumed water is expressed as the reuse dependency RD, originally termed "dependency of reuse schemes". RD is expressed as:

$$RD = DRR_{upstream} * Q_{nc_{upstream}}/Q_w + P \quad (23)$$

or alternatively:

$$RD = \chi_{upstream} * Q_w/(Q_w + P) \quad (24)$$

where $\chi_{upstream}$ is the mixing ratio of upstream users of non-consumed water with the water source, and P is supply of precipitation to the user. The reuse dependency relates to the portion of withdrawal that is provided by non-consumed recoverable water to the gross inflow. Reuse dependency may increase due to a higher mixing ratio, an increase in withdrawals, or a decrease of rainfall. Similar to DRR, this indicator gives a direct assessment of water reuse, but requires a large amount of input data.

The Water Saving Efficiency (WSE) is introduced to express the effectiveness of water saving measures in an indicator. WSE is defined as the ratio between the increase in river discharge, and the reduction in on-farm irrigation water application that caused this increase in inflow. Or, in more general terms:

$$WSE = \left(Q_{sw_{downstream\_new}} - Q_{sw_{downstream\_old}}\right) / \left(Q_{w_{old}} - Q_{w_{new}}\right) \quad (25)$$

where $Q_{sw_{downstream\_new}}$ is surface runoff at a certain downstream point after an implementation of the water saving measure, $Q_{sw_{downstream\_old}}$ is downstream runoff before implementation, $Q_{w_{old}}$ is water withdrawal before implementation, while $Q_{w_{new}}$ is water withdrawal after implementation.

The downstreamness of a function in the basin (e.g., water availability or water use) is defined as the downstreamness-weighted integral of that function divided by its regular integral. For example, the comparison between D_{χ} of storage capacity and D_{χ} of actual stored volume is proposed as an indicator of closure of the (sub-) basin that supplies the location under consideration. An analysis of downstreamness is useful to evaluate water reuse and the vulnerability of a type of water use. For a basin with n geographical units:

$$D_{wd} = \frac{\sum_{\chi=1}^{n} WD_{\chi} D_{\chi}}{\sum_{\chi=1}^{n} D_{\chi}} \quad (26)$$

where D_{χ} = downstreamness of water demand at location χ; and WD_{χ} = water demand of location χ. D_{wd} is a measure of how far downstream water demand in the basin is located on average, and can therefore be viewed as a proxy for water reuse. The observation of a high value for D_{wd} for a type of water use could indicate a larger dependence on recoverable water from upstream users.

2.6 Water Resources Models in South Africa

The Water Resource Yield Model (WRYM) and the Water Resource Planning Model (WRPM), supported by WQT, and in the Berg, ACRUSalinity are used to develop reconciliation strategies. These models use the naturalised and stochastic flow sequences generated using the river basin models and determine the sequence of actions that need to be undertaken to reconcile the water requirements with the available water at an adequate reliability of supply. The links between the models are shown in Figure 3.

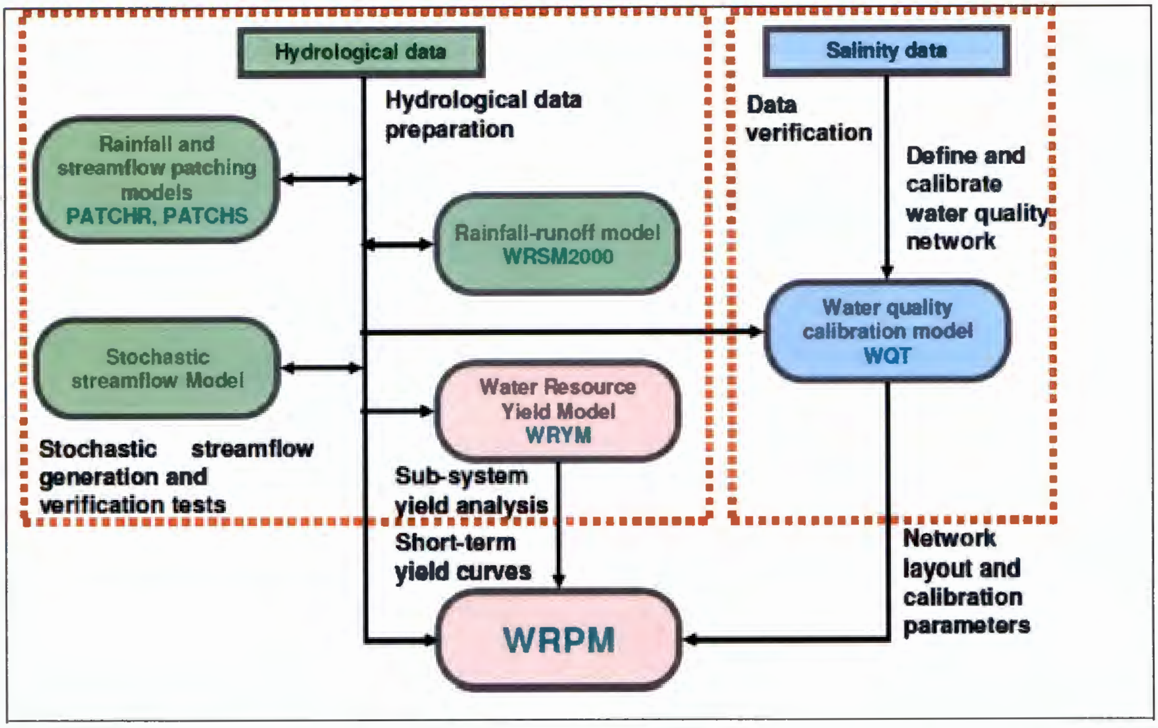

Figure 3: Schematic showing the processes and links between models used for water resources planning

2.6.1 Water Resources Yield Model (WRYM)

The WRYM is a monthly stochastic yield reliability model used to determine the system yield capability at present day development levels (ORASECOM 2011). It was developed by the South African Department of Water Affairs (SA-DWA) for the purpose of modelling complex water resource systems and is used together with other simulation models, pre-processors and utilities for the purpose of planning and operating the country's water resources. The model allows for scenario-based historical firm and stochastic long-term yield reliability analysis. It can also be used to determine short term reservoir yield reliability.

The WRYM uses a sophisticated network solver in order to analyse complex multi-reservoir water resource systems for a variety of operating policies. It is designed for the purpose of assessing a system's long- and short-term resource capability (or yield). Analyses are undertaken on a monthly time-step and for constant development levels, i.e. the system configuration and modelled demands remain unchanged over the simulation period. In addition, the major strength of the model lies in the fact that it enables the user to configure most water resource system networks using basic building blocks. This means that the configuration of a system network and the relationships between its elements are defined by means of input data, rather than by fixed algorithms embedded in the complex source code of the model.

Recently, SA-DWA has developed a software system for the structured storage and utilisation of hydrological and water resource system network model information. The system, referred to as the WRYM Information Management System (IMS), serves as a user friendly interface with the Fortran-based WRYM and substantially improves the model's performance and ease of use. SA-DWA incorporates the WRYM data storage structure in a database and provides users with an interface which allows for system configuration and run result interpretation within a Microsoft Windows environment.

Finally, the SA-DWA recently made available the WRYM Release 7.5.6.7 which incorporates a number of new sub-models designed to support the explicit modelling of water resource system components in various studies. Detailed information in this regard may be obtained from the Water Resources Yield Model (WRYM) User Guide – Release 7.4.

2.6.2 Water Resources Planning Model (WRPM)

The WRPM, which is similar to the WRYM, uses short term yield reliability relationships of systems to determine what a specific planning horizon's likely water supply volumes will be on the basis of given starting storages, operating rules, user allocation and curtailment rules. The model is used for the operational planning of reservoirs and inter-dependant systems, and provides insight into infrastructure scheduling, probable curtailment interventions and salt blending options (ORASECOM 2011).

The nature of the analysis methodology is novel and significant. The WRPM analysis methodology has a unique feature evident in its ability to simulate drought curtailments for water users, receiving water from the same resource, with different risk requirements (profiles). This methodology makes it possible to evaluate and implement adaptive operating rules (transfer rules and drought curtailments) that can accommodate changing water requirements (growth in water use) as well as future changes in infrastructure (new transfers, dams and/or dam raisings) in a single simulation model. A combination of these simulation features in one model affords the WRPM the ability to undertake risk based projection analysis for the operation and development planning of water resource systems. The WRPM, therefore, simulates all the interdependencies of the aforementioned variables and allow management decisions (operational and/or developmental) to be informed by results where all these factors are properly taken into consideration (Saruchera and Lautze 2016; ORASECOM 2011).

It is of paramount importance to establish a point of departure when attempting to compare models. Models are compared in terms of strengths, weaknesses and data functionality (ORASECOM 2010). Opinions on the particular strength or weakness of a model are relatively subjective. What may be considered the strength of a model to one modeller could be that very model's weakness to another. For this reason, the discussed categories have been selected on the basis of the specific purposes of the WRYM and WRPM, especially as they relate to the management of the Orange-Senqu Basin water resources.

The strengths and weaknesses of the WRYM and WRPM are described under the following categories: general, hydrological features, river and infrastructure features, risk based analysis and other functionality. Both the WRYM and WRPM models have a good service track record and have been tailored to suit the Southern African hydrological conditions. They are also both network based in that they have a fully modularised network that is solved sequentially. The WRYM and WRPM are both monthly time step models that do not necessarily require huge amounts of data based on this region's long droughts (i.e. >15yrs). The nature of input and/or output data handling in WRYM can be in tabular or graphical formats, though output may not be via GIS nor animated whereas WRPM output files are large, labour-intensive and require more computing power. The WRYM has a basic network visualiser and allows data manipulation through this visualiser whereas the WRPM does not have this ability. Both models do not have GIS capabilities.

The WRYM model has a structured database, including a number of data input files. It also has a pre-processor functionality and has the ability to store metadata and reports. Should it be required, there is also an option to store study metadata. These functions are, to a lesser extent, available in the WRPM through the data input files, which are edited using a text editor. Plans are underway to build a user interface for the WRPM similar to that of the WRYM, which will assist with data and information management. Both models can carry out multiple runs since they can carry out a scenario management.

One major weakness of both models is the lack of user friendliness. In addition, technical model support can only be obtained telephonically or by e-mail and by very few people, thus making the whole exercise difficult. It is often very costly. Both models require high and very scarce levels of skills to maintain and upgrade. However, the SADC-sourced water experts and software developers can improve on the functionality of both models. This can be proved by two instances from Lesotho and Namibia in which special additional features were added to accommodate a given requirements (ORASECOM 2010). This leads to an analysis of the impacts of socio-economic changes and climatic variability on agricultural trade and embedded water resources because South Africa relies on increasingly stressed water resources (Dalin and Conway 2016).

2.7 Water Governance in South Africa

South Africa's water resources are managed from an Integrated Water Resources Management (IWRM) perspective (Shah and van Koppen 2016; van Koppen and Schreiner 2014; UNDP 2013). This IWRM, designed in conjunction with the Global Water Partnership (GWP), the World Bank, the United Nations Development Programme (UNDP) and the Swedish International Development Cooperation Agency (SIDA), is "is a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital eco-systems and the environment" (GWP 2009:18). The IWRM concept is founded upon five guiding principles, which were formulated during the International Conference on Water and Environment in Dublin in 1992 (GWP 2012):

Principle 1: Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.

Principle 2: Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.

Principle 3: Women play a central part in the provision, management and safeguarding of water.

Principle 4: Water is a public good and has a social and economic value in all its competing uses.

Principle 5: Integrated water resources management is based on the equitable and efficient management and sustainable use of water.

The scarcity of water is a global crisis that has to be tackled as a problem of governance and through the implementation of IWRM, both of which are highly dependent upon a country's water resources governance framework (Mehta *et al.* 2016; Cook 2014; Lim 2014; Mehta 2014; van Koppen and Schreiner 2014). At all different levels of society, water governance requires the careful use, development and management of water resources and the delivery of water services while mindful of political, social, economic and administrative systems and scales (Wutich *et al.* 2014; DWA 2013a; DWA 2012a; b; c; d; e; f; DWA 2011).

An improved water governance has an environmental dimension characterised by a sustainable use of water resources and ecosystem integrity. It also includes parameters such as the quality and quantity of water resources and acknowledges the relevant importance attached to managing and maintaining ecosystem services. Water quality is on a perpetual decline in many parts of the world resulting in the use of intensive agriculture, which makes poor people's livelihood opportunities often directly dependent upon sustained access to natural resources such as water, particularly in areas prone to droughts, floods and pollution (UNDP 2013). Water governance also acknowledges the provision of the legal framework for all actions in the water sector, hence, it is a primary determining factor for the (sustainable) development of water resources and has a profound impact on people's livelihoods.

The economic dimension thoroughly examines the role of the efficient use of water resources to achieve a holistic growth within all spheres of economic activities. Economic growth is influenced by water and other natural resources. As a result, an effective governance of water leads to the achievement of positive effects on per capita income in many countries around the world. The social dimension of water governance seeks to achieve a proper and equitable use of water resources, because water is often unevenly distributed spatiotemporally, between rich and poor or urban and rural settlements. Water-related services and water allocation have direct impacts on people's livelihood opportunities and their health. Therefore, any governance should underscore the creation of an institutional and administrative framework that enables people from diverse backgrounds and different interests to cooperate peacefully and coordinate their actions (UNDP 2013).

The success of local governments' application of IWRM principles is highly dependent on the water governance framework and existing governance structures' awareness of the need to embrace proper planning and implementation of the IWRM. Local governments have a limitation in that they are not instrumental in the development of legislations and national policies. In addition, they are only capacitated to carry out mandates in water management. Their key responsibility is to actively involve all members of its community, promote participatory decision-making and engage with disadvantaged groups, thus contributing to sustainable bottom up approaches (DWAF 2004a).

South Africa's Constitution Act 106 affirms that everyone has the right to access of sufficient food and water and to an environment that is not harmful to their health or well-being. The Act's proclamation stamps authority on the need to protect the environment for the benefit of all people living in the now and future, by preventing pollution and ecological degradation, promoting conservation, and securing ecologically sustainable development through the use of natural resources that promote justifiable economic and social development. It declares the national government as the custodian of all ground and surface water resources and puts local government in charge of municipal water services (Bill of Rights, Section 24, DWAF 2008). The Constitution furthermore separates the powers between the national, provincial and local government and emphasises cooperation between all levels. The Act also states that the overall management of water resources is allocated to the national government, while the management of water and sanitation services for all citizens is allocated to the municipalities.

South Africa's National Water Act of 1998 provides the legal national framework for the effective and sustainable management of the country's ground and surface water resources, especially with regard to the resources' protection, use, development, conservation and control, in an integrated manner (DWAF 2008; DWAF 2004a). Water resources were historically distributed unequally during the apartheid era in South Africa, as a result, the policy of the multi-racial democratic government tried to address the inequalities by ensuring an equitable allocation of water throughout the Republic in an attempt to satisfy the basic needs of all inhabitants (Movik 2014). The new National Water Act, formulated during the transition from and immediately after the apartheid era, replaced the previous Water Act of 1956. The new Act, which recognises that water is a natural resource that belongs equally to all people in South Africa, brought about a major shift in water resources management in South Africa. It fosters water management at the lowest possible level through decentralised decision-making by established catchment management agencies (CMAs) in order to reach the previously disadvantaged communities and address race and gender inequities (DWAF 2008). Therefore, 1998 National Water Act highlights the important role of stakeholder participation in water management by promoting equal involvement, participation and decision-making at different levels. The Act also highlights the essential role that water plays in the achievement of social and environmental justice and promotes the overall goal to achieve sustainable economic, social and environmental development through integrated water management approaches (Besada and Werner 2015; Acreman *et al.* 2014; Cooper *et al.* 2014; Falkenmark *et al.* 2014; Guzinski *et al.* 2014; Hordijk *et al.* 2014; Sutherland *et al.* 2014).

The first National Water Resource Strategy (NWRS) was published in 2004 with the NWRS (Second Edition) made available in June 2013 in order to put the National Water Act into practice and to ensure an efficient and sustainable water management. The National Water Act requires the Minister to establish a NWRS, which must provide information about how water resources will be managed and about the establishment, function and power of the institutions that will manage water resources within the country (Munnik 2011). This presents the instruments by which to plan, develop and manage water resources in an integrated and sustainable manner across all sectors, so as to achieve national development objectives. Hence, the NWRS sought to put the policy and laws of the national water governance of the DWAF into practice, by addressing social equity and economic growth, without compromising environmental sustainability (see DWAF 2012b).

The NWRS also controls water use and pollution in the country. It achieves this through the economic tool of Water Licensing, which covers all aspects of licensing and permits related to water abstraction in South Africa. Water Licensing controls water abstraction between different water users: from low water users with a minimal risk to impacting water resources to high-volume water users such as the agriculture and industry sectors that have a very high risk of impacting water resources. Therefore, the NWRS aims to obviate water over use, which may have negative impacts on river basins and other water users.

Water licensing is of great significance in water management. It focuses on creating a fairer water allocation between different users, promoting more efficient water use and hence, ensuring the sustainable management of water resources (DWAF 2008). It is compulsory for every new water user that is unlisted in Schedule 1 (small water users such as subsistence farmers) or covered by a general authorisation, to apply for a license. It covers priority areas such as stressed river basins, where water demand exceeds water supply, and these include the Orange-Senqu River basin (DWAF 2008).

The licensing permissions are issued out by responsible authorities such as the DWAF or Catchment Management Agencies and refer only to a specific river or river basin. They can be issued for a period not exceeding 40 years and are subject to revision every five years. A license includes certain conditions, such as the water amount that can be stored in a dam, the quantity of water that can be extracted from certain rivers or boreholes, and the period of time for which the license applies. In case of failure to comply, the authority may withdraw the water license and can prosecute the water user (DWAF 2008).

The National Water Act also includes the Free Basic Water Policy, which was introduced in 2000. This social tool addresses the basic human water needs of the ordinary South Africans who cannot afford to pay for their water use. It contributes towards the government's fight to eradicate poverty. The government guarantees 25 litres per person, per day of domestic water provision, or a free 6000 litres of water per month per household. Water use exceeding 6000 litres per household, are then charged according to stepped tariffs. This policy formally ensures that everyone can have access to sufficient and clean water, but the implementation is the responsibility of the local governments. The government has also committed itself to provide appropriate infrastructure to bring water to an adequate distance from the underprivileged peoples' homes, so as to achieve a minimum state of welfare (van Wilgen and Wannenburgh 2016).

The primary aim of CMAs is "to involve local communities in water resource management. This is in line with the international trend to give effect to principles of participation to achieve integrated water resource management" (DWAF 2008: 37). The CMAs are ultimately responsible for carrying out functions such as water resources planning within the river basin, registration, (compulsory) water licensing, water charge collection, water authorisation and represent further the interests of all stakeholders within a basin (see DWAF 2008). The DWAF established, during the first edition of the NWRS, nineteen CMAs in the nineteen water management areas of South Africa in order to decentralise decision-making. The second edition of the NWRS, which was established in 2012, reduced the 19 CMAs to 9

CMAs in an attempt at reducing bureaucracy (Bourblanc and Blanchon 2014; Bourblanc and G-Eau 2012; DWAF 2012b).

Finally, there also exists the Water Services Act of 1997, which provides the regulatory framework and rights for the provision of basic water and sanitation services by the municipalities, water service authorities and providers to households and other municipal water users at local level (DWAF 2012b). The Act contains rules for municipalities regarding how they should provide water supply and sanitation services, and provides norms and standards for tariffs (DWAF 2008). Both, the National Water Act from the national level and the Water Services Act from the local level provide legal instruments and the legal framework with which to manage water resources and water services sustainably (DWAF 2012b).

2.8 Water Demand in the Study Area

The current economic paradigm is no longer compatible with the biophysical limits of the finite Earth such that global fresh water resources are finite in space and time (Galgano 2016; Vos and Hinojosa 2016; Dessu *et al.* 2014). This scarcity of fresh water arises from the ongoing economic development, increasing human population, and the higher standard of living being achieved by different societies. Further to the growing water demand (Brown *et al.* 2014) is a situation in which natural river flow is being challenged by land ownership, economic growth, advances in technology, various legislations, political will and social barriers. River basin scale hydrological processes are also being affected by climate and land use change/variability (Dessu *et al.* 2014).

These challenges are felt at varying levels by different river basins. For example, Butler (2014), Hannaford *et al.* (2014) and Thornton *et al.* (2014) argue that the vulnerability of the economy and livelihood to climate variation and limited capacity has witnessed Africa encountering more severe implications from climate change. Legal, moral, political and other prevailing soft decision inputs compete with the economic return of water use, thus making water resource problems both a demand–supply centred and complex social and environmental challenge. Meyer (2013) reports that the South African public exercises complex decision procedures in water resource utilisation that transcend the sphere of traditional social psychological definitions of equity and procedural justice. Water management is anthropocentric in its nature that ecological demands are treated equally with other demands to their humanly derived benefit (Dessu *et al.* 2014).

A low adaptive capacity and vulnerability to the changing climate have been observed in Africa (Meissner 2016; Kusangaya *et al.* 2014). The southern African region is also considered as the most vulnerable African region (Meyer 2013). Interestingly, water resources are at the epicentre of projected climate change impacts within the climate change matrix. Thus the potential impact of climate change on water resources is likely to increase in magnitude, diversity and severity should the changes in climate observed in the last century persist into the future. Thornton *et al.* (2014) acknowledge that the already existing large spatial and temporal variability of southern Africa to climatic factors suggest a projected increase in the impact of climate change on the region's water resources. Climate change impacts on water resources will have both direct and indirect effects on the socio-economic and the biophysical environments. Already, this is evident in several sectors, such as agriculture (Nhemachena *et al.* 2014; O'Dell *et al.* 2014; Rhodes 2014), health (Mahasa and Ruhiiga 2014; Wright *et al.* 2014; Mahasa 2013), ecosystems and biodiversity (Kjellstrom *et al.* 2014; Lazenby 2014) and energy generation (Cole *et al.* 2014).

2.9 Climate Change and Hydrologic Models: Existing Gaps and Recent Research Developments

All kinds of models find their usefulness in different applications. The models that are complex in terms of structure and input requirements are equally expected to provide adequate results for a wide range of applications, while the more simple models that have a smaller range of applications are also expected to produce adequate results at greatly reduced cost, provided that the objective function is suitable. The distinction between simple and physically-based distributed-parameter models is not only one of lesser or greater sophistication, but also intimately bound up with the purposes for which such models are to be used. Thus, choosing a suitable model is equivalent to distinguishing the situation between when simple models can be used and when complex model must be used.

2.9.1 Gaps between Climate and Hydrologic Modelling

While the atmospheric components of the GCMs are often very sophisticated (dividing the atmosphere into many layers), Kite *et al.* (1994) has shown that the land-phase parameterisations in current GCMs do not agree on predictions of most hydrological variables, even when all atmospheric forcings are identical. There exist various gaps in the relationship between hydrologic modelling and climate modelling. The gaps shown in Table 1 below are discussed in the following sections. The discussion here, therefore, seeks to make a significant improvement in the hydrologic component of climate models.

Gap 1: The spatial and temporal scale mismatches between GCMs ability and hydrology need: General circulation models (GCMs) are the current primary tools in the study and estimation of the nature of climate change. The models, which are based on the physical laws for the atmospheric composition and behaviour, attempt to provide a calculable model of the earth's climate system, the internal and external forcing and feedback in the climate system. However, the size of the climate system (atmosphere, oceans, and land) and the time range of climate experiments (several decades to thousands of years) places a heavy constraint on the design of the GCMs. This leads to spatial and temporal coarseness, where, for, hydrological models become concerned with small, sub-river basin (even hillslope) scale processes, occurring on spatial scales much smaller than those resolved in GCMs.

Table 1. Some existing gaps between GCMs' ability and hydrology need

Mismatch	Not well-simulated	Less-well simulated	Better simulated
Spatial scales	Local 0 - 50 km	Regional 50 × 50 km	Global 500 × 500 km
Temporal scales	Mean daily	Mean seasonal monthly	Mean annual and seasonal
Vertical scale	Earth surface	800 hPa	500 hPa
Working variables	Evapotranspiration Runoff Soil moisture	Cloudiness Precipitation Humidity	Wind Temperature Air pressure
GCMs' ability increases			
Low ⟶			High
Hydrological importance decreases			
High ⟶			Low

The GCMs deal most proficiently with fluid dynamics at the continental scale and operate on horizontal grid resolutions ranging from 200 to 600 km. Operation on such large spatial scales prevents the explicit modelling of climate-modifying local geographic factors such as topography and land/water-distribution or vegetation type. Moreover, although GCMs use short time steps, commonly 10 - 30 min that cascade through 10 or more atmospheric layers and then provide information for a range of climatic variables (e.g. T, P), most verifications of the models have been based on long term mean simulations for base cases similar to present conditions with the most reliable temporal scale to date remaining seasonal (e.g. Schulze 1997).

Nonetheless, hydrological impact models use a time step of one day and commonly cascade rainfall through two to three soil layers to produce output on hydrological variables, such as Q, E and 1S. Table 1 reveals that the GCMs' ability to predict spatial and temporal distributions of climatic variables decline from global to regional to local river basin scales, and from annual to monthly and then daily amounts.

The hydrological importance of climate predictions increases from global to local scales and from annual to daily amounts. Gap 2: The vertical level mismatches between GCMs' ability and hydrology need. This is due to the fact that the free troposphere is more spatially and temporally homogeneous than the earth's surface, with the GCMs being more skillful in simulating the free troposphere climate than the surface climate. However, hydrological models have to work with surface variables. It is known that the higher the altitude, the better the prediction expected from GCMs, but a less correlation with ground surface variables exists. A GCMs' output from 500 or 700 mb level is commonly used (see Table 1).

Gap 3: The mismatches between GCMs' accuracy and the hydrological importance of the variables: GCMs were conceptually designed to simulate average and large-scale atmospheric circulation. Variables, such as wind, temperature and air pressure field, can be predicted quite well. Precipitation and cloudiness are less well predicted variables. There are other variables of key importance in hydrologic regimes, such as runoff, soil moisture and evapotranspiration which are not well represented by GCMs (e.g. Loaiciga *et al.* 1996).

Table 1 shows that the GCMs' simulation skills decrease from climate variables to hydrological variables, while the hydrological importance increases along the same direction. Precipitation is less well-simulated because its common events, such as hurricanes and thunderstorms, occur at smaller spatial scale than the GCM's grid size. Evapotranspiration is not well represented by the GCMs since it occurs at model boundaries, i.e. it represents an exchange of latent heat and water mass between the earth's surface and the atmosphere. Consequently, the estimation of runoff from GCM output, as the difference between precipitation and evapotranspiration, is bound to be inaccurate (e.g. Loaiciga *et al.* 1996). There is an even more important problem with many GCMs from a hydrological point of view (e.g. Kite *et al.* 1994). The problem is that most GCMs contain no lateral transfer of water within the land phase. Such models carry out a vertical water distribution at each grid point at each time interval using precipitation, evapotranspiration, and groundwater storages. However, any 'water excess' or overflow is simply discarded and plays no further role in model computations, so that even if GCMs were able to simulate water excess correctly, they would still be operating with an incomplete hydrological cycle.

A review of current studies also indicates a number of problem areas. These problem areas are related to the GCMs' current capacity, downscaling techniques' limitations and hydrological modelling tools. One fundamental problem is that the spatial and time scales of the GCMs and hydrological models are very different.

The existing problems offer opportunities for cooperative research between hydrologists and climate modellers that could be both intellectually stimulating and potentially useful. The challenges to the two communities are specified.

Development of hydrological macro-scale models based on a more physically-based understanding of hydrologic processes and their interactions. It is only through the use of parameterisations that do not require calibration that the problems of climatic and geographic transferability can be resolved. Firstly is the development of approaches for an assessment of the uncertainty in climate prediction scenario as well as in the downscaling procedures and hydrological impact modelling. Uncertainty measures could provide an estimate of confidence limits on model results and would be of value in the application of these results in risk and policy analyses. Secondly, improved methodologies to develop climate change scenarios are needed. Removing the uncertainties in current scenarios is dependent on improvements in both GCMs and downscaling techniques are necessary. Scenarios must provide the spatial and temporal resolution required by assessment models and they must incorporate the simulated changes in mean and variability of climate variables.

Simulation capacities have generally exceeded available data bases. The collection of reliable data at a range of spatial and temporal scales is critical to the improvement of our understanding of hydrologic processes and in testing and validating the downscaling techniques and hydrological models that are being developed. The experimental response to this challenge is important because significant gains cannot be achieved through a continued extraction of information from our past measurements. Integrated measures of relevant fluxes and measurements of states that have previously not been measured or were sampled at inappropriate spatial and temporal scales are, therefore, necessary and applicable to progress at all scales.

2.9.2 Gaps in Models used in South Africa

It is worth-noting that data availability is scarce in the region thereby placing a constraint on model selection. Models have to be used for drought forecasting both at regional and continental scale. These models are suited for operational purposes such that they are continuous simulation models (i.e., not event-based models), with an assumption that if necessary they can be modified to suit the use in an operational environment. These models are not primarily used for the purpose of assessing their suitability for drought forecasting. They, however, sufficiently represent all the important water balance components for semi-arid areas. This may be due to the fact that most models do not represent the hydrological processes, such as transmission losses along the river channel, re-infiltration and subsequent evaporation of surface runoff, and the interception of the wet surface, which could be significant in arid regions. Moreover, semi-arid regions are characterised by a high temporal and spatial variability of rainfall, thus resulting in high uncertainty in rainfall estimations. This of course has an impact on the hydrological model and the simulated water balance components (DEA 2013; Trambauer *et al.* 2013; Xu 1999).

Just as stated by Trambauer *et al.* (2013), it is critical to examine each model's strengths and weaknesses in the representation of different hydrological processes and fluxes. Major assessment criteria for the model's suitability are: (1) the representation of the processes that are most relevant for the simulation of drought conditions, such as evaporation, interception, interactions of surface water and groundwater in flood plains and soil moisture dynamics and wetland areas; (2) the capability of the model to be downscaled from a continental scale to a large river basin scale model; and (3) the applicability of the model for use operationally in the early drought warning, given the data availability of the region. It is imperative that these models are suitable for hydrological drought forecasting and conditional on spatial scale, data availability and end-user forecast requirements.

2.10 Summary

An examination of the development of the GHMs showed that these models sought a hydrological balance, energy balance or both. The chapter also noted that model objectives and applications often impacted on the model complexities. Various models handled many structural issues differently and the issues include, irrigation water applications, reservoir storage, the number of soil layers, number of land-use classifications and crop growth models. Most studies on intercomparison of models have shown very little agreement. An inclusion of anthropogenic disturbances, vegetation growth models and the type of model used, accounted for these structural differences.

The use of satellite-based or Climatic Research Unit (CRU) weather input data available in gridded format has now become a norm as this is tied to the spatial resolution of the models. Most of the GHMs run on a daily time-scale. However, it may seem sufficient to use a monthly temporal scale, though it should be calibrated, in an effort to get a long-term basis in assessing the impact of climate change on global water and food trade.

While not replacing the modelling applications at local levels, the global models also need to refine their spatial resolution. An improvement in access to the observed hydro-meteorological data from developing countries is of paramount importance to the progress in the GHMs. This improvement in access can result in a more improved overall accúracy of the global hydrological modelling efforts of various hydrological cycle components. These ground-based measurements may only be a temporary solution for 'data-poor' areas because ground observations will probably never take off while RS data may need several decades to ensure a reasonably long enough time series. Hence, simulations are an absolute necessity in these areas. Improving the accuracy of the GHMs could lead to a more increased international cooperation and economic/humanitarian assistance. However, countries need to show preparedness in cooperation and granting permission for better access to national archival data of observed hydro-meteorological processes.

An improvement of the GHMs, by incorporating satellite-derived products and models, can minimise the internal uncertainties within the models making for a binding case for studies at the river basin level in southern Africa, such as the Orange-Senqu River basin, since water resources management decisions are upheld at this level. Therefore, there is need to (a) improve the use of downscaled climate change information for input into hydrological modelling, (b) reanalyse data so as to increase our understanding and improve climate change predictions, and (c) to improve, quantify and acknowledge compounded predictive uncertainty available in model outputs.

Huggins *et al.* (2010) state that there is evidence that a relative scarcity of surface and groundwater resources in the Orange-Senqu Basin is critical for South Africa, Lesotho, Botswana and Namibia's sustainable social and economic development. Furthermore, a comprehensive review of existing patterns of land and water use needs has to be done in order not to over-exploit the scarce and vulnerable water resources. The interconnectedness of the Orange system and the Vaal River makes it important that we examine the impact of the sub-systems, such as the Lesotho and other sub-systems, which feed into the Vaal (DEA 2013: 43). This will enable an understanding of the cross correlations between the drivers of climate change and the overall conditions experienced in the Orange region and its sub-systems.

The next chapter outlines water users in the Upper Orange River basin.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

The first part of this chapter presents details about the study area. This is followed by the methodology structured in terms of the different objectives as follows: for objective 1 on *identifying water users*, this appears under section 3.3; for objective 2 covering *the actual allocation of water needs*, this appears under section 3.4; for objective 3 covering *water accounting* in the study area, the applicable section is 3.5. In objective 4 covering *the state of equity in water allocation*, the methodology is presented under section 3.6 and objective 5 on *developing a water demand model* appears under section 3.7.

3.2 The Study Area

3.2.1 The Catchment

The total catchment area of the Orange-Senqu River basin is 1 000 000 km^2 and is the largest river basin in South Africa. Almost 600 000 km^2 of this area is inside the Republic with the remainder in Lesotho, Botswana and Namibia. The determination of the areal extent of the catchment area is difficult to obtain since it includes many pan areas and numerous large tributaries which rarely contribute to flows in the main river channel. The Orange River, (called the Senqu River in Lesotho), originates at *Thabana Ntlenyana* 3 482 m above sea level in the Lesotho Highlands. The average natural run-off from the total basin is more than 12 000 million m^3/a. This represents the average river flow that would occur if there were no developments of any nature in the catchment. However, this value can be very misleading since the basin is now heavily developed with the result that the current average annual run-off reaching the river mouth at Alexander Bay is less than half of the natural run-off (DWA 2012a, DWAF 2011).

A significant driver of change in the water balance of the Orange River System has been witnessed from 1994 onwards due to the storing of water in the Katse Dam as the first component of the multiphase Lesotho Highlands Water Project (LHWP). Currently Phase 1 of the LHWP (consisting of the Katse and Mohale dams, Matsoku Weir and associated conveyance tunnels) transfers 780 million cubic metres per annum via the Liebenbergsvlei River into the Vaal Dam to augment the continuously growing water needs of the Gauteng Province. Phase 2 of the LWHP, comprising of Polihali Dam and a connecting tunnel to Katse Dam, is already in its planning stages. Polihali Dam is expected to be in place by 2022. Flows that are currently still entering into Gariep and Vanderkloof dams will then be captured by Polihali Dam, thus reducing the inflow to the Gariep and Vanderkloof dams. This will result in a reduction in yield of the Orange River Project (Gariep and Vanderkloof dams) to such an extent that shortages will be experienced in the ORP system. Some sort of yield replacement will be required in the Orange River to correct the yield versus demand imbalance in the ORP system (DWA 2012a).

The Katse Dam in the Senqu sub-area is used for the transfer of water into the Upper Vaal WMA. Mohale Dam, in the same sub-area, is also used to transfer water to the Upper Vaal WMA. Metolong Dam, the latest to be constructed on a tributary of the Caledon River in Lesotho, was completed in 2013. It supplies water to Maseru and surrounding towns (DWA 2012b). The two largest dams in this WMA are the Gariep and Vanderkloof dams, which reduce the incidence of floods in the Lower Orange WMA by about 50%. Other major dams are the Welbedacht and Knellpoort dams in the Caledon catchment and the Krugersdrift, Rustfontein, and Kalkfontein dams in the Modder-Riet River catchment (DWA 2012b).

3.2.2 Water Requirements

The total water requirement for the Upper Orange WMA of the Orange-Senqu River is 4 116 million m^3/a with 3 148 million m^3/a constituting water transfers out of the area. The local water requirements for irrigation stands at 968 million m^3/a) but only 80% of the local requirements (i.e. 780 million m^3/a) is possible. Included in the transfers is the release obligation to the Lower Orange WMA of 2 035 million m^3/a. The main demand centres for urban/industrial requirements are Bloemfontein and Botshabelo and these are supplied from the Riet/Modder sub-catchment. The amount used in Lesotho is comparably insignificant at 23 million m^3/a. The projected total water requirements for the area are projected to reach 4 688 million m^3/a by the year 2025, for the base growth scenario. This rise will result from an anticipated allocation of 12 000ha of land earmarked to resource poor farmers. The diffuse irrigated area in the Upper Orange WMA of the Orange-Senqu River will, however, only be 4000 ha.

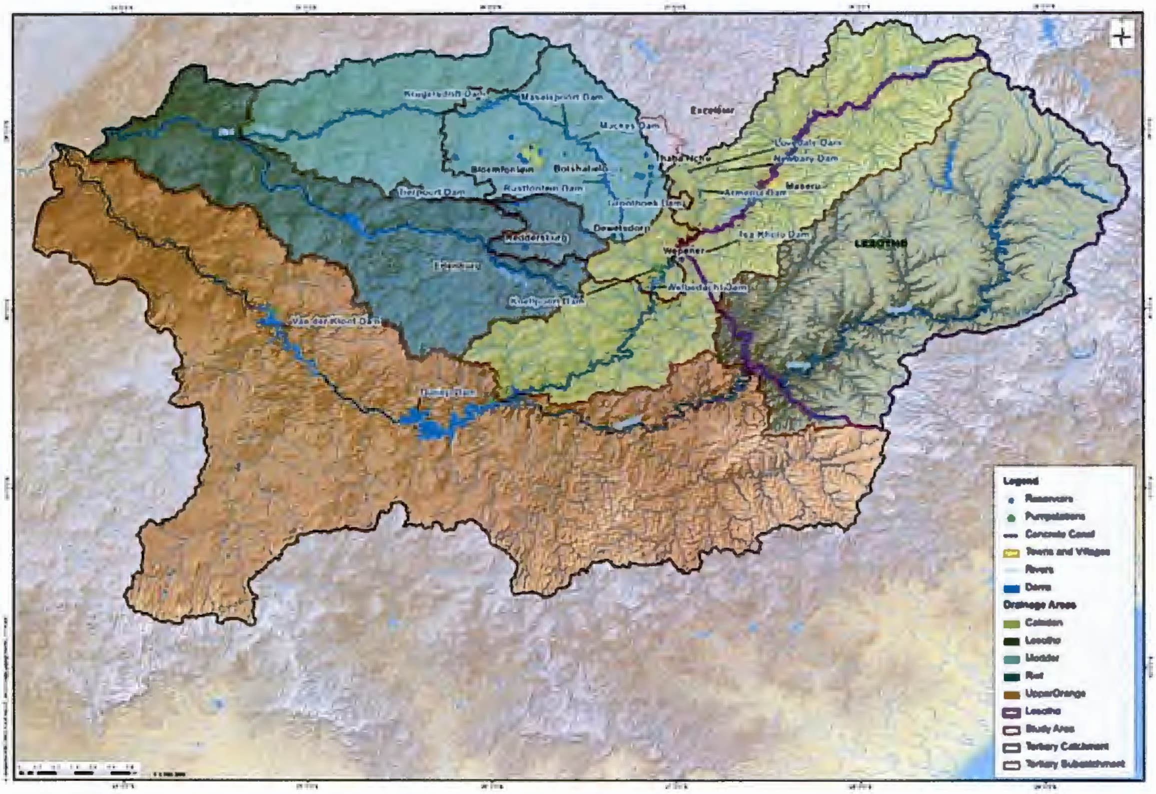

Figure 4: Major Dams per Sub-catchment

(DWA 2012c: 10)

It is noted further that the developments in the Bloemfontein, Botshabelo and Thaba 'Nchu area could limit growth in the urban/industrial and mining sectors. Initially it was thought that transfers of 344 million m³/a to the Upper Vaal WMA will suffice but that amount has since been increased to 491 million m³/a.

3.2.3 Current Infrastructure

3.2.3.1 The Greater Bloemfontein Area Water Supply System

The supply of bulk potable water to urban centres in the Modder / Riet sub-catchment is carried out by the water board organisation called Bloem Water. The area's water requirements are met from the water that is transferred from the Orange and Caledon River Systems. The main transfer water supply schemes are: (1) the Caledon – Bloemfontein transfer which supplies Bloemfontein, Dewetsdorp, and small users from Welbedacht Dam, (2) the Maselspoort Scheme, and (3) the Caledon – Modder (also known as the Novo Transfer Scheme) which supplies water via the Rustfontein Treatment Works to Bloemfontein, Botshabelo, and Thaba Nchu (DWA 2012b). A brief description of these transfer schemes is provided in the following sections.

3.2.3.2 The Caledon – Bloemfontein Transfer

The Caledon-Bloemfontein pipeline was commissioned in 1974 to supply potable water from the Welbedacht Dam on the Caledon River to Bloemfontein, Botshabelo, Thaba Nchu, Dewetsdorp, Reddersburg, and Edenburg. Sediment deposition has significantly reduced the yield from the Welbedacht Dam, a condition that led to the commissioning of Knellpoort Dam to supplement the supply of water in the above-mentioned areas. Water is pumped after purification by the Welbedacht Water Treatment Works (WTW), located downstream of Welbedacht Dam and with a capacity of 145 Ml/day, via a 6.5 km pressure pipeline and a 106 km gravity pipeline to Bloemfontein. The average capacity of the pipeline is 1.7 m^3/s and the maximum capacity 1.85 m^3/s. This infrastructure is owned and operated by Bloem Water (DWA 2012b).

3.2.3.3 The Maselspoort Scheme

The Maselspoort Scheme includes the Maselspoort WTW (110 Ml/day) and the Maselspoort Weir, which is located on the Modder River downstream of Mockes Dam (which is downstream of the Rustfontein Dam) (DWA 2012b). The Maselspoort WTW supplies approximately 25% of Bloemfontein's water needs and is owned and operated by the Mangaung Metropolitan Municipality (MMM).

3.2.3.4 The Lesotho Highlands Water Project

DWA (2012b) indicates that the development of the Lesotho Highlands Water Project (LHWP) is a result of an agreement titled the Lesotho Highlands Water Project Treaty signed between South Africa and Lesotho in October 1986. The project comprises of a number of phases with both parties having already met the condition of implementing Phase I. The Treaty also provides for the development of further phases seeking to transfer up to a maximum of 70 m^3/s (or 2 208 Mm^3/a) from the Highlands of Lesotho (Senqu/Orange River) to the Vaal River system in South Africa. Phase I of the project, however, comprises of two sub-phases, namely Phases IA and IB. Phase IA of the project comprises the 185 m high double curvature concrete arch dam at Katse. From here, water is transferred under gravity via the 44km long and 4.35m internal diameter concrete lined Transfer Tunnel to the 'Muela Hydro Power Station which discharges into the 55m high 'Muela concrete arch dam before flowing through the 38km long delivery tunnel (i.e. Trans-Caledon Transfer Tunnel - TCTA) to the Ash River outfall in South Africa. The water then flows down the Ash, Liebenbergsvlei and Wilge Rivers into the Vaal Dam.

Phase IB comprises the 145m high concrete faced rockfill dam at Mohale. A 32km long concrete lined gravity tunnel connects Mohale Dam with Katse Dam from where the water flows further through the Transfer Tunnel constructed under Phase IA to the 'Muela Hydro Power Station, and is finally discharged into the Ash River. An additional component of Phase I was the 19m high Matsoku diversion weir that transfers water to the Katse reservoir. The published Nominal Annual Yield (NAY) of Phase I is 24.7m^3/sec or 780 million m^3/annum.

The proposed Phase II works will comprise of Polihali Dam, with a wall height of 163.5m, and a gravity tunnel to Katse Dam on the Malibamats'o River. Water from the Polihali Dam will be delivered from Katse Dam via the existing Transfer Tunnel to 'Muela Hydro Power Station and then via the existing Delivery Tunnel to the Ash River. The incremental yield of Phase II is expected to be 14.75m^3/s or 465 million m^3/a. Finally, the Phase II Report indicates that Phase II will be commissioned in January 2020 and there is an anticipation that Phase 3 will only be required by 2054 (DWA 2012b).

The option of making additional early transfers from the LHWP needs to be considered for Bloemfontein and surrounding towns. Possible options for transfers in excess of the proposed delivery schedule to South Africa include additional releases into a tributary of the Caledon River to temporarily augment supplies to Maseru, Bloemfontein and other urban towns within the catchment area. This supply could delay additional capital expenditure on improvements to the existing bulk water infrastructure supplying Maseru and Bloemfontein. The implications of making additional early transfers in excess of those provided for in the treaty between Lesotho and South Africa are uncertain and would need to be resolved from a National perspective before this option can be considered (DWA 2012b).

It is proposed that water from the LHWP be released into one of the tributaries of the Caledon River probably at the existing release structure on the Little Caledon River. Water released into the Caledon River will be abstracted at Tienfontein Pump Station and delivered to the Knellpoort Dam, from where it will be transferred via the Novo Transfer Scheme and Modder River to the Rustfontein Dam to augment the supply to Bloemfontein and the surrounding towns. Currently the Novo Transfer Scheme has a pump station capacity of $1.5m^3/s$ which can be upgraded to $2.4m^3/s$ by the provision of additional pumps. This capacity can also be doubled by duplicating the Novo Pump Station and pipeline.

3.2.3.5 The Novo Transfer Scheme

The Novo Transfer Scheme, which became operational in 1998, includes Tienfontein Pump Station, a pipeline and canal from Tienfontein pump station to the Knellpoort Dam, Knellpoort Dam, and the Novo Pump Station and pipeline. The Novo pump station, which is situated on the northern side of the Knellpoort Dam, transfers water from Knellpoort Dam to the Modder River (current installed capacity is approximately $1.5m^3/s$), via a 20km pipeline running from Knellpoort Dam to the headwaters of the Modder River. Water flows from the outfall of the Novo pipeline down the Modder River to Rustfontein Dam for a distance of ±50km. Water stored in the Rustfontein Dam is treated at the Rustfontein WTW and pumped to Botshabelo/Thaba Nchu or Bloemfontein.

Water can also be released, as an alternative, from Rustfontein Dam and made to flow downstream into Mockes Dam from where it can be abstracted at the Maselspoort Weir, treated at Maselspoort WTW, and pumped to Bloemfontein. The above infrastructure is owned by DWA and operated by Bloem Water (DWA 2012b). This Caledon-Modder System supplies water to the Mangaung-Bloemfontein urban cluster, which is the largest urban centre in the study area (DWA 2012a).

3.2.3.6 Potable Water Bulk Infrastructure

Bloem Water supplies about 100 million m^3/a to about 580 000 people and is the main supplier of bulk potable water to the urban centres in the Modder / Riet River sub-catchment. The total current capacity of reservoirs (i.e. Ml = million litres) serving the Greater Bloemfontein is 425 Ml (this includes Mangaung Municipality reservoirs). The capacity of Bloem Water's bulk reservoirs is 278 Ml. The Thaba Nchu and Botshabelo reservoirs have capacities of 156 Ml and 52 Ml, respectively (DWA 2012d). In addition, Bloem Water and the Mangaung Metropolitan Municipality own and operate four WTW with associated infrastructure and these are: Welbedacht WTW (145 Ml/day), Rustfontein WTW (100 Ml/day), Groothoek WTW (18 Ml/d) and Maselspoort WTW (110 Ml/day).

3.2.3.7 Major Wastewater Treatment Works

The following Wastewater Treatment Works (WWTW), as noted by the DWA (2012b), serve Bloemfontein/Mangaung: Bloemspruit (56 Ml/day); Sterkwater (10.2 Ml/day); Welvaart (6 Ml/day); Bainsvlei (5 Ml/day); Northern Works (1 Ml/day); and Bloemdustria (<1Ml/day). In addition, the WWTWs at Botshabelo (20 Ml/day), the Klein Modder River, and Selosesha (6 Ml/day) on the Klein Modder River, serve the Botshabelo/Thaba Nchu area.

3.2.4 Available Water Supply

3.2.4.1 Surface Water

Nearly 70% of the total overland flow, which would flow through the Upper Orange Water Management Area (WMA) under natural conditions, originates from Lesotho with just more than 30% from within the WMA. The surface water resources, both within the WMA and Lesotho, are well developed and have a high degree of utilisation. The two largest dams in this WMA are the Gariep and Vanderkloof dams, which reduce the incidence of floods in the Lower Orange WMA by about 50%. Other major dams include the Welbedacht and Knellpoort dams in the Caledon catchment, and the Krugersdrift, Rustfontein, and Kalkfontein dams in the Modder-Riet River catchment (DWA 2012b). A description of the major dams per sub-catchment is provided in the following sections.

3.2.4.2 Caledon River Sub-catchment

The Welbedacht Dam is situated on the Caledon River and supplies water to urban users in Bloemfontein, Botshabelo, Dewetsdorp, and various other smaller users, as well as irrigators downstream of Welbedacht Dam along the Caledon River. The irrigators downstream of the Welbedacht Dam, however, have no claim to any water stored in the Welbedacht Dam. Only the inflow can be released for irrigation purposes. The Welbedacht WTW at Welbedacht Dam supplies water via the Caledon-Bloemfontein pipeline to Bloemfontein, Botshabelo, and other minor consumers.

The decreasing yield of the Welbedacht Dam, owing to siltation and the increasing demand on the Caledon-Bloemfontein Regional Water Supply Scheme, compelled the DWA to supplement the yield of the Welbedacht Dam by constructing the Knellpoort off-channel storage dam on the Rietspruit, a tributary of the Caledon River. The Knellpoort Dam is itself supplied with water from the Caledon River by the Tienfontein Pump station. Water pumped from the Caledon River into Knellpoort Dam is then released back into the Caledon River to allow abstraction at Welbedacht Dam by Bloem Water all year round. Furthermore, the Novo Transfer pump station is located at the Knellpoort Dam and is able to transfer water into the Modder River, which supplies the Rustfontein and Mockes Dams (DWA 2012b).

The Welbedacht Dam, from its 1973 completion, has lost more than 90% of its storage capacity due to the high siltation rates. The existence of a minimal storage capacity in Welbedacht Dam has meant that the Tienfontein pumps must operate at a high reliability on a run-of-river basis to supply Knellpoort Dam. The current pumps have a total discharge of approximately 2.5 m^3/s (design 3 m^3/s) and experience high maintenance costs as a result of fine debris and sediment that reach the pumps. The Tienfontein pump station is considered as the most critical component of the water supply infrastructure providing Bloem Water with raw water, as Bloem Water receives approximately 70% of its water supply from the Welbedacht Dam via the Tienfontein Pump station and Knellpoort Dam (DWA 2012b).

3.2.4.3 Modder River Sub-catchment

Krugersdrift Dam is located on the Modder River and supplies water for irrigation purposes to the Modder River Government Water Scheme. More than 50 weirs are constructed in the Modder River between the dam wall and the confluence with the Riet River. Mockes Dam on the Modder River supplies water to Bloemfontein via the Maselspoort WTW. Groothoek Dam is located on the Kgabanyane River, a tributary of the Modder River, and supplies water to Thaba 'Nchu. The Rustfontein Dam is located on the Modder River and forms the major storage reservoir in the Modder River. Water is released from the Rustfontein Dam to supplement the abstraction from the Mockes Dam and currently provides the major portion of water supplied to Bloemfontein at Maselspoort (DWA 2012b).

3.2.4.4 Riet River Sub-catchment

The Tierpoort Dam is situated on a tributary of the Riet River upstream of the Kalkfontein Dam and supplies water to the Tierpoort Irrigation Board through a network of unlined canals. The Kalkfontein Dam is on the Riet River and supplies water for irrigation through a network of canals and syphons to the Riet River Government Water Scheme. Urban water is also supplied to the towns Koffiefontein and Jacobsdal through the canal system (DWA 2012b).

3.2.4.5 Upper Orange River

The Gariep Dam and Vanderkloof Dam are the two largest reservoirs in South Africa and are both situated in the Upper Orange River. Both reservoirs form the main component of the Orange River Project and are utilised to supply water to urban and irrigation users in close proximity to the river course in the study area. They are also used for hydro-power generation and flood control (DWA 2012b).

3.2.4.6 Lesotho

The Lesotho Highlands Water Project (LHWP), through the construction of the Katse Dam as the first component of the multiphase LHWP, has altered the water balance condition of the Orange River System. This transfer of 780 million cubic metres of water through an infrastructure consisting of Katse, and Mohale dams, Matsoku Weir and associated conveyance tunnels alleviates the continuously growing water needs of the Gauteng Province. The water flows via the Ash, Liebenbergsvlei, Wilge and Vaal Rivers into the Vaal Dam.

Phase 2 of the LWHP, which is set to comprise of the Polihali Dam and connecting tunnel to the Katse Dam, is already in its planning stages. The Polihali Dam is expected to be completed and standing by around 2022. Flows that are currently entering into the Gariep and Vanderkloof dams will then be captured by the Polihali Dam, thus reducing the inflow to the Gariep and Vanderkloof dams. This will result in a reduction in yield of the Orange River Project (the Gariep and Vanderkloof dams) to such an extent that shortages will be experienced in the ORP system. Some sort of yield replacement is then required in the Orange River to correct the yield versus demand imbalance in the ORP system (DWA 2012a).

The Katse Dam in the Senqu sub-area is used for transfer of water to the Upper Vaal WMA. Mohale Dam, which is in the same sub-area, is also used to transfer water to the Upper Vaal WMA. The Metolong Dam, the latest construction in Lesotho and lying on a tributary of the Caledon River, was completed in 2013. It supplies water to Maseru and surrounding towns (DWA 2012b).

3.2.4.7 Groundwater

Groundwater is currently not utilised for the supply of potable water to Bloemfontein. However, some individuals use groundwater to irrigate gardens in residential areas while some in the Bainsvlei/Kalkveld area and that to the south-west of Bloemfontein, use groundwater extensively for agricultural purposes. Groundwater is also utilised by a small sector of industry in close proximity to the city limits for the bottling of water and micro irrigation of vegetables and nurseries (garden centres). Small towns and communities in the vicinity of Bloemfontein, such as Dewetsdorp, Reddersburg, Edenburg, Wepener, and Excelsior, are partially dependent on groundwater for drinking and domestic purposes. Groundwater is, therefore, considered as an essential resource, specifically for the smaller towns (DWA 2012b).

3.2.4.8 Climate

The climate over the water management area is cool to temperate and ranges from semi-arid to arid. Rainfall mainly occurs as summer thundershowers, and reduces dramatically from as high as 1000 $mmyr^{-1}$ in South Africa at locations in the east to about 200 $mmyr^{-1}$ in the west. Rainfall in Lesotho, which is the source of most of the water in the Upper Orange water management area, varies between 600 and 1500 $mmyr^{-1}$. Potential evaporation in the entire water management area is well in excess of the rainfall (DWA 2012a).

3.2.4.9 Dams

There are now three main storage reservoirs on the Orange-Senqu River and these are the Katse Dam in Lesotho, and the Gariep Dam and Vanderkloof Dam in South Africa. At 5 000 million m^3, the Gariep Dam is the largest reservoir in South Africa while Vanderkloof Dam comes second at 3 200 million m^3. Although the storage of the Katse reservoir is lower at a modest 1 950 million m^3, it is the highest dam in the Southern Hemisphere with a height of approximately 185m above foundation (Brown and King 2012, DWA 2012a).

The Vanderkloof Dam is currently the last main dam on the Orange-Senqu River and effectively controls the flow of water along the 1 400km stretch of river between the dam and Alexander Bay on the Atlantic Ocean. The banks of the Orange-Senqu River, downstream of Vanderkloof Dam, are heavily developed in many areas, principally for irrigation purposes. Both the Gariep and Vanderkloof dams are used to regulate the river flow for irrigation and to produce hydro-electricity during peak demand periods. Very little of the Orange-Senqu River water is used for domestic or industrial purposes, with the exception of that used in the Vaal River basin (DWA 2012a).

There also exist some smaller dams that are of varying levels of importance in the area. First are Armenia and Egmont dams on tributaries in the Caledon sub-area. Second are the Welbedacht dam lying on the main stem of the Caledon River and the Knellpoort Dam an off-channel storage dam that supplements the water supply to Bloemfontein. Third are the Rustfontein, Mockes and Krugersdrift dams, situated on the Modder River, and the Tierpoort and Kalkfontein Dams lying on the Riet River.

3.3 1dentification of Water Users

3.3.1 Research Design

For the objective on identification of water users a qualitative methodology was used involving questionnaires, interviews with specialists and key role-players, document analysis and observations (i.e. ground-truthing). The questionnaire dealt with general demographic data of respondents in an effort to ease the mood between the researcher and the respondent as it had no bearing on the study. It further addressed policy, water allocation, financial, technical, human and material resource capacity information of the selected water institutions. In total, there were sixty questions in the questionnaire. Most questions were close-ended and respondents were guided by given options that were already set out. The water users who were chosen for interviews were identified on the basis of a particular status; whereas the inclusion criteria were based on data availability and their role in the local economy. The interviewees were selected on the basis of their working area and expertise in the areas of water management in their respective institutions. Only one interviewee was chosen per institution. It was fore-thought that the key respondents could confirm or correlate existing information in allocation schedules.

The study considered the allocation schedules from the Department of Water Affairs (DWA) and Orange-Senqu River Commission (ORASECOM), questionnaires and interviews. In addition, field observations were also used where possible and after permission had been granted.

Finally, four questionnaires were allocated in order to retrieve key policy information on both external and internal issues from the two countries (South Africa and Lesotho). Each distributor was allocated one questionnaire in this tier level. As a result, a total of seven water users in the study area and immediate surrounds were considered.

3.3.2 Sampling Procedure

One expert from each water department or entity was interviewed. The interviews were conducted on a four tier setting at national, water management agency (WMA) or provincial, district, and local municipal levels. The total number of interviews conducted on the South African side were two at national, three at WMA level, four at district and twelve at local municipality levels. The statistics of interviews conducted on the Lesotho side are: two at national, one (i.e. Water and Sewerage Company - WASCO) at department level and three at local levels (town council). Justification for this is that there are four levels relating to water management in South Africa whereas there are only three in Lesotho.

The sampling strategy was designed to cover wide range of determining factors such as water allocation needs and number of licenses issued at the key sites, which reasonably represented the whole study area. It also involved retrieving information from the national, provincial, municipal and various users' inventories in the area.

3.3.3 Data Collection

Data sources

Primary data was collected through field surveys. Allocation schedules indicating water licensing from DWA and ORASECOM were used. Secondary data sources in the form of archival data was made available to this researcher in digital format by the Department of Water Affairs, Department of Environmental Affairs (DEA) and various stakeholders dealing with water management issues. Similar secondary data was obtained from the Lesotho Highlands

Development Authority (LHDA) of the Lesotho Highlands Water Project (LHWP), Ministry of Water, Energy and Mining (WEMMIN), (WASCO) and the Maseru Municipal Council.

In addition, structured interviews were conducted with selected transnational departments, namely DWA – RSA, Lesotho Highlands Development Authority (LHDA) and Department of Water Affairs (DWA – Lesotho) in order to identify the various users in the study area. The water users were determined in accordance with data availability and their relative role in the local economic sectors such as agriculture, industrialisation, residential consumption and tourism. Experts from three WMAs, Bloem Water and Sedibeng Water – RSA side and WASCO, on the Lesotho side, were interviewed to obtain this data.

3.3.4 Data analysis

Data retrieved from available records of water users and allocation policy documents in the study area and descriptive statistics was employed to analyse this data. An identification of the critical managerial and technical limitations in the efficient water demand management practices against allocation schedules was done to answer the objective stated earlier. A set of limitations were extracted for further use in the discussion section of the project.

3.4 Allocation of Water Needs

3.4.1 Research design

For objective 2 on allocation of water needs, the study followed a research design alluded to in section 3.3.1. The next sub-sections outlines the methodologies which were followed.

3.4.2 Sampling Procedure

One expert from each water department or entity was interviewed. The interviews were conducted on a four tier setting at national, water management agency (WMA) or provincial, district, and local municipal levels. The number of South African interviews, which were conducted are: two at national, three at WMA level, four at district, and twelve at local municipality levels. On the Lesotho side, interviews conducted were two at national, one at department level (i.e., Water and Sewerage Company - WASCO) and three at local levels (town council). The sampling strategy was designed to cover wide range of determining factors (e.g.

water allocation needs, number of licenses issued, etc.) at the key sites, which reasonably represented the whole study area.

The document analysis involved retrieving information from the national, provincial, municipal and various users' inventories in the area.

3.4.3 Data Collection

Data sources

Primary data was collected through field surveys. Structured interviews were conducted amongst selected transnational departments, DWA – RSA, Lesotho Highlands Development Authority (LHDA) and Department of Water Affairs (DWA – Lesotho), in order to identify the various users in the study area. The water users were determined on the basis of data availability and their relative role in the local economy (i.e. relative to agriculture, industrialisation, residential consumption and tourism). Experts from the three WMAs, Bloemwater and Sedibeng Water on the RSA side, and WASCO on the Lesotho side, were interviewed in an attempt to gather data on water users.

Secondary data in the form of archival data, made available in digital format from the Department of Water Affairs, Department of Environmental Affairs (DEA) and various stakeholders dealing with water management issues, was used. Similar secondary data was obtained from the Lesotho Highlands Development Authority (LHDA) of the Lesotho Highlands Water Project (LHWP), Ministry of Water, Energy and Mining (WEMMIN), WASCO and the Maseru Municipal Council.

3.4.4. Data analysis

Qualitative analysis of interview data was employed to analyse this data. This was also done for data retrieved from available records of water users and allocation policy documents in the study area was analysed using descriptive statistics. The study used Statistical Package for the Social Science (SPSS) software for multiple regression analysis and analysis of variance (i.e., one way Analysis Of Variance (ANOVA) between the groups) at 95% confidence level (equation 27). Pearson correlation was used to determine the measure of the linear correlation between all variables that were thought could have an influence of some sort on water allocation.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots\ldots \beta_n X_n \quad (27)$$

where y = water demand,

β = parameter, (i.e. water demand per user or volume of water per user, etc.)

X = independent variables (i.e., financial, technical, institutional and human-related variables).

The results from the objective were used to identify the critical technical and managerial limitations in the efficient water demand management practices in relation to allocation schedules. A set of limitations were extracted for further use in the discussion section.

3.5 Water Accounting 1994 – 2014

3.5.1 Research design

For objective 3 on water accounting the study used a qualitative methodology which involved the use of research questionnaires, interviews with specialists and key role-players, document analysis and observations where possible. The questionnaire dealt with general demographic data of respondents in an effort to ease the mood between the researcher and the respondent as it had no bearing on the study. It further addressed policy, water allocation, financial, technical, human and material resource capacity information of the selected water institutions. In total, there were sixty questions in the questionnaire. Most questions were close-ended and respondents were guided by given options that were already set out. The water users who were chosen for interviews were identified on the basis of a particular status; whereas the inclusion criteria were based on data availability and their role in the local economy. The interviewees were selected on the basis of their working area and expertise in the areas of water management in their respective institutions. Only one interviewee was chosen per institution. It was fore-thought that the key respondents could confirm or correlate existing information in allocation schedules. The period 1994 – 2014 marks a shift in water policy issues for post-apartheid South Africa.

The study considered the allocation schedules from the Department of Water Affairs (DWA) and Orange-Senqu River Commission (ORASECOM), questionnaires and interviews. In addition, field observations were also used where possible and after permission had been granted.

Finally, four questionnaires were allocated in order to retrieve key policy information on both external and internal issues from the two countries (South Africa and Lesotho). Each distributor was allocated one questionnaire in this tier level. As a result, a total of seven water users in the study area and immediate surrounds were considered.

3.5.2 Sampling Procedure

One expert from each water department or entity was interviewed. The interviews were conducted on a four tier setting at national, water management agency (WMA) or provincial, district, and local municipal levels. The total number of interviews conducted on the South African side were two at national, three at WMA level, four at district and twelve at local municipality levels. The statistics of interviews conducted on the Lesotho side are: two at national, one (i.e. Water and Sewerage Company - WASCO) at department level and three at local levels.

The sampling strategy and network was designed to cover wide range of determining factors such as water allocation needs and number of licenses issued at the key sites, which reasonably represented the whole study area. It also involved retrieving information from the national, provincial, municipal and various users' inventories in the area.

The document analysis involved retrieving information from the national, provincial, municipal and various users' inventories in the area.

3.5.3 Data Collection

Data sources

Primary data was collected through field surveys. Allocation schedules indicating water licensing from DWA and ORASECOM were used. Secondary data sources in the form of archival data was made available to this researcher in digital format by the Department of Water Affairs, Department of Environmental Affairs (DEA) and various stakeholders dealing with water management issues. Similar secondary data was obtained from the Lesotho Highlands Development Authority (LHDA) of the Lesotho Highlands Water Project (LHWP), Ministry of Water, Energy and Mining (WEMMIN), (WASCO) and the Maseru Municipal Council.

In addition, structured interviews were conducted with selected transnational departments, namely DWA – RSA, Lesotho Highlands Development Authority (LHDA) and Department of Water Affairs (DWA – Lesotho) in order to identify the various users in the study area. The water users were determined in accordance with data availability and their relative role in the local economic sectors such as agriculture, industrialisation, residential consumption and tourism. Experts from three WMAs, Bloem Water and Sedibeng Water – RSA side and WASCO, on the Lesotho side, were interviewed to obtain this data.

3.5.4 Data analysis

A qualitative methodology which involved the use of research questionnaires, interviews with specialists and key role-players, document analysis and observations where possible was used. From available records of water users and allocation policy documents in the study area and descriptive statistics was employed to analyse this data. An identification of the critical managerial and technical limitations in the efficient water demand management practices against allocation schedules was done to answer the objective stated earlier. A set of limitations were extracted for further use in the discussion section of the project.

3.6 Equity in Water Allocation System

3.6.1 Research Design

For this objective a similar route was followed as that outlined section 3.5.1. The area has a total of seven *water user association*s and/or irrigation boards (IBs). Out of the seven, five are located within the study area while two are outside the study area. The two are supplied from the study area through Inter-basin Transfers (IBTs) on the Orange River upper reaches of the area and "which is notably much interconnected" (DEA 2013: 43). According to ORASECOM (2011: 2), "it is a tremendously integrated water resource system that is highly complex with numerous large intra- and inter-basin water transfers. Globally, the Orange River basin is the most complicated and integrated river basins and is operated using highly sophisticated system models which have been developed over a period of more than 25 years." The seven *water user associations* are Kalkfontein *water user association*, Orange Riet *water user association*, Lower Modder River *water user association*, Orange Vaal *water user association*, Christiana *water user association* (Bloemhof Dam), Boegoeberg *water user association*, Vaalharts *water user association* and Sand Vet *water user association*.

3.6.2 Sampling Procedure

A similar sampling procedure to that of section 3.5.2 was followed.

3.6.3 Data Collection

Data sources

Both primary and secondary data was collected as outlined in section 3.5.3.

3.6.3 Data Analysis

The analysis followed a similar route carried out in section 3.5.4.

3.7 Water Demand Management Model

The section that deals with the development of this suitable model is covered in detail in chapter 6 of this thesis. All the findings relating to sections 3.3.1 to 3.3.6 link well and have prompted the need for development of a suitable model for the study area. Current models in use were viewed to address the water management issues in the study area inadequately.

3.7.1 Research Design

The methodology employed for objective 5 on the development of a suitable water demand management model used data acquired through RS. The variables used here included evapotranspiration (ET), rainfall and land-use. The main RS-derived variable in the study was ET since the variables, rainfall and land-use, were obtained from archival data sources.

3.7.2 Data Collection

In order to achieve objective 5 relating to the development of a suitable model in the area, RS and land use data that freely downloaded from the LandSat 7 ETM^+ of the United States Geological Survey (USGS). Water allocation quotas, current water demands and cropping patterns were obtained as archival data from the water user associations in the study area.

3.7.3 Remote Sensing Data for Water Accounting Plus (WA+)

The estimation of evapotranspiration is based on equation (28) for the surface energy balance. This equation partitions natural radiation absorbed at the earth surface into physical land surface processes. Evapotranspiration is a key process of the energy balance since latent heat (energy) is a vital requirement for the occurrence of evaporation.

At the earth surface the energy balance is assumed as:

$$LE = R_n - G - H \ (Wm^{-2}) \tag{28}$$

where G is the soil heat flux, R_n is the net radiation, H is the sensible heat flux, and LE is the latent heat flux. The sensible heat flux H is a function of the temperature difference between the lower part of the atmosphere and the canopy surface, and the soil heat flux G is a similar function related to the temperature difference between the top soil and the land surface. A rise of surface temperature generally increases the H and G fluxes. Evaporative cooling reduces H and G, and always result in an overall cooling of the lower surface.

The latent heat flux LE is the equivalent energy amount (Wm^{-2}) of the ET flux ($kgm^{-3}s^{-1}$ or mmd^{-1}). The net radiation absorbed at the land surface is computed from shortwave and longwave radiation exchanges, where solar radiation is the shortwave and most important supplier of energy. More information on the energy balance is provide in background material such as Allen *et al.* (1998) and Campbell and Norman (1998).

Surface temperature is measured routinely by space borne radiometers such as the Landsat, Visible Infrared Imager Radiometer Suite (VIIRS), Moderate Resolution Imaging Spectrometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), the China Brazil Earth Resources Satellite (CBERS), and the Chinese HJ and Feng Yung satellites. The Landsat 8 images for January 2016 and December 2016, denoting a normal year in terms of precipitation amounts and a drought year respectively, were used in this study because Landsat 8 satellite provides enhanced resolution from its two main sensors, the Thermal Infrared Sensor (TIRS) and the Operational Land Imager (OLI). The use of the high spatial resolution thermal band of Landsat enables the estimation of ET from wet soil and water-stressed vegetation evaporation (Numata *et al.* 2017) leading to the clear presentation of the differences. Remotely sensed surface temperature is the major input variable in ET algorithms. Thermal infrared ET algorithms are provided by Atmosphere-Land Exchange Inverse (ALEXI) (Anderson *et al.* 1997), EARS (Rosema 1990), ETWatch (Wu *et al.* 2012). METRIC (Allen *et al.* 2007), SEBAL (Bastiaanssen *et al.* 1998), SEBS (Su 2002) as well as in the two-source energy balance model (TSEB) (Norman *et al.* 1995).

Internalised calibration (METRIC) was used in this study to map evapotranspiration at high resolution. The versatility of METRIC is such that the primary inputs for the model are thermal images from a satellite (e.g. Landsat and MODIS), a digital elevation model and ground-based weather data measured within or near the area of interest. The METRIC's calibration is made using reference ET and not the evaporative fraction. In addition, neither the specific crop type, nor the crop development stages need to be known with METRIC. The energy balance can also detect reduced ET caused by water shortage (Allen *et al.* 2007). The differences among these algorithms are related to the parameterisation of *H*, general model assumptions, and the amount of input data required to operate these models.

3.7.4 Land Use Data

WA+ divides the river basin landscape into four main land and water groups:

Conserved Land Use: areas where changes in land and/or water management practices are prohibited by law. Typical examples include national parks and ramsar sites.

Utilised Land Use: areas where vegetation is basically responding to natural processes. The human interference is minimal with typical examples including forests, natural pastures, and savannas.

Modified Land Use: areas where vegetation and/or soils are planned and managed by mankind, but all water flows, rainfall, infiltration and runoff, are natural. The typical examples here include urban areas, rain-fed agriculture and forest plantations.

Managed Water Use: areas with water use sectors that abstract water from surface water and/or groundwater resources. The examples of such areas include irrigated agriculture, urban water supply and industrial extractions.

The results of WA+ are presented in three accounting sheets: (i) Resource Base Sheet (Figure 5), (ii) Evapotranspiration Sheet (Figure 6), and (iii) Productivity Sheet (Figure 7). Moreover, some key summarising indicators were computed to assist water managers, policy

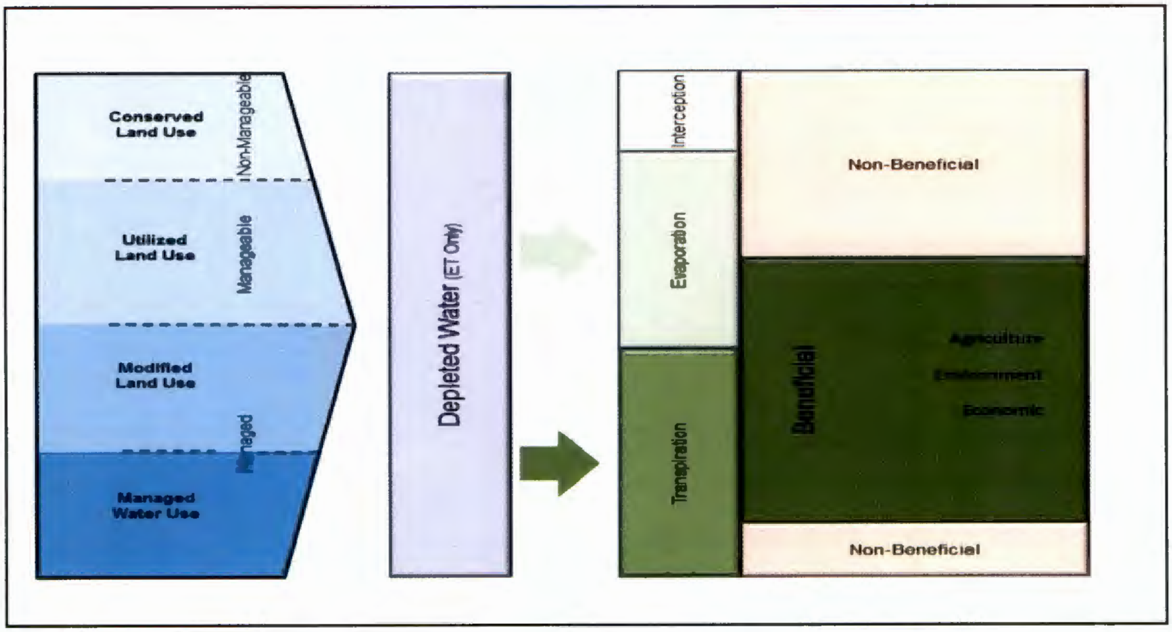

Figure 6: Water Accounting Plus: Evapotranspiration Sheet

(Dost *et al.* 2013: 9 and Karimi *et al.* 2013: 2466)

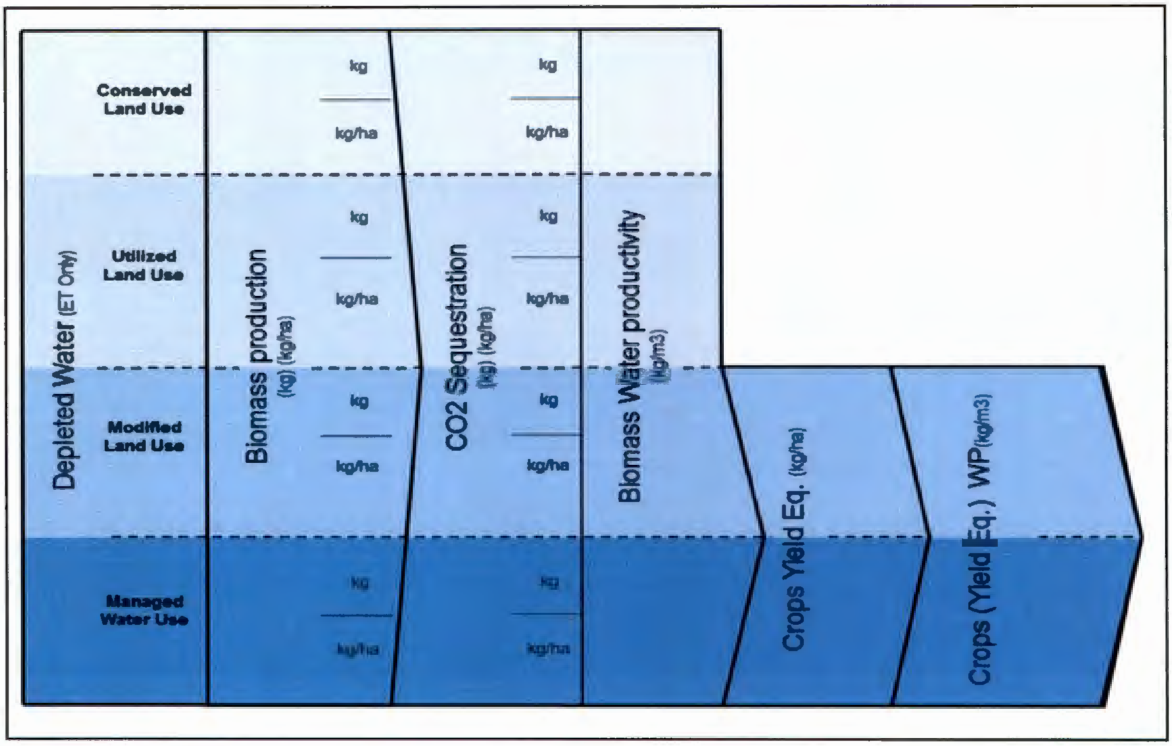

Figure 7: Water Accounting Plus: Productivity Sheet

(Dost *et al.* 2013: 10 and Karimi *et al.* 2013: 2467)

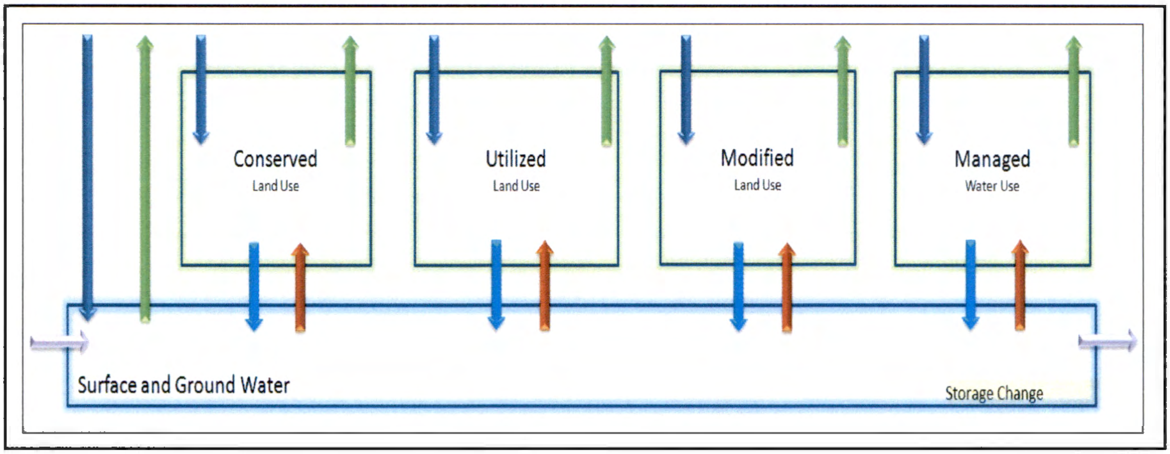

Figure 8: Resource Base calculation framework

(Dost *et al.* 2013: 10)

3.7.5 Key Indicators

An important aspect of financial accounting is the deliverance of key indicators that express performances in summarising numbers. A set of key indicators have been defined along the same lines for Water Accounting Plus (WA+) and these provide a quick and clear overview of water resources issues in the area under consideration. The four WA+ sets of indicators are used and these are summarised below. The indicators are defined in consultation with the Land and Water Division of FAO and are not necessarily identical to the indicators proposed by Karimi *et al.* (2012).

The first set of indicators can be related to the Resource Base Sheet:

$$ET\ Fraction = ET_{tot}/(P + Q_{in})\ (\%) \quad (29)$$

The ET fraction indicates both the portion of total inflow of water consumed and that converted into renewable resources. A value higher than 100% indicates over-exploitation or a dependency on external resources.

$$Stationarity\ Index = \Delta Storage/ET_{tot}(\%) \quad (30)$$

The Stationarity Index is an indication of the depletion of water resources. Positive values indicate that water is added to the groundwater and/or surface water storage, while negative values indicate a depletion of the storage.

makers and donors in their tasks regarding accountable water resources management. These indicators are discussed in the following paragraphs.

The Water Accounting Plus (WA+) is based on the standard water balance approach with specific emphasis on the various water users. Figure 8 (Resource Base calculation framework) demonstrates that every land use category has a certain surplus between rainfall (P) and ET. When P > ET applies, then the area yields water that flows into streams, lakes and aquifers. When ET > P applies, a withdrawal must occur as consumptive use cannot be explained by rainfall. The withdrawal can be manmade and in the form of diversion dams and pumping stations, or it can occur naturally by seepage zones or inundation of rivers.

The parameters addressed in the Resource base sheet are largely correlated to the intrinsic soil and water properties. They largely alter the nature of water storage behaviour regarding absorption and/ or yields. These properties are shown in Figure 5 as surface water (sw), soil moisture (sm), groundwater (gw), storage of fresh water (ΔSf) and storage of polluted water (dSp).

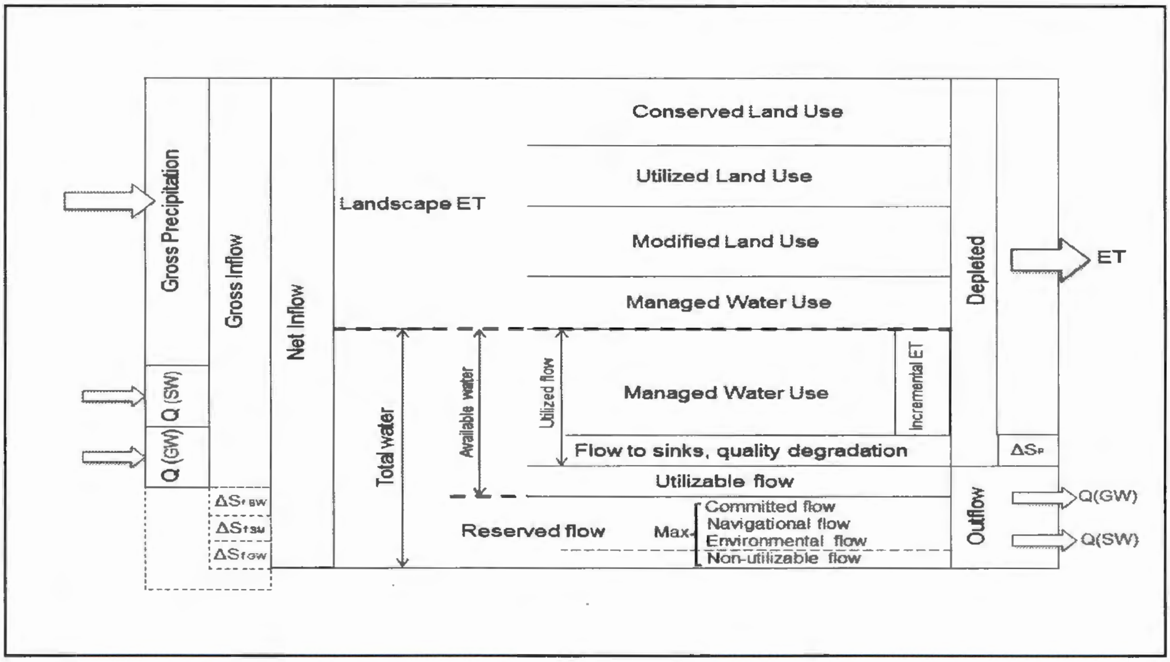

Figure 5: Water Accounting Plus: Resource Base Sheet

(Dost *et al.* 2013: 9 and Karimi *et al.* 2013: 2464)

$$Basin\ Closure = 1 - Outflow/(P + Qin)\ (\%) \tag{31}$$

Basin Closure defines the percentage of total available water resources (= precipitation + basin inflow) that is consumed and/or stored within the basin. A value of 100% indicates that all available water is consumed and/or stored in the basin.

The second set of indicators focuses on the actual amount of water that is currently managed, or is available for management:

The total amount of water that is available for management is expressed thus:

$$Available\ Water\ (AW) = Total\ Water - Reserved\ Flow - \Delta S\ (MCM) \tag{32}$$

The total amount of water that is abstracted for Managed Water Use is expressed thus:

$$Managed\ Water\ (MW) = Withdrawals\ by\ Managed\ Water\ Use\ (MCM) \tag{33}$$

The percentage of water is actually managed from the total amount of water that is available:

$$Managed\ Fraction = Managed\ Water/Available\ Water\ (\%) \tag{34}$$

Finally the third set of indicators are related to the Consumption Sheet.

The percentage of actually consumed water should be beneficially. The policy maker should make a flexible decision regarding the portion of ET that is assumed beneficial to either agriculture, the economy or environment for a certain land cover type. The beneficial consumption is determined thus:

$$Beneficial\ Consumption\ (\%) = ET_{ben}/ET_{tot} \tag{35}$$

The percentage of beneficial water consumption attributed to agriculture is expressed thus:

$$Agricultural\ Consumption\ (\%) = ET_{agr}/ET_{ben} \tag{36}$$

Percentage of beneficial water consumption attributed to the environment.

$$Environmental\ Consumption\ (\%) = ET_{env}/ET_{ben} \tag{37}$$

The percentage of beneficial water consumption attributed to the economy is expressed thus:

$$Economic\ Consumption\ (\%) = ET_{econ}/ET_{ben} \quad (38)$$

Finally, the last set of WA+ indicators compares the current year with the long-term averages value and are expressed thus:

$$Deviation\ Beneficial\ Consumption = 1 - ET_{agr,current}/ET_{agr,long\ term} \quad (39)$$

$$Deviation\ Beneficial\ Consumption = 1 - ET_{env,current}/ET_{env,long\ term} \quad (40)$$

$$Deviation\ Beneficial\ Consumption = 1 - ET_{ben,current}/ET_{ben,long\ term} \quad (41)$$

$$Deviation\ Beneficial\ Consumption = 1 - ET_{econ,current}/ET_{econ,long\ term} \quad (42)$$

3.7.6 Water Allocation Quotas

Data on water allocation quotas was obtained from the Department of Water Affairs and *Water user associations* within the study area. This data was supplemented by data obtained from Statistics South Africa (StatsSa).

3.7.7 Current Water Demands

Data on current water demands was obtained from inventory records held by the DWA.

3.7.8 Cropping Patterns

Cropping patterns were obtained from the DWA, Department of Agriculture and associated *Water user associations*.

3.7.9 SEEA-Water Accounting Framework

The SEEA water accounting framework outlines the use for the flows from ecosystems (*ecosystem services*) and stock of ecosystems (*ecosystem assets*) in order to determine them relative to each other and to a set of other social, economic and environmental factors. The SEEA-CF focuses mainly on the flows of energy and materials that enters into the economy as natural inputs or residual to the environment upon return from the economy. It is carried out on the basis of individual environmental assets, such as water, soil and timber resources. SEEA-Water is peculiarly adapted to the Central Framework and its implementation facilitated by the Department of Economic and Social Affairs of the United Nations Secretariat and supported by other institutions such as the statistical office of the European Union (EUROSTAT). The provision of a conceptual framework for organising hydrological and economic information is thus presented in a consistent and coherent manner. The system's origin is firmly grounded in economics, but also includes information that is of a physical nature. The hybrid nature of the system's accounts permits the analyst the opportunity to study both economic and physical aspects.

This standard approach ensures the measurement of the economy on the basis of human activities that are traceable to market transactions and prices. The SEEA supplements the monetary description of economic activities by taking into account the natural resources, such as water stocks (m^3) or water flow (m^3s^{-1}), in physical terms. Principally, the framework captures the dependency of the economy on flows from the environment and vice versa. Hence, the SEEA-Water's application has been successfully done in several countries as outlined below.

- Edens and Graveland (2014) present an experimental evaluation of Dutch water resources in line with SEEA illustrated guidelines for the valuation of the water resources provisioning services to the Dutch economy.

- Statistics Canada (2013) highlight an accounting framework on the basis of the SEEA that was designed to support the valuation of ecosystem services and goods and created a pilot ecosystem accounts that were then applied to wetlands valuation.

- Gan *et al.* (2012) embarked on a comparative exercise of the Chinese National Water Accounting Framework (CWAF) relative to the SEEA-Water tables.

- Vardon *et al.* (2012) adapted and compare the national water accounts from the Australian Bureau of Statistics to the SEEA-Water framework, and the associated similarities between both frameworks.

- Lange *et al.* (2007) used the SEEA-Water tables for the transboundary Orange River Basin, on national water accounts for South Africa, Botswana and Namibia, and make a comparison of each country's contribution to the water supply and to the amount it consumes.

Most of the above-mentioned applications capitalise on the hybrid nature of the tables that account for ratios of apparent water productivity by region/sector. Unfortunately, and with the exception of examples mentioned herein above, the implementation of SEEA-Water remains scarce, and full exploitation of the economic tables of the framework is still negligibly small. It is only recently that several research is erupting on this subject as well as with regard to the accurate estimation of evapotranspiration (ET) in the study of water resources and climate change, as well as various valuable applications in effective water resources development, crop water management, drought forecasting and monitoring, management, and utilisation (Bhattarai *et al.* 2016; Borrego-Marín *et al.* 2016; Chen *et al.* 2016b; c; Ding *et al.* 2016; Jian *et al.* 2016; Jorgensen *et al.* 2016; Lidén *et al.* 2016; Lutter *et al.* 2016; Obst and Eigenraam 2016; Olmanson *et al.* 2016; Pan *et al.* 2016; Pedro-Monzonís *et al.* 2016a; b; Sharma *et al.* 2016; Simons *et al.* 2016; Song *et al.* 2016; Verma *et al.* 2016; Vicente *et al.* 2016).

The SEEA-W has, until now, been the most well-known approach of hybrid accounting and its development has been witnessed in many European countries, such as Germany, Greece, Bulgaria, Slovenia, Italy and Spain (Dimova *et al.* 2014; EC 2015; Pedro-Monzonís *et al.* 2016a). It has been created by the United Nations Statistic Division (UNSD) in conjunction with the London Group on Environmental Accounting. This chapter and the study will, therefore, assist in the entrenchment of the knowledge about the applicability of the System of Environmental-Economic Accounting for Water (SEEA-W) (UNDS 2012) in stressed river basins.

SEEA-W's main purpose was normalisation of concepts pertaining to water accounting so as to provide a conceptual framework that organises hydrological and economic information. The SEEA-W categorises accounts into classes and these are: (1) physical supply and use and emission accounts that focus on the quantity of water used and discharged back into the environment together with the quantity of pollutants discharged into the water; (2) hybrid and economic accounts which provide a link between the economic aspects of water and the physical supply and use data; (3) asset accounts focusing on water balance, and the measurement of stocks and their changes due to natural causes and human activities); (4)

quality accounts related to the quality of the water stock; and (5) valuation of water resources. More information can be found at UNDS (2012).

There are two objectives that were addressed in this section. Objective 1 sought to perform water accounting through the employment of remote sensing between the different users in the study area during the period 1994 to 2014 based on the actual allocation of water needs by Department of Water Affairs (DWA) Republic of South Africa, Lesotho Highlands Development Authority (LHDA) and the Department of Water Affairs (DWA) Lesotho. Objective 2 sought to assess the state of equity in water allocation with respect to the institutional establishments referred above that include the different *water user associations* located in different parts of the study area. Two research hypotheses are advanced for this study. Hypothesis 1 states that there are differences in determining water accounting for different water users, while hypothesis 2 suggests that there are differences in the determination of the equitable distribution of water between different water users.

3.8 Methodology for the development of a suitable water demand management model

The section that deals with the methodology for the development of a suitable model is covered in detail in chapter 6 of this thesis.

3.9 Summary

The chapter has addressed the characteristics of the study area. It has also outlined methodology employed to identify water users, determine allocation of water needs, perform water accounting, establish equity in water allocation systems and finally propose a water demand management model for the study area.

The next chapter present results on water allocation and assessment of equity needs.

CHAPTER 4

ASSESSMENT OF EQUITY IN WATER ALLOCATION

4. Introduction

This chapter focuses on the different users found in the study area. South Africa uses 97% total water withdrawal from the Orange River thus making the country the largest water user of this river. Although Lesotho contributes to over 40 % of the stream flow, it only uses 1% of the water resources, while further downriver and outside the study area, Botswana accounts for less than 1% and Namibia about 2% of the total use. Agriculture is the main activity in the basin and this accounts for 61% of the water demand in the area such that the agriculture-inclined employment accounts for more than 50% of the basin's population. Most agricultural activities are carried along the fertile strips next to the river, while the bulk of commercial agriculture is artificially irrigated using water both from the river and groundwater due to the region's aridity. Large parts of the basin are indeed used for commercial rain-fed agriculture, especially for the production of maize and wheat. Other users in the area include the large urban residential centres and industries in the Greater Bloemfontein area and to a limited extent, the rural centres scattered across the study area. This Caledon-Modder System supplies water to the Mangaung-Bloemfontein urban cluster, the largest urban centre in the study area (DWA 2012a).

4.1 Water Allocation

The conflict between limited water resources and increased water demands has over the past decades become an increasingly pressing issue due to the rapid socio-economic development and continuing population growth. Irrigated agriculture, the biggest consumer of limited water resources, uses about 70 % of the world's freshwater withdrawals, especially in arid and semi-arid areas whose climate are mainly characterised by low rainfall and high evaporation (Li *et al.* 2016a). The optimal spatial allocation of irrigation water under uncertainty has become a serious concern because of irrigation water shortage and uncertain factors that affect irrigation water allocation (Hou *et al.* 2016).

The traditional optimal allocation problem of irrigation water is frequently simplified and solved using deterministic optimisation methods. In fact, this problem is affected by uncertain factors such as precipitation, evaporation, water supply, irrigation area, crop planting structure and water saving technology. The values of most uncertain factors are marginal, nevertheless, water resource allocation may produce errors if these uncertain factors are coupled. A reasonable and effective allocation of the limited irrigation water supply to various crops is difficult because of such errors; consequently, the adjustment and upgrading of the industrial structure are affected. As a result, several methods have been introduced in an attempt to solve the uncertain problem of irrigation water allocation and these include stochastic, fuzzy, grey and interval analyses as well as fusion methods (Hou *et al.* 2016).

4.2 Water Use in Lesotho

Table 2 shows Lesotho farmers' categories and crops produced.

Table 2: Lesotho farmers' categories and crops produced (ORASECOM 2011: 29)

Type of Farmer	Irrigation System	Crops	Size of Farm (ha)
Subsistence Farmer	None	Maize, sorghum, beans	0.1 – 0.2
	None	Cereals, maize, sorghum, legumes, potatoes	>0.2 - 1
Micro-irrigating Farmer	Watering can, hose pipe / low pressure sprinklers	Vegetables, fruit trees	0.025 (home garden)
	Gravity-fed irrigation	Vegetables, fruit trees	0.1 – 0.5
Small-scale semi-commercial Farmer	High-pressure irrigation system	Vegetables, fodder	1 – 4
Medium-scale commercial Farmer	High pressure system with travelling guns	Vegetables	10 – 20

4.3 Water Use in South Africa

Data from the Water Authorisation and Registration Management System (WARMS) (DWA 2013c: 18) reveals that 60% of water is used for irrigation. Nonetheless, Table 3 summarises South Africa's estimated volume of water allocation per sector.

Table 3: Proportion of water use per main economic sector

Economic sector	Proportion of water use
Agriculture / Irrigation	60%
Municipal /Domestic	27% (i.e. 24% Urban, 3% Rural)
Industrial	± 3% (If not part of Urban Domestic)
Hydro-electricity generation	2%
Mining and associated activities	± 2%
Livestock and Nature conservation	2.5%
Afforestation	3%

Three things are worth-noting about the above-noted user sectors:

This water related to the Ecological Reserve (environmental - in-stream flow requirements) is not consumed.

Alien vegetation has not been included though provision of water for its existence should be allowed for.

Hydropower - This water is not consumed but it is subject to losses. It should be noted that while irrigation requirements are the primary concern of the Gariep and Vanderkloof darns, hydropower is a secondary determinant of the weekly releases from both dams.

4.3.1 Irrigation within the Study Area

Irrigation schemes in South Africa are categorised as Government Water Schemes (GWS), Irrigation Boards (IBs) or *Water User Associations* (WUAs) (ORASECOM 2011: 10). The Orange River is divided, as it stretches from the Lesotho border to the Orange River delta, into 22 River Reaches that cater for irrigation. Irrigation is facilitated through canal infrastructure that runs asymptotic the river or as direct abstractions from the river. Irrigation mostly occurs on commercial farms that have freehold tenure and on farming units that are 50 ha on average. However, numerous farms acquired larger irrigated areas after the consolidation of irrigation units under one owner so as to improve or maintain financial viability of irrigated farming. There is also another initiative from the Government that sought to introduce and develop resource poor farmers within the smallholder irrigation schemes (ORASECOM 2011: 10). Calibrated sluice gates facilitate the distribution of irrigation water to the farmers within schemes that are in close proximity to the river, while inline flow meters with telemetry are used in some schemes located further afield or more centrally in the basin. The irrigation infrastructure that distributes water and the lined open canals are old, thus warranting widespread rehabilitation as an immediate requirement. Nonetheless, approximately 85 000ha is under irrigation in these schemes.

The objective addressed in this section is to identify the actual allocation of water needs by Department of Water Affairs (DWA) - Republic of South Africa (RSA), Lesotho Highlands Development Authority (LHDA) and Department of Water Affairs (DWA) - Lesotho. The suggested two null hypotheses are: (i) There are differences in the methods of identifying different water users in the study area, (ii) There are differences in the methods of allocating water in different municipal areas.

4.4 Results

The area has a total of seven *water user associations* and/or Irrigation Boards (IBs). The last two are outside the study area but are supplied from the area through Inter-basin Transfers (IBTs) on the Orange River upper reaches of the area and "which is notably much interconnected" (DEA 2013: 43). According to ORASECOM (2011: 2), "it is a tremendously integrated water resource system that is highly complex with numerous large intra- and inter-basin water transfers. Globally, the Orange River basin is the most complicated and integrated river basins and is operated using highly sophisticated system models which have been developed over a period of more than 25 years." The seven *water user associations* are Kalkfontein *water user association*, Orange Riet *water user association*, Lower Modder River *water user association*, Orange Vaal *water user association*, Christiana *water user association* (Bloemhof Dam), Boegoeberg *water user association*, Vaalharts *water user association* and Sand Vet *water user association* (Mahasa *et al.* 2015a; DWA 2013b; c).

The model summary indicates the R-square equal to 1.000, an unusually high value of ANOVA and predictors on the dependent variable (i.e. water allocation) to be: total area, number of irrigators supplied within WUAs, servicing from canals and pumping directly from river. The irrigation mode differs from centre pivots, flood irrigation, allocation and operation via a telemetry system, laser levelling to improve water flow, micro- and drip irrigation, allocation towards cultivation of table-grapes, maize, wheat, lucerne, cotton and other crops.

The Pearson correlation does not indicate any significance. There is a weak correlation between all variables that were thought could have an influence of some sort on water allocation (Appendix 3). These dependent parameters on water allocation include: total area, number of irrigators supplied within WUAs, servicing from canals, pumping directly from river, irrigation mode (centre pivots), flood irrigation, operation via a telemetry system, laser levelling to improve water flow, micro and drip irrigation, allocation of water towards cultivation of table-grapes, maize, wheat, lucerne, cotton and other crops. In addition, no correlation could be picked from WUAs that bore old infrastructure (-1.250), and in industrial and domestic supply (-1.250).

4.4.1 Characteristics of Individual *Water User Associations*

This section discusses the individual characteristics of *water user associations*. The last two *water user associations* are not in the study area but due to the complex inter-transfers between basin and sub-divisions it can be argued that they are supported from the Orange River due to an upstream transfer into the Ash River and finally into the Liebenbergsvlei River.

4.4.1.1 Kalkfontein Water User Association

The Kalkfontein scheme, which was originally established as a GWS, became an IB in 1994 and was the first IB to be transformed into a *water user association* in accordance with the 1998 New Water Act's stipulations. The Kalkfontein Dam receives its water from three basins, The Riet River, Kromellenboogspruit and Tierpoort Dam catchments. The Kalkfontein Dam receives its water directly from the Riet River catchment which generates a runoff of 83.96 million m^3/a and provides 49.97km^2 of water in support of irrigation purposes with 31.34 million m^3 remaining in the catchment's reservoirs (Mahasa *et al.* 2015a). This dam also receives water from the Kromellenboogspruit catchment in the form of runoff of 101.89 million m^3/a and 20.71km^2 in support of irrigation with 26.58 million m^3 remaining in the catchment's reservoirs, and the Tierpoort catchment as runoff of 23.23 million m^3/a and 23.35 km^2 in support of irrigation with 17.25 million m^3 remaining in the catchment's reservoirs (DWA 2013b; c).

A total of 120 irrigators are supplied from the Kalkfontein *water user association*. The irrigators are supplied with water by lined canals on either sides of the Riet River downstream. Other irrigators pump directly from the Riet River. It was found that, just as noted with ORASECOM (2011), 3526ha was initially under irrigation, with canals supplying water for 3046ha while pumping directly from the river supplies to the remaining 480ha. A total serviced area of 3502.9ha that remained after pumping from the river was reduced to 456.9ha. The original intention was that canals should provide water for flood irrigation but the current practice is that about 10% is provided through flood irrigation, while the other 90% irrigation is delivered via centre pivots (Mahasa *et al.* 2015a; DWA 2013b; c).

Measurement of all water for irrigation use is carried out to determine water demand. Calibrated sluices are used to measure water consumed by canal users while in-line water meters are used to determine water extracted directly from the river by irrigators (DWA 2013c). On average, maize occupies 60% of the area planted on a two year rotational basis with wheat and three other crops. Lucerne is planted on 20% of the land while a variety of other crops occupy the remaining 20% (ORASECOM 2011). The users in this area consist of the Kalkfontein *water user association* which supplies irrigators, and other users such as the urban areas of Koffiefontein, Jacobsdal, Jagersfontein and Fauresmith. Water is also supplied to two De Beers mines at Jagersfontein and Koffiefontein (DWA 2013b). Water allocated is 11 000 m^3/ha/yr. However, billing on users is done on the actual use and on a volume basis. It is a common phenomenon for water to be in short supply within this WUA, as a result, the area's Kalkfontein Dam is frequently impacted negatively to the extent that farmers sometimes receive as little as 15% of their allocation in some years. Furthermore, there is a noticeable deterioration of water quality because the Riet River rarely flows. As a result, the farmers in this part of the study area are highly conscious of Water Conservation and Water Demand Management (WC/WDM) because of regular shortages of water (ORASECOM 2011).

4.4.1.2 Orange Riet Water User Association

The Orange Riet scheme, which is one of the schemes formed in 2000, is the most complicated. It is the result of the transformation of the Riet River GWS, formerly consisting of the Riet River Settlement, Ritchie Irrigation Area and the Scholzberg Irrigation Area, and the Lower Riet IB. Numerous lined canals serve the scheme while other irrigators pump water directly from the Riet River. Water is often in short supply in the Riet River, hence the construction of the Orange Riet Transfer Scheme as a means to convey water from the Vanderkloof Dam, on the Orange River, to service these areas (Mahasa *et al.* 2015a; DWA 2013b; c). Water from the Orange River is pumped to a point high enough so that it can move under the influence of gravity via a canal to the serviced area. Irrigators along this transfer canal draw water directly from the canal. Initially, 16 903ha were under irrigation but the area has been expanded to 17 050ha after allocation purchases from the Eastern Cape. The canals were initially meant for flood irrigation purposes. In addition 90% of the area is presently under irrigation through centre pivots while 9% still maintains flood irrigation and the remaining 1% uses other systems. In total, 190 irrigators are supplied from the Orange Riet *water user association*. Wheat (37%) and lucerne (26%) are the main crops. The remaining 37% caters for crops such as maize, potato, barley, oats, groundnut, grapes and other crops (Mahasa *et al.* 2015a; ORASECOM 2011).

All users are measured by either in-line water meters or calibrated sluices. Telemetry is connected to a central 24 hour control station that monitors all measuring stations, thus making water available only on demand. The level of expertise shown by the Orange Riet *water user association* in South Africa for the measurement and use of water is the best so far (ORASECOM 2011). Allocations are done on a volume basis such that 11 000 m^3/ha/yr is allocated. However, the billing of actual use on users is on a volume basis. The water in the Riet River, just as with the Kalkfontein *water user association's* case, does not always flow and there is drastic deterioration of water quality further down the river. As a result, a virtual water bank is operated by the Orange Riet *water user association* (Mahasa *et al.* 2015a; DWA 2013b). Here, subject to a decrease in water use, irrigators may trade their water allocations or hand the water back to the *water user association* who may sell the water to willing buyers at a premium (ORASECOM 2011).

4.4.1.3 Lower Modder River Water User Association

The Lower Modder River *water user association*, which incorporated the former Modder River GWS, was established in 2010. Its location next to the well-managed Orange Riet *water user association* compelled the Lower Modder River Board to "piggyback" on the expertise of the Orange Riet *water user association* which also manages the Lower Modder River *water user association*. As a result both *water user associations* utilise the services of a common CEO (Mahasa *et al.* 2015a; DWA 2013b; c; ORASECOM 2011). Nonetheless, the Lower Modder River *water user association* obtains its water from the Krugersdrift Dam on the Modder River with irrigators abstracting directly from the Modder River to provide for the irrigation of 3 526ha. Water use is measured using in-line water meters fitted with telemetry for about 90% of the irrigators (ORASECOM 2011). Plans were put in place in 2011 to measure the remaining 10%. The major observation here is that the annual allocations and crop mix are similar to those of the Orange Riet *water user association*, and that the *water user association* is managed in a similar manner as the Orange Riet *water user association* using the same operating procedures and personnel (Mahasa *et al.* 2015a; DWA 2013c).

4.4.1.4 Orange Vaal Water User Association

The Orange Vaal *water user association* was formed in 2007, after the conversion of the Orange Vaal IB's into a *water user association*. The initial total irrigated area of 8 113ha was increased to 11 058ha after a successful purchase of water allocations from outside the scheme (ORASECOM 2011). The scheme is situated at the confluence of the Orange and Vaal Rivers. Initially its water was extracted from the Douglas Weir, situated on the Vaal River, a condition that was improved after the construction of a transfer scheme from the Orange River to the Douglas Weir due to an increase in water use upstream of the Vaal River basin (Mahasa *et al.* 2015a). This transfer scheme, known as the Orange Vaal Transfer Scheme, has an installed pumping system that conveys water into the Bosman Canal flowing into the Douglas Weir in another catchment area. The Vanderkloof Dam supplies the entire scheme's water allocation via the Orange Vaal Transfer Scheme (Mahasa *et al.* 2015a; DWA 2013c). The land area under irrigation is about 90% and pumps water directly from the Douglas Weir, the

Bosman Canal or the Orange River downstream of the Douglas Weir. About 10% of the area is serviced by water from two canals, the Atherton and Buckland Canals, which were originally established to provide flood irrigation supply. However, 90% of the irrigation is done through centre pivots, 7% by other systems and only 3% still maintains flood irrigation (ORASECOM 2011). Finally, the Orange Vaal *water user association* also supplies 180 irrigators (Mahasa *et al.* 2015a).

The canal users' allocations are measured using calibrated sluices, while water use by irrigators is not measured physically but is calculated on a pre-season basis. About 90% is under irrigation through centre pivots, which is easy to operate and irrigates directly on the crops. The *water user association* determines the allocation on the basis of the irrigator operational plans relating to planting that have to be communicated to the *water user association* (Mahasa *et al.* 2015a). Water allocation is calculated as a product of average weekly evaporation rates for the past five years multiplied by a crop factor to determine the amount of water required for the crop and the area (DWA 2013b; c). Ultimately, the water association consults with the irrigator during the adjustment of areas' allocation until the annual requirement is equal to the irrigator's allocation and both parties are in agreement. Planting is only limited to areas that have been agreed upon by the irrigator and the *water user association*, with this information usually being validated afterwards (Mahasa *et al.* 2015a). Maize is planted to about 5000ha (45%) and in rotation with wheat and three other crops that are grown every two years. Lucerne occupies 2000ha (18%) while cotton occupies 2000ha (18%). The remaining area (19%) may be used for a wide variety of other crops (ORASECOM 2011).

The Orange Vaal *water user* association's users are charged on a volume per area per year (i.e. m^3/ha/annum) basis. Originally allocations were about 9140 m^3/ha/yr but these have increased due to purchased allocations to 10 000 m^3/ha/yr (ORASECOM 2011). As a result of poor quality water from the Vaal River, the Orange Vaal *water user association* faces major water quality problems. Industrial pollution and acid mine drainage from the Vaal River catchment, and nutrient rich sub-surface drainage water from the upstream Vaalharts scheme result in as high as 861mg/L of total dissolved solids (TDS), while an alarmingly high value of 1500 mg/L TDS is produced by the drainage water from the Orange Riet and Kalkfontein schemes upstream on the Riet River (ORASECOM 2011). In contrast, the water from the Orange River has a TDS of only 145 mg/L. Nonetheless, water from all three sources is deposited in the Douglas Weir (Mahasa *et al.* 2015a; DWA 2013b; c; ORASECOM 2011). It should also be stated that research has shown that the different densities of the good and poor quality water do not mix but remain in envelops which cause problems for irrigators when poor quality water pass the extraction points (Viljoen *et al*. 2006). This means that water has to be sourced far away from the WUA at an increased cost.

4.4.1.5 Christiana Water User Association (Bloemhof Dam)

Submission of a proposal for establishing a *water user association* has been delayed until so far. This is because a consensus could not be reached on the registration of water use over this area and questions arose on how registered volumes of irrigation water could be utilised without exceeding the permit abstraction flow-rate (Mahasa *et al.* 2015a; ORASECOM 2011).

4.4.1.6 Boegoeberg Water User Association

The Boegoeberg *water user association* was established in 2003 after an amalgamation of the Boegoeberg GWS- formed in 1931, the Gariep IB, the Northern Orange IB, a portion of the Middle Orange Irrigation Area, and the Karros Geelkoppan Water Board (ORASECOM 2011). The scheme now has a total area of 9198ha under irrigation. Field observations revealed similarities with other schemes in the area in that lined canals run downstream along one or both sides of the Orange River until downstream of the river (Mahasa *et al.* 2015a; DWA 2013b; c). Most farmers' irrigation activities are fed from canals while some farmers pump directly from the rivers. It was also observed that the Boegoeberg *water user association* supplies 306 irrigators and nine livestock farmers with water for domestic and animal purposes, with livestock farming occupying 60 000ha of the area in this scheme (Mahasa *et al.* 2015a; ORASECOM 2011).

The initial design of the scheme was to use flood irrigation such that presently flood irrigation accounts for 90% of the area, while irrigation with micro- and drip irrigation constitutes the remaining 10%. Laser levelling has been done on 30% of the flood irrigated area to improve on irrigation efficiency. Calibrated sluices are used to measure the 297 canal users' consumption, while only 9 river users are not measured. Grapes account for 80%, maize and lucerne (1 %), with other crops such as peas, wheat, cotton and pecan accounting for 10% of the area (ORASECOM 2011).

While irrigation water is rarely in short supply, users are billed on a volume/area/annum basis and presently the allocation is 15 000 m^3/ha/yr for users on the Boegoeberg, Gariep and Northern Orange portions and 10 000 m^3/ha/yr for the Middle Orange portion (DWA 2013b). The infrastructure is very old and the entire scheme needs immediate rehabilitation, as a result, high losses of water are experienced. The operating philosophy, observed here, is that the *water user association* has preserved the natural setting in terms of flow-rate by constructing a divergence of discharge and retaining losses as if the water is still in the river-course (Mahasa *et al.* 2015a; DWA 2013b; c).

4.4.1.7 Vaalharts Water User Association

The Vaalharts *water user association* was established in 2001 after an amalgamation of the Vaalharts GWS and the Harts GWS. This WUA receives irrigation water from the KB canals and Taung Irrigation Scheme. The Bloemhof Dam on the Vaal River is the main source of supply with some water supplied from the Spitskop Dam on the Harts River. The Vaalharts Weir collects water released from the Bloemhof Dam and distributes it via lined canals to the Vaalharts, Taung and KB canal areas. In addition, water from the Spitskop Dam is distributed via a canal to users downstream of the dam, while certain users also pump directly from the Vaal and Harts rivers (Mahasa *et al.* 2015a; DWA 2013b; c).

The Vaalharts *water user association* serves 900 users on a total area of 35 700 ha (ORASECOM 2011). It was initially designed as a flood irrigation scheme with 40% currently remaining under flood irrigation with 40% under centre pivot irrigation and the last (20%) uses micro- and drip irrigation systems (Mahasa *et al.* 2015a; DWA 2013b; c). Water released to irrigators is measured using calibrated sluices except for the Taung which is not measured at all (ORASECOM 2011). Maize, wheat, vegetables, pecans, lucerne, groundnuts, citrus, cotton, olives and grapes are grown in this water user association. The irrigators are billed on a cubic meter per hectare basis. In addition, the Vaalharts and KB canals areas jointly obtain 9140 m^3/ha/a, Taung 8470 m^3/ha/a and the Harts area 7700 m^3/ha/a (ORASECOM 2011). Finally, it was observed that the infrastructure in the water user association is very old (i.e., >80 years) and thus requires major investment in rehabilitation activities (DWA 2013b; c).

Acid mine drainage from the Gauteng area causes the water quality from the Vaal River to deteriorate rapidly. The Vaal River also has high nutrients and these lead to excess algae and water hyacinth growth which often blocks canals and structures used for measuring water use. Salinity in the Vaalharts scheme is also a problem. Consequently, sub-surface drainage was installed on large portions of the scheme so as to drain away excess salinity and acidity. Furthermore, nutrient rich sub-surface drainage water from Vaalharts is collected in the Spitskop Dam resulting in water quality problems for users of this dam (Mahasa *et al.* 2015a; DWA 2013b; c; ORASECOM 2011).

4.4.1.8 Sand Vet Water User Association

The Sand Vet *water user association* was created in 2007 after an amalgamation of both the Sand Vet GWS (supplied by the Allemanskraal Dam on the Sand River) and the Vet River GWS (supplied by the Erfenis Dam on the Vet River). Raw water for irrigation purposes is supplied to more than 700 privately and government-owned settlement properties by means of the Allemanskraal Dam and the Erfenis Dam via a 651.84 km long system of channels and drains ((Mahasa *et al.* 2015a; DWA 2013b; c; DWA 2011). An area of 12 317 ha consisting of 7162 ha on the Vet River and 5155 ha on the Sand River is currently under irrigation. Both schemes comprise of lined canals on one or both sides of the river tracking of the river course. The majority of farmers are supplied from these canals while some pump directly from the rivers. A total of 535 irrigators rely on this association, whereby the Vet scheme supplies 301 irrigators are supplied and the Sand scheme 234 (Mahasa *et al.* 2015a; DWA 2013b; c).

The scheme was initially designed to cater for flood irrigation and only about 1% maintains the status quo. Irrigation by centre pivots accounts for 90% with the remaining 9% falling under micro- and drip irrigation (ORASECOM 2011). Canal users are supplied with irrigation water by means of calibrated sluices while river users are supplied by means of in-line water meters. The prominent crops grown are maize and wheat with some potatoes, groundnuts sunflower, oats, lucerne, and various vegetables also cultivated under irrigation. Observations revealed that the Sand-Vet also supplies raw water that is later purified for commercial and household use in Theunissen, Bultfontein, Brandfort and Virginia as well as at Harmony Mine, Virginia Correctional Services and the Agricultural experimental farm in Virginia (Mahasa *et al.* 2015a; DWA 2013b; c). The annual operating cost for the Sand-Vet Water Scheme is approximately R 11 million (Mahasa *et al.* 2015a; DWA 2011). Users are charged on a cubic meter per hectare basis using calibrated sluice gates. Finally, the scheme suffers from regular water shortages and users seldom receive their full annual allocation (ORASECOM 2011).

4.5 Water Requirements

Most land use is under natural vegetation with livestock farming producing sheep, cattle, goats and in some cases game, and conservation areas occupying large parts in the area. Dry land cultivation to produce grains covers extensive areas in the north-eastern parts of the water management areas. Large areas are supplied with irrigation water for grain production, fodder crops, and a wide variety of grapes have been developed along the main rivers situated downstream of the dams.

The 2012 estimates stated that irrigation accounted for 88% of the total gross water use of 1 996 million m^3/a and constituted the dominant water use sector in the Orange River WMAs (ORASECOM 2011). This amount, however, excluded the transfers out of the WMAs. However, the urban, industrial, mining and rural sectors account for only 12% of the water use. Furthermore, transfers from the Orange River, which are mainly from Lesotho and the Upper Orange WMA, account for 2 159 million m^3/a of water use. An expected future growth will result from the 12 000ha allocated to resourcing poor farmers and limited growth in urban/ industrial and mining sectors in the Bloemfontein and Thaba 'Nchu area. The projected water use required for 2025 is 2 134 million m^3/a and this does not include the transfers. Until 2025, no new transfer schemes may be expected out of this area.

4.6 Understanding growth in Water Requirements

The prediction of water requirements, for planning purposes, is usually based on the primary drivers of water demand, which are population growth and local economic growth. These two factors are intertwined as economic growth may stimulate population growth owing to migration from the rural areas or other urban areas with a poor economy. There are also numerous other contributing factors that can impact future water requirements in general and specifically for the Greater Bloemfontein area. These factors include:

- Changes in the level of service, such as improvements in the water services, sanitation, and health awareness are most likely to impact on the future requirement scenarios. Typical initiatives in the study area include the eradication of water and sanitation backlogs linked to the UN Millennium Goals and the delivery of houses to the poor to meet SA's National target with regard to housing.

- The impact of HIV/AIDS, where the highest occurrences are witnessed in the rural areas of South Africa, is a significant factor in the estimation of population projections, and more specifically, its influence on the mortality rate. (DWAF 2004).

- Improvement in water management with regards to water meter coverage, the extent and accuracy of meter reading and billing, and the effectiveness of credit control policies.

The historic growth in water requirements has been fluctuating quite significantly and thus is indeed inconsistent. The water growth has included periods of negative or relatively flat growth possibly as a result of the above average rainfall that was experienced from 2008 to 2011 (DWA 2012e). Water use, when expressed on a per capita basis, is in the region of 200 litres per person per day. There are uncertainties, however, associated with the future population growth rate figures as described below.

4.6.1 Population Growth Rates

Population growth rates are based on the birth rate, mortality rate, and migration. The following reviewed sources and references describe the historic and possible future population growth rates. This are listed as follows:

Information obtained from the IDP report 2007/2008 for the Mangaung Metropolitan Municipality indicates that the future population growth rate for Bloemfontein will be 3.1% per annum. The population growth rate between 1996 and 2001, as presented in the 2001 Census figures for the Bloemfontein areas, was estimated to be 3.1 % per annum.

A report entitled "Identification of Bulk Engineering Infrastructure in Support of Housing Development in Mangaung, Master-plan prepared for the Mangaung Metropolitan Municipality (MMM)" determined that the anticipated population growth figures for Bloemfontein up to 2030 would be 1% per annum.

Population projection scenarios were also developed for the "All Towns study for Central Region" (June 2009). This study proposed two alternative population growth scenarios, a High Population Growth Scenario and a Low Population Growth Scenario. The high population growth scenario translates to an aggregate population growth rate for Bloemfontein, Botshabelo and Thaba 'Nchu of 1% per annum, whilst the low population growth scenario translates to an aggregate population growth rate of 0% per annum.

Migration is proportional to economic growth rate. A strong economic growth will result in "immigration" whereas a decline in economic growth will result in "emigration". Migration affects the rural and smaller towns more significantly, as a result of people seeking economic and employment opportunities in the larger urban centres. Nevertheless, the migration figures that could be relevant to the study area were sourced from Provincial trends as abstracted from the "2009 StatsSA Mid-Year Projections for the Orange Free State Province (2006 to 2011 Projection)". Here, migration is assumed to vary between 0.00 % and 0.25 % for Bloemfontein and Botshabelo, assuming that more people migrating to, and residing in these towns. For the smaller towns with less economic opportunity, the migration rates vary from -0.4 % to 0.0 %. The assumption is that current residents could be leaving the smaller towns to reside and seek opportunities in the larger centres.

The impact of HIV/AIDS is a significant factor in the estimation of population projections, and more specifically, its influence on the mortality rate. The impact of HIV/AIDS to the study area has been based on National statistics, where the highest occurrence is in the rural areas of South Africa. The mortality rate, as a result of HIV/AIDS related diseases, has been assumed to be as high as 0.4% for the urban towns, and 0.75 % for the rural towns and villages.

4.6.2 Economic Growth Rates

The largest urban centre in the area is Bloemfontein, followed by Botshabelo and finally Thaba 'Nchu; and these receive most of the private and public investment. The 2007/2008 Integrated Development Plan (IDP) suggests that Bloemfontein will be the focus of future development as it was anticipated that Bloemfontein will be home to about 65 % of the study area's total population by 2016.

The economy of the MMM plays a significant role in the Motheo District economy (92.5 %) as well as the Free State economy (25.5 %), but it is relatively small when compared to the national economy (1.6 %). Of importance is the relatively small share of the local agriculture, mining and manufacturing sectors compared to the province and the country.

Mining's small share is understandable as the Mangaung area competes with the goldfields area, which is very strong in mining. However, the MMM's share of agriculture and manufacturing is low. The tertiary sector of the local economy is very significant within the context of the province, as approximately 87% of economic production in the MMM area occurs in Bloemfontein while only 7% and 6% occur in Botshabelo and Thaba 'Nchu, respectively. The overall annual economic growth rate for the Mangaung area was 3.59 % between 2001 and 2004 and a significantly higher growth of 9.5 % occurred between 2004 and 2007. Bloemfontein's economic growth rate between 2004 and 2007 amounted to 9.86%, while Botshabelo recorded 8.55 % and Thaba 'Nchu recorded a considerably less 5.08 % per annum during the same period. This confirms that the Bloemfontein economy is and will be increasing its proportional share of the economy.

While community services contribute to over a third of Mangaung's economy, other prominent sectors include finance, retail and trade, transport, and manufacturing. The remaining sectors, such as agriculture and mining, are very small and make a minor contribution to the local economy. Community services contributes 35% to the city's economy, finance 18 %, trade 16 %, transport 13 %, manufacturing 8%, agriculture 4%, construction 3% and utilities 3%. Growth in the transport sector, given the strategic central location of Bloemfontein, is likely to be stimulated by increasing economic activity elsewhere in the country.

4.7 Future Water Requirement Scenarios

The following assumptions were made with regard to the development of the future water requirement scenarios for the Greater Bloemfontein Water Supply System:

The High Growth Water Requirement Scenario will take place on account of a high population and economic growth rates. A consideration of the relatively low population projection growth rates and the contrasting high historic growth in water requirements (the authorised billed and unbilled water consumption figures for the last 3 years have grown at a rate of 3% per annum) led to the use of the long term historical growth rate of 3% per annum as the basis for the high growth scenario (DWA 2012e).

The Low Growth Water Requirement Scenario will take place on account of a low population and low economic growth rates. It was decided to base the low growth scenario on a growth in water requirement of 1 % per annum.

The high and low water requirement projections have been projected from the 2009 base by DWA (2012e) for the following reasons listed:

There were significant summer rains in the 2010/11 rainy season and this may have resulted in a depressed water demand (DWA 2012e).

It is still too early to ascertain whether or not the drop in 2010 can be ascribed to structural reasons (e.g. improved metering, WC/WDM) or is as a result of climatic influences.

It is conservative to plan from a higher base. The future years' actual water requirements are becoming known, as a result, the base from which the projections will be made can always be changed.

4.8 Important Qualification

It is important to note that the above-presented water requirement scenarios were developed during the global economic crisis. The global recession and a slow recovery from this recession are likely to have significant implications for the water requirement growth projections of the Greater Bloemfontein Water Supply System. The implications of the recession towards the strategy to meet future water requirements are listed as follows:

The economic uncertainty increases uncertainty concerning the growth in water requirements;

Water use must be continuously and carefully monitored;

Future scenarios/projections need to be revised frequently, basing on updated information;

Planning to increase water availability needs to be as flexible as possible; and

Interventions that are more flexible in terms of timing should be favoured, all other considerations being equal.

4.9 Agricultural Water Requirements

The only expected growth in irrigation requirements is the allocation of 12 000ha to resource poor farmers. The effect of the 12 000ha (4 000ha each for the Upper Orange WMA, Lower Orange WMA and Fish-Tsitsikama WMA) is estimated to be in the region of 114 m^3/a. The Implementation Strategy for the development of 3 000ha for irrigation in the Free State Province indicates that there is ± 200 ha available near Ficksburg drawing on the Caledon River and ± 2 000ha available next to the Orange-Riet Canal, which starts at the Vanderkloof Dam. The agricultural water requirement for the 200ha near Ficksburg takes into account the determination of the available yield.

4.10 Water Balance Reconciliation

The Upper Orange WMA, a component of the extended Orange and Vaal River System, has been the subject of various water balance and reconciliation studies. The latest water balance from the Orange River System indicates a surplus of 274 million m^3/a for the year 2008. Subsequent planning on the supply of water to emerging farmers and for the growth in water requirements of the Upper Orange, Lower Orange and the Fish to Tsitsikama WMAs would reduce this surplus to only 40 million m^3 by 2025 (DWA 2012e). Furthermore, the proposed Phase 2 developments of the Lesotho Highlands Water Project, in the form of the proposed Polihali Dam and transfer, will reduce the yield of the Orange River downstream by approximately 283 million m^3/a. It can be inferred, basing on a conceptual estimate of the mass balance across the Orange River system that, a system deficit of about 243 million m^3/a can be expected by 2037 (DWA 2012e).

There currently exist surplus water that is available in the Orange River system and including the Caledon River that can be allocated to the Greater Bloemfontein Area. Other water resource development options on the Orange River will only become feasible after the water requirements from the Vaal WMA have increased to such an extent that they reduce the availability of water in the Orange River, and a new supply intervention is implemented to augment the loss in yield (DWA 2012e).

The future Polihali Dam site is situated on the Senqu River approximately 1.5km downstream of the confluence of the Senqu and Khubelu Rivers. The Polihali Dam will increase the water delivered from Lesotho Highlands Water Project to the high value industries in the Vaal catchment, but will in the long term, result in a reduction of the water that will be available at the downstream Gariep and Vanderkloof dams. It is envisaged that the Polihali Dam will reduce the yield of the Orange River downstream by approximately 283 million m^3. This is based on the assumption that the overall yield of the system increases by 182 million m^3/a, however, an additional 465 million m^3/a might be transferred to the Gauteng Province, which is likely to cause a shortfall of 283 million m^3/a (465 – 182 = 283) (DWA 2012e).

The Upper Orange WMA, whose mass water balance is presented in Table 4 below, has a large commitment to support the local water requirements and transfers to the Upper Vaal WMA, Fish to Tsitsikama WMA, and release obligations to the Lower Orange WMA. A number of augmentation interventions have been identified to provide additional yield to the Orange River System to make up for the envisaged shortfall caused by transfers from the Polihali Dam to the Gauteng area. Some of the interventions identified include: using the lower level storage in the Vanderkloof Dam; the construction of the Bosberg/Boskraai Dams; and the raising of Gariep Dam. It is the intention of the DWA to initiate a separate reconciliation strategy study on the Orange River System, which will draw on the information from the Greater Bloemfontein Reconciliation Strategy Study (DWA 2012e).

The anticipated surplus yield in the Orange River System and the Caledon River is approximately 44 million m^3/a. According to the Internal Strategic Perspective for the Upper Orange River WMA (DWA 2012e), this surplus is reserved for the growth in demands in the urban, industrial, and mining sectors in the Upper Orange WMA, the Lower Orange, and the Fish to Tsitsikama WMAs. It is not anticipated that there will be any further growth in agricultural water requirements in the Greater Bloemfontein Area (with the exception of the allocation made to the resource poor farmers). Therefore, reality that the agricultural sector and urban sector in the Greater Bloemfontein Area and surrounds do not share any yield from a common surface water resource suggests that it is possible to undertake a reconciliation of supply and requirement based on the current urban water requirements and available yield of the surface water schemes serving the Greater Bloemfontein area and surrounds.

Table 4: Orange River Water Balance (DWA 2012e:19)

	Surplus Yield (million m^3) - 2004	**Surplus Yield (million m^3) - 2012**
Year Surplus Yield	**333** (2000)	**274** (2008)
Less Transfer to Gauteng from the Mohale Dam (impact on Orange River)	-175	-175
Net Available Yield	**158**	**158**
Less Allocation for Resource Poor Farmers	-114	-144
Net current available yield for growth in urban water requirements	**44**	**44**
Less growth in urban , industrial and mining sectors in the Upper Orange WMA, the Lower Orange and allocation for resource poor farmers of the Fish-Tsitsikama area (NWRS 2025)	-90	-90
Net deficit in yield in 2025	**-46**	**-40**
Less Transfer to Gauteng from the Polihali Dam (impact on Orange River in 2053)	-283	-283
Anticipated net yield (will be higher with additional growth in urban water requirements)	**-329** (2053)	**-243** (2037)

4.11 The Greater Bloemfontein Area

The comparison of available surface water supply and current water requirements for the High and Low water requirement scenarios in the Greater Bloemfontein Area based on 2009 data was realistic. The current water requirement was approximately 83 million m^3/a while the available supply was 84 million m^3/a (Historical Firm Yield). It appeared that the 2009 water requirement was in balance with available supply (historical firm yield) and any increase in use (as predicted by the high and low water requirement scenarios) would put the system at risk. The higher the growth in water requirements, the higher the risk would be. It is clear that measures to increase the surety of supply needed were implemented immediately. This included measures to increase the supply of water as well as WC/WDM measures to reduce the demand.

4.12 Issues which can impact on the reconciliation of supply and requirement

There are a number of issues which can impact on the reconciliation of supply and requirement in the longer term. These issues are listed as:

Effectiveness of WC/WDM;

Existing bulk water supply infrastructure capacity i.e. bulk water pipelines and water treatment works;

Illegal use of water;

Impact of HIV/AIDS;

Migration of people from the rural areas to the urban centres, particularly in Bloemfontein;

Sedimentation; and

Surface and groundwater quality.

4.13 Discussion

The statistical results from the study area that are indicated above were scrutinized and rejected as unrealistic and unreliable and not useable to make any scientific conclusion.

Numerous observations were made on the importance and benefit of best management practices in the basin. One issue which came up repeatedly is the importance of measuring water usage at the farm and distributor level. This step is fundamental to successful implementation of a whole range of practices which can lead to improved water conservation and water demand. The water payments methods are also directly linked to the issue of measurement. A whole range of incentives can be put in place, once water is paid for volumetrically, to encourage farmers to use their allocations of water more efficiently (ORASECOM 2011). Another important observation was that although identification and description of best management practices can be done individually, concerted efforts at working in a holistic approach to scheme and farm management can bring about the full realisation of the benefits of each best management practices.

Finally, and perhaps most importantly, there was general agreement that, within the South African context, the South African Water Act and its provisions for *water user associations* and water management plan provides an excellent framework for water conservation and water demand management to take place. The establishment of the irrigation database has shown that significant changes in irrigation practices are taking place and that additional areas are being put under irrigation (ORASECOM 2011).

4.14 Challenges of Water Requirement Allocation in the Orange River WMA

An equitable water allocation should be provided to the irrigation, mixed middleclass urban population and expanding industries, electricity generation and mining sectors. The rehabilitation or construction of new infrastructure that can be paid back by users is financed off-budget through commercial loans with state guarantees. This is done through the Trans-Caledon Tunnel Authority (TCTA), which was established to finance the Lesotho Highlands Water Project (van Koppen and Schreiner 2014: 552). Subsequent pricing strategies have been gazetted to boost cost recovery, but with limited success. In 2012, only 43% of the amount due was collected. At the same time, the costs for outstanding maintenance reached an estimated USD 1.4 billion (van Koppen and Schreiner 2014).

The National Development Plan 2030 announced that an additional 500,000ha of land should be irrigated, as "the driving force" behind integrated rural development. The announcement, however, does not specify to whom, between smallholders and large-scale farmers this land under irrigation is designated for. The New Growth Path also envisages 300,000 households in smallholder schemes by 2020, six times as many as in 2010 but this has to allow 20% of mean annual runoff as environmental flow (van Koppen and Schreiner 2014). It is further suggested by van Koppen and Schreiner (2014) that there is limited infrastructure development for smaller-scale productive water users who cannot pay the capital investments, and, as exposed in a recent policy review, there are many instances of pipes and canals bypassing the multiple water needs of rural communities and supplying distant users (DWA 2013c).

Other impacts of the project are listed and included:

A reduction in water consumption largely due to the presence of a virtual water bank;

Greater accountability resulting from volumetric metered payment system;

Increased levels of awareness and expertise amongst irrigators; and the

Demonstration of best practices which can be taken up by other *water user associations*.

4.15 Summary

The evidence provided in this chapter indicates that allocation of quotas is not based on any applicable scheme. It is rather made haphazardly and hence no correlations are established in the results provided.

The next chapter addresses the study area's water accounting.

CHAPTER 5

WATER ACCOUNTING PLUS (WA+)

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5. Introduction

This chapter seeks to show the role of water accounting in facilitating the comparison of hydrological data at spatio-temporal scales. The Upper Orange River Basin is considered as an example of a water stressed river basin. The chapter also draws on the fact that simulation models are known to determine the difficulties associated with monitoring of components the hydrological cycle, and that precise knowledge of the costs of water services may lead to the sustainable use of water resources. Finally, the chapter also considers that remote sensing (RS) irrigated areas and actual evapotranspiration could be utilised to: (i) conceptualise an understanding of irrigation dynamics, (ii) identify areas that need better ground-based monitoring, and (iii) constrain irrigation models in territories of data-scarcity.

5.1 Water Accounting Plus (WA+)

The scarcity of water entices scientists to be innovative and come up with new analytical tools that lead to the enhancement of water resource management. Water accounting and distributed hydrological models are exemplary of such newly acquired tools. The primary requirement for water accounting is accurate input data for adequate descriptions of water depletion and distribution in river basins. Ground-based observatories are on the decrease, and remote sensing-acquired data is a suitable alternative towards the attainment of an enhance measurement of the required input variables (Bastiaanssen and Steduto 2016; Karimi and Bastiaanssen 2014; Karimi *et al.* 2014; Romaguera *et al.* 2012). WA+ is a unique tool based on among others the System of Environmental Economic Accounting for Water (SEEAW), FAO's Aquastat, and Water Accounting Standard of Australia, "track inflows, assets, liabilities, stocks and reserves for a particular area over a period of time" (Karimi *et al.*, 2013: 1).

A proper application of water management planning measures ensures optimal decision-making in the identification and choice of the most adequate alternatives in the Integrated Water Resources Management (IWRM) processes (Mehta *et al.* 2016; Matthews 2015; Lim 2014; Magombeyi and Taigbenu 2014; Martínez-Santos *et al.* 2014; Maleksaeidi and Karimi 2013; Lorimer 2012; Mas-Pla *et al.* 2012; Pahl-Wostl *et al.* 2012; Quinn 2012). The System of Environmental-Economic Accounting for Water (SEEA-W) is a useful tool for reconciling water balances in a river basin, and it provides as well as display a standard approach that achieves an enhanced comparability of the results between different regions (Pedro-Monzonís *et al.* 2016b). The approach is shown in Figure 8 below.

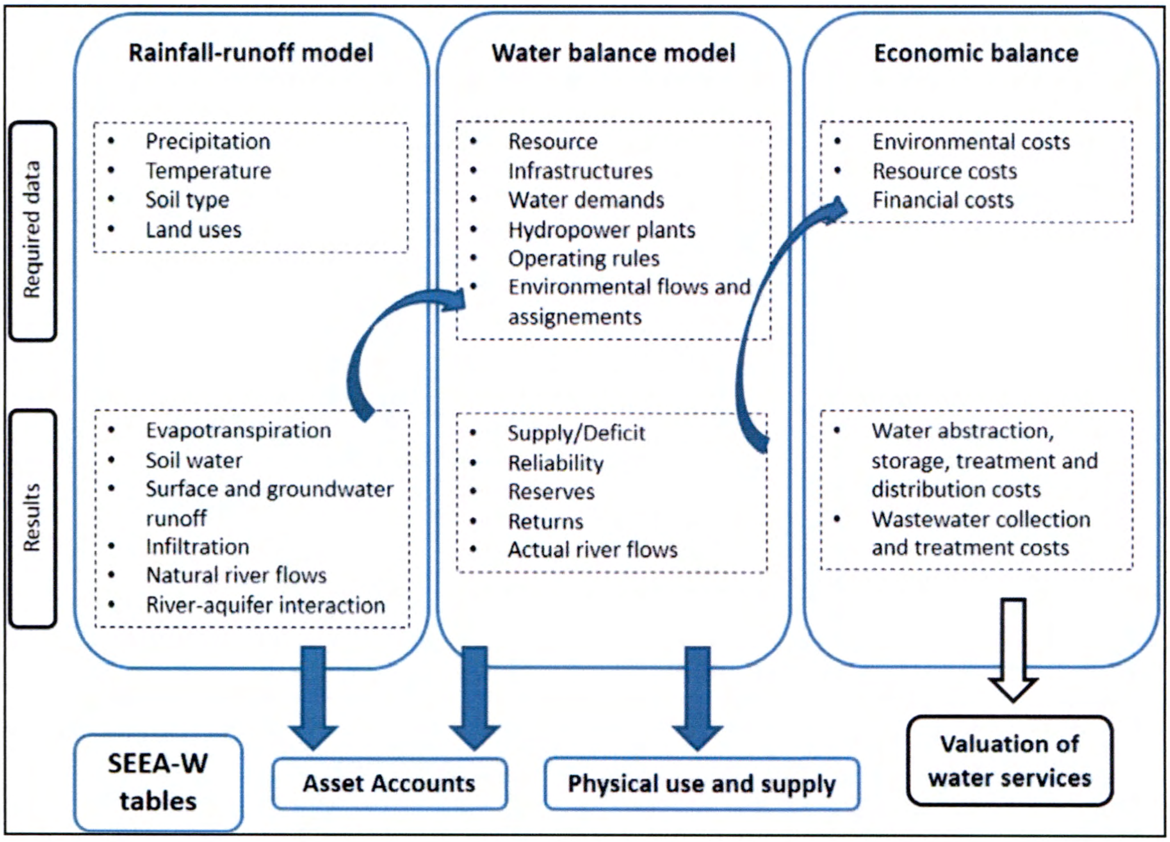

Figure 9: Different types of models' approach for obtaining the SEEA-W tables related to water resources management

(Pedro-Monzonís *et al.* 2016b: 183)

One of the main challenges in the 21st century pertains to the sustainable use of water. This is because water is a vital compound for the life of all inhabitants of our planet. The existence of various global cases of an absence of rational water use are the result of lack of an economic valuation of water resources (Pedro-Monzonís *et al.* 2016a; b). Globally irrigated agriculture comprises 70% of human water demand and produces 40% of humanities' food-supply. The rapid population growth in recent decades warranted an increase in agricultural productivity, especially in water-scarce regions, such as Australia, northwest India, Mexico, North plains of China, Pakistan, Saudi Arabia, and the US high plains, where the resultant large irrigation water demand emanated from a shift or expansion of the abstraction of surface water to groundwater have caused unsustainable use of groundwater (Peña-Arancibia *et al.* 2016a). Hence, an irrational use of water and the growth of agricultural activities within water scarce regions are some of the factors behind the global crises regarding sustainable water use.

The continuing rapid population growth within an uncertain climate points to the need for large capital investments aimed at increasing irrigation efficiency and/or additional surface water storage in order to reduce both the transfer of water from agriculture to urban users and unsustainable use of groundwater. Future financial investments probably need detailed expertise about current and historical irrigation practises. However, the retrospective spatial extent and the temporal dynamics as well as the water use of many important irrigated areas are a source of major uncertainty in the global and regional irrigation assessments of water use. The hydrologic model is used to assess global water supply and irrigation requirements and thus ensuring that irrigated areas are sufficiently provided with water to maintain optimal crop growth. Heuristic rules are used in the determination of the appropriate amounts of surface water and/or groundwater required to satisfactorily provide for irrigation demand, which inter alia, depends on: irrigation infrastructure, stored water in reservoirs, streamflow and soil moisture.

An estimation of the irrigation water use involves the computation of actual evapotranspiration (ET_a) for different crop types using meteorological data and generic crop factors (Campos *et al.* 2016). ET_a is a function of spatial disaggregation that uses static maps of *irrigable areas* (i.e. availability of resources and areas that are under irrigation given a supply network) and a function of temporal disaggregation that uses available (often unreliable) regional and national-level statistics of areas under irrigation (Campos *et al.* 2016). This traditional approach may lead to the overestimation of crop water use as certain assumptions that crops are almost at optimal growing conditions can be generated, which is not always the case when resources are in short supply. These data uncertainties and assumptions constrain the usefulness of this approach at management-relevant scales (i.e. individual irrigation and river systems as well as at aquifer level), particularly in data-scarce regions where resultant climate variability may warrant complex irrigation practises that are difficult to model (Campos *et al.* 2016; Peña-Arancibia *et al.* 2016).

One of remote sensing's greatest advantages is the acquisition of biophysical data that is timely and spatially distributed. This means that constrainment of the earth system models can optimally be achieved. This potential can lead to improved assessments of irrigation water use at management-relevant scales. Both the ET_a estimates and active crop growing areas are critical inputs in irrigation modelling. Thus, remote sensing may be used to determine accurate estimates of *irrigated areas* (i.e. actual areas under irrigation) by determining the phenological development of crops through multi-temporal image classification. Remote sensing can also be used to determine accurate estimations of ET_a for the entire land surface, continents or, large regions at spatial (i.e. < 1 km^2) and temporal (i.e. sub-monthly) resolutions that are considered ideal for monitoring water use and irrigation dynamics (Peña-Arancibia *et al.* 2016).

It is therefore clear that remotely-sensed derived assessments on irrigation dynamics (of both ET_a rates and irrigated area) are useful in the determination of quantities of irrigation water use and water provenance (either groundwater or surface water) in a basin subjected to extreme climatic variability. Until now, there have been meagre comparisons of, on the one hand, the actual evapotranspiration and remotely-sensed (RS) irrigated areas with, on the other hand, surface water allocations, such as the quantity of surface water stored in a dam that is availed for irrigation and other productive activities, and sub-basin water extractions. The estimation of the provenance of water used in irrigation and the extent of the serviced area usually involves a combination of RS irrigated areas and ET_a rates with a monthly river-reach hydrologic model (Peña-Arancibia *et al.* 2016). Finally, in most comparisons, accurate and reliable climate forcing and extraction data have to be carefully used so as to obtain meaningful results. This has been achieved as shown in the results section of this chapter.

5.2 Theoretical Considerations

5.2.1 ET Algorithm Logic

The primary components of the ET algorithm require modifications for: (1) the replacement of the computation of heat storage and soil heat flux since it is a more physically-based constant fraction of net radiation derived by equations, (2) the Normalised Difference Vegetation Index (NDVI) versus the derivation for the dominant global biome types of biome-specific canopy conductance equations considering the meteorological measurements and associated daily eddy covariance from globally distributed tower sites, (3) calculation of ET for land cover types since it is a composite of component ET amounts for the distinctly growing vegetation forms (e.g. evergreen versus deciduous) consisting of this class as opposed to a single biome type (Zhang *et al.* 2010).

Algorithm leads to equation 43, the surface energy balance is used to determine the incoming solar radiation.

$$R_n = H + \lambda E + G, \tag{43}$$

where R_n (Wm^{-2}) is the net radiation flux, H (Wm^{-2}) is the sensible heat flux of the surface, λE (Wm^{-2}) is the latent heat flux of the surface (LE), and G is the sum of the soil heat flux and heat storage in areas under vegetation or heat storage in water bodies. R_n is computed using

$$R_n = R_{ns} - R_{nl} = (1 - \alpha)R_{s\downarrow} - R_{nl}, \tag{44}$$

where R_{ns} is the net incoming shortwave solar radiation, $R_{s\downarrow}$ is incoming shortwave radiation, α is surface albedo, and R_{nl} is outgoing net longwave radiation. R_{nl} is computed following from Allen *et al.* (1998),

$$R_{nl} = \sigma \left[\frac{T^4_{max,K} + T^4_{min,K}}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_{s\downarrow}}{R_{so}} - 0.35\right), \tag{45}$$

where σ is the Stefan-Boltzmann constant (4.903 x 10^{-9} MJ K^{-4} m^{-2} d^{-1}), $T^4_{max,K}$ and $T^4_{min,K}$ are the daily maximum and minimum air temperature in Kelvin, respectively, e_a (Pa) is the actual daily air water vapour pressure, and R_{so} (Wm^{-2}) is incoming shortwave radiation for the clear-sky.

The vegetated pixels that use a remote sensing-derived classification of the global land cover and open water body are easily identified in this algorithm. For the vegetated pixels, the Penman-Monteith (PM) equation with a biome-specific NDVI-based canopy conductance model could be used to compute transpiration in vegetation while a modified PM equation is used to determine evaporation above the soil. The PT method can thus be utilised to compute evaporation for water body pixels.

5.2.2 Evapotranspiration for Areas under Vegetation

The ET for vegetated areas is computed as soil evaporation and direct plant transpiration and in that way partitions available energy for ET because it uses the fractional vegetation cover (f_c) obtained from satellite observations of the NDVI (Zhang *et al.* 2010). Mu *et al.* (2007) have extensively researched on fractional vegetation cover. The available energy for ET (A: Wm^{-2}) is obtained as the difference between R_n and G. For vegetated areas, G is computed as a function of R_n and f_c according to Su *et al.* (2001) equation 31.

$$G = R_n \times [\Gamma_c + (1 - f_c) \times (\Gamma_s - \Gamma_c)], \tag{46}$$

where Γ_s and Γ_c are the proportions of G to R_n for bare soil and full vegetation canopy, respectively. Su *et al.* (2001) make an assumption that Γ_s and Γ_c are global constants, while Γ_s and Γ_c are also regarded as biome-specific constants in the current study. The A term is then directly proportional to energy components that are available for the soil surface (A_{Soil}: Wm^{-2}) and canopy (A_{Canopy} : Wm^{-2}) using f_c thus showing:

$$A_{Canopy} = A \times f_c \tag{47}$$

$$A_{Soil} = A \times (1 - f_c) \tag{48}$$

The PM equation can compute vegetation transpiration as

$$\lambda E_{Canopy} = \frac{\Delta A_{Canopy} + \rho C_p(e_{sat} - e_a)\, g_a}{\Delta + \gamma\,(1 + g_a/g_s)} \tag{49}$$

where λE_{Canopy} (Wm^{-2}) is the canopy latent heat flux (i.e. LE_{Canopy}) and λ (Jkg^{-1}) is the latent heat of vaporisation $\Delta = d\,(e_{sat})/dT$ (Pa K^{-1}) and is the slope of the curve demarcating saturated water vapour pressure (e_{sat}: Pa) to air temperature (T: K); $e_{sat} - e$ is equivalent to the deficit of vapour pressure (VPD: Pa); ρ (kgm^{-3}) is the air density; C_p (J $kg^{-1}K^{-1}$) is the specific heat capacity of air; and g_a (ms^{-1}) is the aerodynamic conductance. The psychrometric constant is obtained from $\gamma = (M_a/M_w)(C_p P_{air}/\lambda)$ where M_w ($kgmol^{-1}$), M_a ($kgmol^{-1}$), and P_{air} (Pa) are the molecular mass of wet air, the molecular mass of dry air, and the air pressure, respectively. In the original PM equation the g_s (ms^{-1}) is the surface conductance. Since the PM function was used to compute plant transpiration at the canopy in this section, the g_s term is identical to the canopy conductance (g_C), where g_C is computed using a biome-specific NDVI-based Jarvis-Stewart-type canopy conductance model (Zhang *et al.* 2010),

$$g_C = g_0(NDVI) \times m(T_{day}) \times m(VPD), \tag{50}$$

where $g_0(NDVI)$ is the biome-dependent potential (i.e., maximum) value of g_C, which is a function of NDVI; T_{day}(°C) is the daylight average air temperature; $m(T_{day})$ is a temperature stress factor and function of T_{day}; $m(VPD)$ is a water/moisture stress factor and function of VPD. The temperature stress factor $m(T_{day})$ follows the equation detailed by June *et al.* (2004) with an optimum temperature T_{opt},

$$m(T_{day}) = \begin{cases} 0.01 & T_{day} \leq T_{close\_min} \\ exp\left(-\left(\frac{T_{day} - T_{opt}}{\beta}\right)\right) & T_{daclose\_min} < T_{day} < T_{close\_max} \\ 0.01 & T_{day} \geq T_{close\_max} \end{cases} \tag{51}$$

where T_{opt}(°C) is a biome-specific optimal air temperature for photosynthesis; T_{close_max} (°C) and T_{close_min} (°C) are the biome-specific maximum and minimum critical temperatures for stomatal closure and the effective cessation of plant photosynthesis; β (°C) is a biome-specific parameter and he difference in temperature from T_{opt} at which temperature stress factor falls to 0.37 (i.e. e^{-1}) (Zhang *et al.* 2010). The $m(VPD)$ term is computed as,

$$(VPD) = \begin{cases} 1.0 & VPD \leq VPD_{open} \\ \frac{VPD_{close} - VPD}{VPD_{close} - VPD_{open}} & VPD_{open} < VPD < VPD_{close}, \\ 0.1 & VPD \geq VPD_{close} \end{cases} \tag{52}$$

where VPD_{open} (Pa) is the biome-specific critical value of VPD at which the canopy stomata are completely open; VPD_{close} (Pa) is the biome-specific critical value of VPD at which canopy stomata are completely closed.

Soil evaporation is computed using the soil evaporation equation from Zhang *et al.* (2010) and Mu *et al.* (2007), which is a combined adjustment of the PM equation and the complementing hypothesis relationship (Fisher *et al.* 2008). The soil evaporation equation and its auxiliary equations include,

$$\lambda E_{Soil} = RH^{VPD/k} \frac{\Delta A_{Soil} + \rho C_p \, VPD g_a}{\Delta + \gamma \times g_a / g_{totc}}, \tag{53}$$

$$g_a = g_{ch} + g_{rh}, \tag{54}$$

$$g_{rh} = \left(4.0 \times \sigma \times T_{day}^3\right) / \left(\rho C_p\right), \tag{55}$$

$$g_{totc} = g_{tot} \times G_{corr}, \tag{56}$$

$$G_{corr} = \left(\frac{273.15 + T_{day}}{293.15}\right) \times \frac{101300}{P_{air}}, \tag{57}$$

where RH is the relative humidity of air and values are the range 0 to 1; $RH^{VPD/k}$ is a moisture constraint on soil evaporation (Fisher *et al.* 2008), which is the soil water deficit index on the basis of the complementary equation where status of surface moisture is correlated to and provides a reflection of the evaporative demand of the atmosphere. It is assumed that soil moisture has an influence on the adjacent atmospheric moisture. k (Pa) is a complementary factor on the relationship and is relatively sensitive to VPD (Fisher *et al.* 2008). The k parameter for different vegetation types was empirically adjusted in the consideration of the possible impacts of different root zone structures and vegetation morphology among different biomes on this complementary relationship (Zhang *et al.* 2010). The g_{rh} (ms^{-1}) is the radiative heat transfer conductance and is computed from equation (55) based on Choudhury and DiGirolamo (1998). In equation (55), T_{day} is in Kelvin. The g_{ch} (ms^{-1}) is the convective heat transfer conductance that is based on the assumption that it is equivalent to the boundary layer conductance (g_{bl}: ms^{-1} (Thornton 1998). It is should be noted that the g_{ch} and g_{bl} were assigned as biome-specific constants from assumptions drawn by Mu *et al.* (2007) and Thornton (1998). The g_{tot} (ms^{-1}) is the total aerodynamic conductance to vapour transport and the combination of surface and aerodynamic conductance components. The g_{totc} (ms^{-1}) is the corrected value of g_{tot} from the standard temperature and pressure conditions (STP) that uses the correction coefficient (G_{corr}) based on Jones (1992). It should be noted that g_{tot} has undergone land cover class adjustment based on Zhang *et al.* (2010).

The mixed evergreen and deciduous forest (MF) land cover class accounts for an average 7% of the global vegetated land area as defined by a global land cover map of 500m resolution (Friedl *et al.* 2010). For purposes of this chapter, the evergreen and deciduous components of the MF class were distinguished for the ET derivation. The relative proportions of each specific tree type were derived within MF pixels using available satellite remote sensing-derived percentage of tree cover products that represent leaf longevity (deciduous and evergreen) and leaf type (broad-leaf and needle-leaf) components (DeFries *et al.* 2000a, 2000b). Soil evaporation and above canopy transpiration algorithms were utilised to compute ET for each specific tree type and weighted to yield composite ET values for each MF pixel (Zhang *et al.* 2010).

5.2.3 Evaporation over Water Bodies

For water bodies, G is computed as a function of effective water depth ($\Delta Z: m$) for heat exchange and air temperature, on the premise that water surface temperature generally follow after air temperature (e.g. Morrill *et al.* 2005; Livingstone and Dokulil 2001; Pilgrim *et al.* 1998),

$$G = \rho_w \times c_w \times K \times (T_{avg,i} - T_{avg,i-1}) \times \Delta Z, \quad (58)$$

where ρ_w (1.0 x 103 kgm^{-3}) is the water density; c_w (4.186 Jg^{-1}°C^{-1}) is the specific heat of water; $T_{avg,i-1}$ and $T_{avg,i}$ are the daily average air temperatures for the previous day and current day, respectively; and K is the slope of the simple linear regression of water surface temperature on air temperature and represents the ratio of water temperature change to surface air temperature change. Pilgrim *et al.* (1998) reported a slope of 0.82 for the linear relationship between water temperature records and associated air temperature records in 39 Minnesota stream temperature monitoring stations. Morrill *et al.* (2005) studied a set of streams at diverse geographical locations to determine the relationship between stream water temperature and air temperature and the results showed that a majority of streams have slopes in the range of 0.6 - 0.8 for the linear regression between air temperature and stream temperature. Therefore, K was set at the mean (0.7) of previously reported values. Zhang *et al.* (2010) mentions that the effective water depth is the uppermost well-mixed layer of the epilimnion and is dependent on the morphology of open water bodies and other climatic factors. The depth of epilimnion varies from tens of centimetres to several metres as suggested in the literature (e.g. Mazumder *et al.* 1990). For simplicity, the value of ΔZ was set at 1.5 m in this study.

The PT equation (Priestley and Taylor 1972) is used to compute the evaporation for open water pixels (Zhang *et al.* 2010).

$$\lambda E_{Water} = a \frac{\Delta A}{\Delta + \gamma}, \quad (59)$$

where the PT coefficient accounts for evaporation arising from the atmospheric vapour pressure deficit in addition to the equilibrium term and is set at 1.26 following Priestley and Taylor (1972). The PT coefficient of 1.26 is generally valid for the saturated surface (Priestley and Taylor 1972) and is even valid for wet meadow (Stewart and Rouse 1977) and well-watered grass (Lhomme 1997). Therefore, this approach may be considered for the estimation of evaporation for smaller (< 8km) water body lengths.

5.2.4 Biome-Specific Potential Canopy Conductance versus NDVI Functions

The biome-specific relationships between g_0 and NDVI can be established by measuring energy fluxes and daily meteorology from eddy covariance flux towers with corresponding NDVI time series from the Advanced Very High Resolution Radiometer Global Inventory Modelling and Mapping Studies – Global Inventory Modelling and Mapping Studies (AVHRR – GIMMS): Normalised Difference Vegetation Index dataset (Pinzon *et al.* 2005; Tucker *et al.* 2005). The computed soil latent heat flux (LE_{Soil} or λE_{Soil}) (method introduced in section 5.3.2) is driven by in situ tower meteorology from the tower LE measurements. This is used to determine canopy latent heat flux (LE_{Canopy} or λE_{Canopy}) was removed. The canopy conductance term (g_c) from LE_{Canopy} and the in situ tower meteorology using the rearranged Penman-Monteith (PM) approach were derived using,

$$g_c = \frac{g_a \gamma LE_{Canopy}}{[\Delta A_{Canopy} + \rho C_p VPD g_a - LE_{Canopy}(\Delta + \gamma)]}, \quad (60)$$

The unavailability of vertical wind profile measurements resulted in the setting of the values of g_a as biome-specific constants based on evidence that the range of g_a variability is generally conservative over low wind speeds (e.g. ≤ 5 ms^{-1}) and aerodynamically rough surfaces following Monteith and Unsworth (2007). Although the use of a constant g_a can introduce uncertainty into the ET estimates, this simplification has been successfully applied for similar satellite based ET mapping studies (e.g. Zhang *et al.* 2010; Zhang *et al.* 2008; Mu *et al.* 2007). The substitution of g_c in equation (60) with g_c in equation (50) and the rearrangement of the equation resulted in the potential surface conductance being derived as follows:

$$g_0 = \frac{g_a \gamma LE_{Canopy}}{[\Delta A_{Canopy} + \rho C_p VPD g_a - LE_{Canopy}(\Delta + \gamma)] \cdot m(T_{day}) \cdot m(VPD)}, \quad (61)$$

The researcher (1) computed daily g_0 for the major global biome types that use daily surface meteorology and LE measurements from selected representative flux towers within each biome; (2) accomplished the sorting of the g_0 series for each NDVI interval (interval size = 0.04) in numeric order and thus removing outliers that fall less than the 10th percentile and are more than the 90th percentile for g_0; (3) computed average daily values of g_0 and NDVI for each NDVI interval with sufficient (≥10) samples; and (4) fitted the scatter plots of g_0 versus NDVI using sigmoid response functions for each biome type following Zhang *et al.* (2010),

$$g_0(\text{NDVI}) = [1/b_1 + b_2 \times exp(-b_3 \times NDVI)] + b_4, \quad (62)$$

where b_3 (dimensionless), b_4 (ms^{-1}) are empirical, b_2 (sm^{-1}), and b_1 (sm^{-1}) parameters. It was also considered that the constraint g_0 $(0) = 0$, the b_4 parameter is equivalent to $-1/b_1 + b_2$. An adaptive Markov chain Monte Carlo (MCMC) method (Haario *et al.* 2006) with a chain of 6000 length to yield the 99% posterior distribution of the fitted relationship of g_0 versus NDVI for each biome type may be applied to analyse the uncertainty in the fitted relationship of g_0 versus NDVI.

5.3 Methodology

The methodology employed used data acquired through RS as outlined in Chapter 3. The variables used here included evapotranspiration (ET), rainfall and land-use. The main RS-derived variable in the study was ET since the variables, rainfall and land-use, were obtained from archival data sources.

5.3.1 Data Collection

Remote Sensing Data for Water Accounting Plus (WA+) was acquired as outlined in section 3.7.3, Land Use Data was similarly obtained as per outline in section 3.7.4 and key indicators that have been alluded to in section 3.7.5. Data on water allocation quotas was obtained from the Department of Water Affairs and *Water user associations* within the study area. This data was supplemented by data obtained from Statistics South Africa (StatsSa). With regards to current water demands data was obtained from inventory records held by the DWA and cropping patterns were obtained from the DWA, Department of Agriculture and associated *Water user associations*.

There are two objectives that were addressed in this section. Objective 1 sought to perform water accounting through the employment of remote sensing between the different users in the study area during the period 1994 to 2014 based on the actual allocation of water needs by Department of Water Affairs (DWA) Republic of South Africa, Lesotho Highlands Development Authority (LHDA) and the Department of Water Affairs (DWA) Lesotho. Objective 2 sought to assess the state of equity in water allocation with respect to the institutional establishments referred above that include the different *water user associations* located in different parts of the study area. Two research hypotheses are advanced for this study. Hypothesis 1 states that there are differences in determining water accounting for different water users, while hypothesis 2 suggests that there are differences in the determination of the equitable distribution of water between different water users.

5.4 Results

5.4.1 Remote Sensing-based results

The remote sensing images for the different period 2011 to 2016 were downloaded in an attempt to get an overall idea about the whole study area. All images were downloaded from the United States Geological Survey (USGS) LandSat 7 ETM produced through the Bumper sensor mode. The acquisition date for Figure 10 is November 14, 2011, while Figure 11 was acquired on November 06, 2014 and Figure 12 on November 25, 2015. All images reflect the summer rainfall season in the study area. Figure 10 reflects the conditions prevalent in a normal year, while Figure 11 depicts a transitional period towards the onset of drought in the area and Figure 12 reflects the conditions during the drought of 2015. The images provided in these figures are presented in order to indicate the levels of comparative vegetation intensities on a wider area without limiting the view to the immediate proximity of agricultural operations. Such a comparative exercise was also performed by Dohn *et al.* (2017) and Jin *et al.* (2017). The figures indicate a natural setting in the area, particularly in an intensely agricultural area, which is downstream of the Gariep and the Vanderkloof Dams.

These images, however, represent a non-drought period. This is unlike in the drought period where expected trends could be that precipitation and soil moisture were much lower than in the non-drought period, and a higher than normal air temperature was detected during the drought period. For this study, and in accordance with Yu *et al.* (2017), conditions were normal until the onset of the 2015 drought which corresponded with the highest reduction of precipitation (>50%). The evaluation and forecasting of precipitation anomalies (rainfall deficit and surplus) are made using the standardised precipitation index, *SPI* (Łabędzki 2017; Pai *et al.* 2017). These images also support the fact that November 2011 was a normal precipitation month whereas November 2015 was associated with the experiencing of drought in the area.

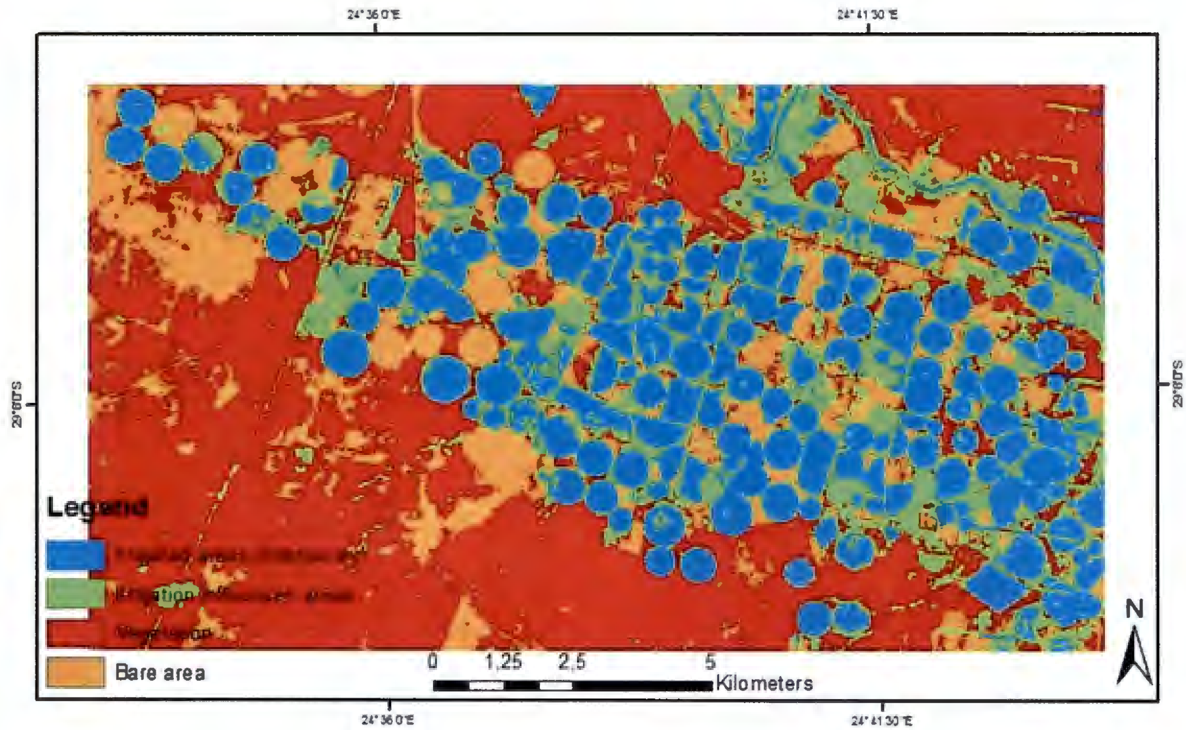

Figure 10: Classification of an agricultural area Landsat 7 ETM$^+$ image of 2011

(Author 2017)

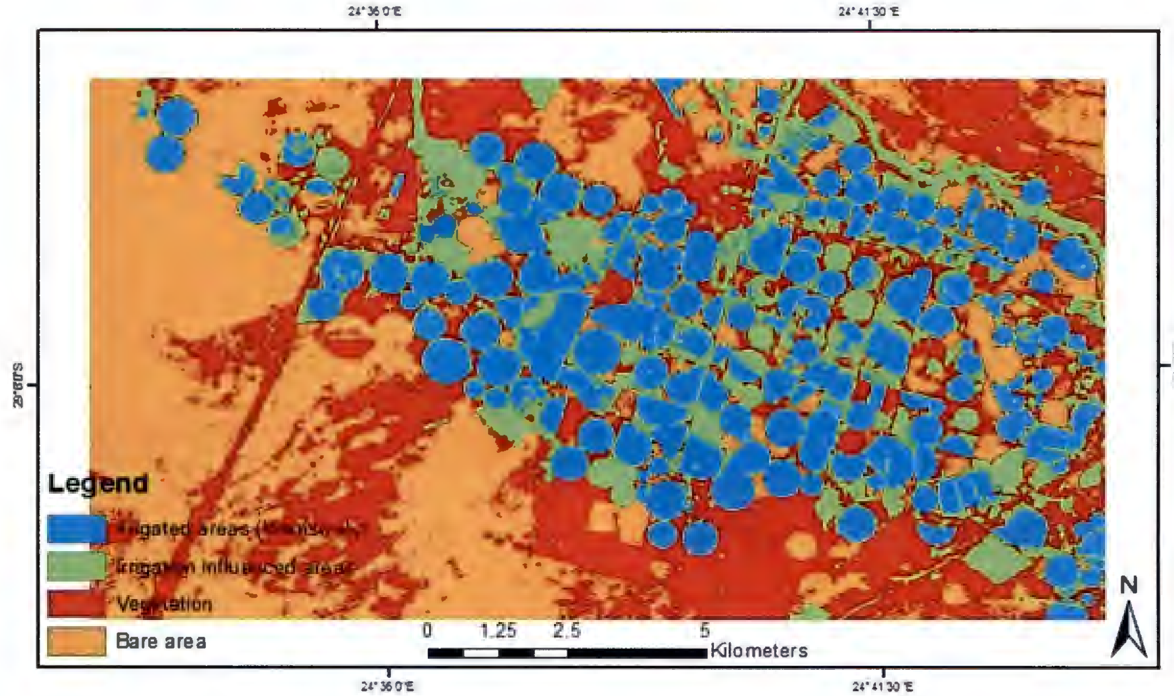

Figure 11: Classification of an agricultural area Landsat 7 ETM$^+$ image of 2014

(Author 2017)

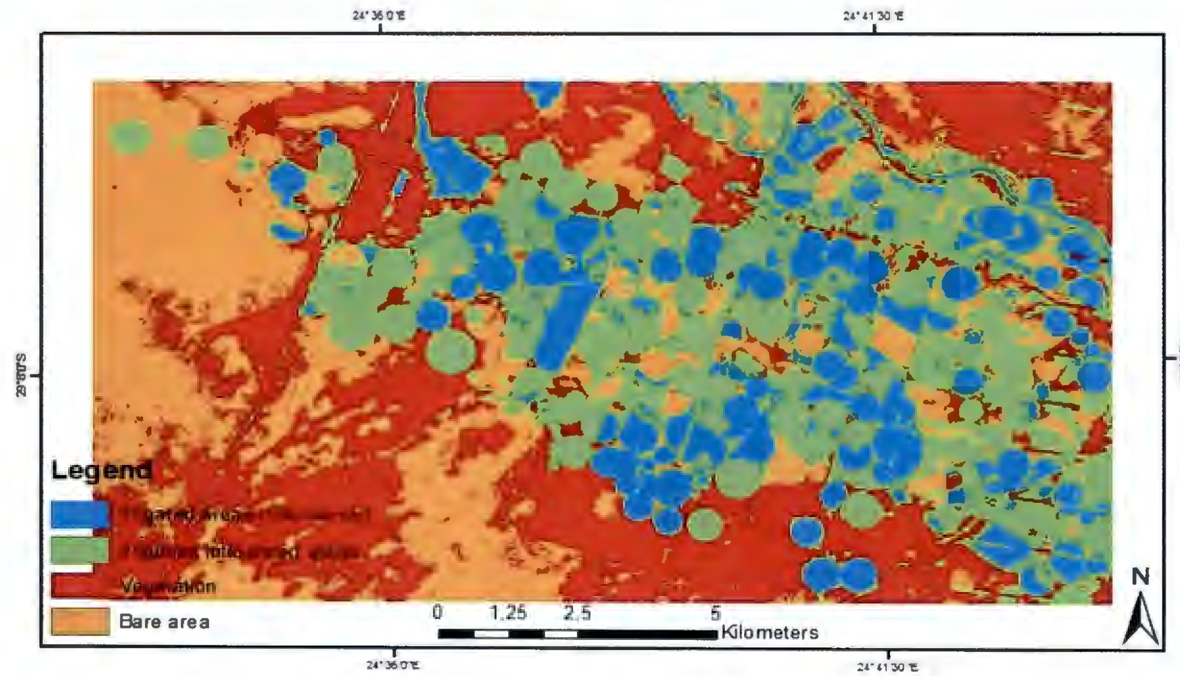

Figure 12: Classification of an agricultural area Landsat 7 ETM$^+$ image of 2015

(Author 2017)

According to the South African Weather Service, the lowest national annual rainfall in South Africa, since 1904, was received in 2015. Figure 13 shows that the 2015 rainfall levels are contextualised against the severe drought in 1992, as well as the long term average annual rainfall (for the period 1970 - 2015). Whilst annual rainfall is a logical departure in comparing different production seasons, it does not present the entire picture, as the monthly distribution of rainfall is also an important consideration in the context of agricultural production.

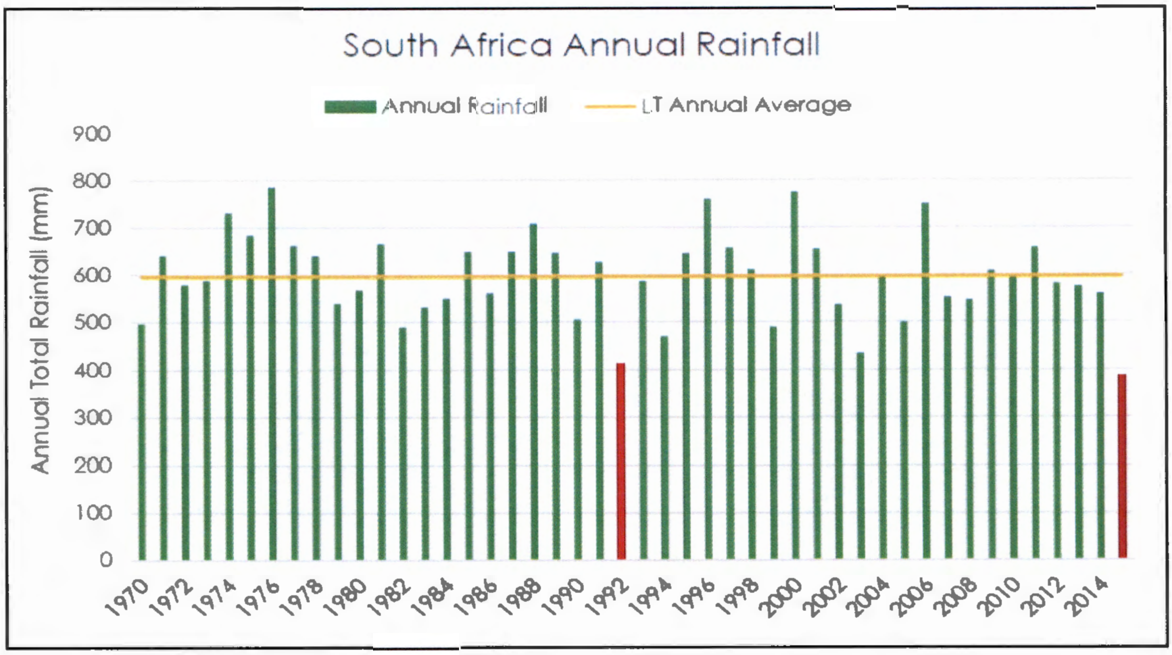

Figure 13: South Africa Annual Rainfall

(Weather SA)

Agriculture has been identified as one sector demanding expansion in the National Development Plan, with intensive, export orientated industries in particular identified as key in creating jobs within the rural economy. Ambitious job creation targets require investment in irrigation infrastructure and consequently, the response to the 2015 drought must continue to foster an enabling environment where investment can flourish.

The severe drought that affected South Africa as a whole witnessed the imposition of water restrictions in several places at differing levels across the country. The farmers in the study area were severely affected as ncted the various lower dam capacities while others even ran totally dry. It was a common sight to see trucks loaded with water tanks delivering water to several town residents. In some, areas long queues of residents awaiting water delivery trucks were a common sight. This was indeed a highly documented and notable drought.

More farming operations are undertaken in the region further downstream of the Gariep and Vanderkloof dams and this is where these images are from. The water bodies indicated in Figures 10 - 12 are the combined features of irrigated agricultural land and water sourced from the Orange River for the farming operations running downstream along the river. One noticeable feature is that these blue spots (i.e. centre pivot irrigation farms) are either flood irrigated and/or centre pivot irrigated. The green spots indicate areas irrigated less often or those that have not been irrigated for some time. The intensity is reflective of amounts applied onto each field. Finally, the fire red spots indicate areas of natural vegetation. The images also show that the spatial distribution does differ much given the different drought infestation during the two periods under consideration.

The trend observed in Figure 10 is that a period in a normal year has precipitation that is assumed sufficient at about 650mm based on the long term average. The assumption is that precipitation amounts peaked, yielded surplus water in the system and finally resulting in runoff. The farmers' abstraction of water amounts was normal according to allocated quotas and not justifiable (i.e. could be unregistered and/or unlawful use). The more suitably arable areas appear much vegetated which indicates much improved activity in the area whereas areas near the Orange River in the north east appear lesser vegetated. Figure 11 shows that this pattern extends into 2014 which marks the transition leading to the onset of a drought. Figure 12 shows an image of November 2015 which was during the drought period. Precipitation amounts were little and resulted in a deficit in the system but the farmers' abstraction of water was still at allowable amounts, as indicated in their quotas. The slight change on the appearance on the image does not suggest that this area witnessed any change in water allocations and /or restrictions but instead shows further that water use was still high.

The implication from the analysed images is that the farmers' abstraction of irrigation water is not justifiable. This is indicative of the Government's considerable lack of implementation of water abstractions, licensing and other regulations. One would think a uniform rationing of water is applied water is scarce, for many countries introduce uniform rationing (i.e. allocation of water on an ex-post basis) during periods of scarcity. This exercise is an attempt at safeguarding efficiency ex-post thus channelling water to those farmers who need it most. The key difficulty, however, is that while the irrigated area is considered ex-post, what is not observable is the productivity of water in each farming unit.

Some of the observed characteristics of the study area are presented in Tables 5 – 7. These tables show SEEA-W ‘asset accounts’ overall balance, a replica of the SEEA-W table ‘matrix of flows between water resources’: overall balance and the cropping information and the relative importance of the crop cover types to the measured signal for the period June 2014 to June 2016.

Table 5: SEEA-W Table 'asset accounts': overall balance.

	Upper Orange – Senqu River System **Time step: Year** **Period: 2014 - 2016** **Water uses: Aggregated**	**EA.131. Surface water**						
		EA.1311 Artificial Reservoirs	**EA.1312 Lakes**	**EA.1313 Rivers**	**EA.1314 Snow, ice and glaciers**	**EA.132 Groundwater**	**EA.133 Soil water**	**Total**
	1. Opening stocks	3490	200		0	400	292	4382
Increase in	2. Returns	196	0	58157		0		58353
Stocks	3. Precipitation				6354	46232		52586
	4. Inflows	24417	136	19376		2333	0	46262
	4.a. From upstream territories	0		0				0
	4.b. From other resources	24417	136	19376		2333	0	46262
Decrease in	5. Abstractions	17127	0	43576		1235		61938
Stocks	6. Actual evaporation/ET	194					33391	33585
	7. Outflows	7300	136	33249	6354	580	7698	55317
	7.a. To downstream territories			9055				9055
	7.b. To the sea							0
	7.c. To other resources	7300	136	24194	6354	580	7698	46262
	8. Other changes in volume	0						0
	9. Closing stocks	3481	200		0	918	292	4892

Table 6: SEEA-W Table 'matrix of flows between water resources': overall balance.

Upper Orange – Senqu River System **Time step: Year** **Period: 2014 - 2016** **Water uses: Aggregated**	**EA.131. Surface water**						
	EA.1311 Artificial Reservoirs	**EA.1312 Lakes**	**EA.1313 Rivers**	**EA.1314 Snow, ice and glaciers**	**EA.132 Groundwater**	**EA.133 Soil water**	**Outflow to other resources in the study area**
EA.1311 Artificial reservoirs			7300		0		7300
EA.1312 Lakes			136				136
EA.1313 Rivers	23040	73			1081		24194
EA.1314 Snow, ice and glaciers			6354				6354
EA.132 Groundwater			580			0	580
EA.133 Soil water	1377	63	5006		1252		7698
Inflows from other resources in the study area	24417	136	19376	0	2333	0	46262

Table 7: Cropping information and relative importance of the crop cover types to the measured signal

Crop Cover	Seeding time	Harvest time	2014 - 2015	2015 -2016
Maize	August	April	34.2%	27.4%
Potatoes	August	February	33.0%	72.6%
Table-grapes	-	-	32.8%	-
Lucerne	-	-	-	-

5.4.2 Irrigation Requirements and Water Demand

Water demand computations

Current and possible future agricultural irrigation activities in the river reaches were identified. The programme, Cropwat (FAO 1992), was used to determine crop water use and irrigation requirements from the evapotranspiration occurring from each crop during its life. Other climatic influences and factors, such as irrigation type, efficiency and the need for extra water for leaching of excess salts from the soil, were taken into account.

Cropping patterns

The overall cropping patterns for the Orange River system are given in Table 8.

Current water demand

The water demand data for each of the 22 river reaches in the entire Orange River system are given in Table 9 whereas Table 10 gives water demand data for only the study area. A river reach is a segment of a river as it flows downstream. In the study area, they range from river reach 1 to 14. It was also necessary to adopt this approach for ease of comparison with previous water demand forecasts done for the entire Orange River. The total current water allocations (scheduled irrigation hectares x water quota) are compared with the computed estimates for overall irrigation requirement and water demand. On the overall, water allocation is lower than water demand in the study area.

Possible future water demand

Water demands were computed for the possible new irrigation developments for both small /community and commercial farmers were identified during the course of the study. The calculations were based on the prevailing water quotas. Table 10 illustrates the results of the irrigation demands found in the study area.

Table 8: Cropping patterns for the Orange River system

Cropping pattern expressed as % total of crop area								
Lucerne	Fodder & pasture	Maize	Wheat	Cotton	Legumes	Vegetables & Potatoes	Table-grapes	Fruit Citrus
11.2	4.4	18.1	33.9	6.4	5.2	2.7	17.5	0.6

Table 9: Overall irrigation requirements and water demands for the Orange River system

Water allocation $m^3 \times 10^6/a$	**Water demand (Cropwat) $m^3 \times 10^6/a$**	**Average water quota $m^3/h/a$**	**Average irrigation requirement (Cropwat) $m^3/h/a$**
1 221	1 382	11 560	13 243

Table 10: Irrigation Demands in the Study Area

River reach	Description	Irrigation demand (million m^3/a)	Irrigation areas (ha)
1	Caledon River: Upstream (U/S) Welbedacht Dam	40.3	9 930
2	Caledon River: Welbedacht Dam to Gariep Dam	36.5	5 835
3	U/S Aliwal North Downstream (D/S) Oranjedraai	6.6	877
4	Aliwal North to Gariep	52.5	8 229
5	U/S Aliwal North	28.0	6 341
6	Gariep Dam to Vanderkloof Dam	27.7	3 121
7	Vanderkloof Dam (through canals)	195.1	17 678
8	Scholzburg and Lower Riet Irrigation Boards (IBs)	50.2	4 564
9	Vanderkloof - Marks Drift	187.4	17 455
10	Krugerdrift Dam to Tweerivier Gauge – Modder River	52.5	7 004
11	Tierpoort Dam to Kalkfontein Dam: Tierpoort IB	8.1	1 018
12	Kalkfontein Dam to Riet River Settlement	56.7	6 187
13	Douglas Weir to Orange – Vaal Confluence (Orange Water)	104.3	11 410
Total {Upper Orange (reaches 1-14)}		**846**	**99649**

Note that the 'u/s' used in the table refers to upstream of the referred place.

5.4.3 Water Demand and Water Conservation Management (WD/WCM)

Water demand management entails a sound policy approach that involves the application of selected incentives to increase the availability of water cost effectively for more equitable, efficient and eco-friendly allocation and usage. This will regulate demand, encourage maximal participation, and define accountability and responsibility of both private and government sectors. As mentioned in Chapter 2, South Africa's water resources under the DWA are managed through IWRM structures that include *Water User Associations* (WUAs), Bulk Water Distributors and Municipalities.

A number of canals and weirs control irrigation water from the Gariep and Vanderkloof Dams along the Orange River. The total length of the Vanderkloof canal that flows to the

Kimberley region and also feeds the Riet/Modder Irrigation schemes is 100km. Calibrated sluice gates are used to distribute the water to farmers while others are serviced by in-line meters with telemetry. However, the infrastructure of these schemes, with the exception of Kakamas *water user association* where comprehensive measures are in place, is old and needs rehabilitation.

The researcher noted some existing measures, which improve the status of irrigation (cf DWA 2013a). These include:

Agronomic aspects: 90% of the farmers opt to stick to relatively low value crops such as maize, wheat, lucerne and other fodder crops. Other related factors include: assurance of irrigation water supply, cost of water, high capital costs involved in vine and orchard establishment, financial viability related to the export of vines and orchard products, climate risk, management intensity, and deteriorating water quality.

On-farm technologies: About 80% of the farming activities catering for orchard and vine crops employ the centre pivot irrigation enhanced by micro-jets and drip irrigation with a minimal practice of flood irrigation taking place lower downstream and outside the study area.

The findings from a determination of water conservation and the views of the interviewees in the study area are listed and show: efficient and effective use of water, care and protection of water resources, maintenance or improvement of water quality and minimisation of loss or waste of water.

5.5 Discussion

Advantages of WA+

WA+ provides strategic insights into the possibilities of securing water resources availability and resilience to climate change and climate variability, while maintaining biodiversity, water conservation for committed flows and preventing land degradation (Karimi *et al.* 2012). The WA+ framework performs evaluations of the impact of interventions such as (i) deficit irrigation, (ii) modernisation of irrigation, (iii) altered cultivation practices, (iv) artificial recharge, (v) cropping pattern change, (vi) deforestation, (vii) introduction of biofuel crops, (viii) reduced groundwater abstractions, (ix) urban expansion, (x) wastewater treatment,

(xi) water productivity improvement, (xii) water re-allocations, and (xiii) water retention and storage.

Limitations of WA+

The WA+ cannot replace hydrological models in their function to provide detailed information on water flows in a basin. WA+ only summarises complicated, rather than analyse, the flow from one location to another (Karimi *et al.* 2012). WA+ only simplifies how hydrological modelling results are obtained for the good a wider audience. It acts as a tentative guideline for water depletion and does not have an operational system to quantify the partitioning flow of surface and/or groundwater systems. WA+ is faced further with a difficulty after initial computations of precipitation to sub-divide utilised and utilisable water. It places more emphasis on net withdrawals than gross withdrawals.

5.5.1 Remote Sensing Considerations

Classified remote sensing images were obtained via supervised classification because results obtained from other operations were not reflective of parameters determined through ground-truthing. METRIC was used on grounds of easy application than the use of algorithms as mentioned hereunder.

Other groups of ET algorithms are based on the vegetation index and its derivatives as published by Miralles *et al.* (2011), Mu *et al.* (2011), Zhang *et al.* (2010), Guerschman *et al.* (2009), and Nemani and Running (1989). ETLook is a new ET model that directly computes the surface energy balance using sub-soil moisture for the root zone to feed vegetation transpiration and surface soil moisture estimations for the top soil to feed soil evaporation (Bastiaanssen *et al.* 2012). Soil moisture data can be inferred from microwave measurements (Dunne *et al.* 2007) or from thermal measurements (Scott *et al.* 2003). Microwave measurements provide a solution for all weather conditions and can be applied at any spatial scale for which moisture data is available.

It is hard to measure in situ crop ET, under actual field conditions, on a routine basis. Instead, the ET_o of a reference crop (e.g., grass) is often considered easy to compute from routine weather station data. The potential ET (ET_{pot}) follows from ET_o and a set of standard crop coefficients K_c that assume pristine growing conditions. In either case, ET_o and ET_{pot} are proxies of ET, with the actual ET values usually being lower. A crop stress coefficient K_s, being either a linear or convex function of root zone soil moisture and soil salinity, should be considered in order to obtain ET_{act} from ET_{pot} (Bastiaanssen and Steduto 2016). The ET_{pot} requires access to soil, rainfall and irrigation data sets at global scale (e.g. Jagermeyr *et al.* 2015). An absence of these data sets results in ET in many studies being assumed to be similar to ET_{pot}.

Alternatively, ET under actual growing conditions can be quantified from satellite multi-spectral measurements in conjunction with surface energy balance models. This excludes the need to have access to in situ soil moisture data. Satellite-based monitoring makes it feasible to determine actual ET globally using one single sensing system. The spatial distribution of crop yield, Y, can also be determined from satellite measurements by applying the concepts of Light Use Efficiency or Water Use Efficiency (WUE). Remote-sensing-based estimates of Y and ET give an allowance to generate populations of (CWP) data from which yield and water productivity gaps are determined.

Remote sensing was also employed in order to support and evaluate the performance of the K_c-NDVI approach, a comparison was made between K_c values (calculated by FAO-56 and corrected) and K_c values (estimated by K_c-NDVI approach). A comparison between K_c derived from remote sensing data and K_c calculated using the FAO method and corrected by the correction factor (K_r) was performed for grapes, vegetables and lucerne. The K_c (FAO) and K_c - NDVI values for grapes were found to be 0.95 and 0.65 – 1.2 respectively. The K_c (FAO) and K_c – NDVI values for vegetables were 0.72 and 0.52 – 0.95 respectively. For lucerne, the K_c (FAO) and K_c – NDVI values 0.48 and 0.35 – 0.65 respectively. Therefore, remote sensing is essential in the provision of a data set independent from soil water balance models, tabulated crop coefficients and statistics (Bastiaanssen and Steduto 2016).

The appearance of remote sensing classification images under texture and supervised operations were not representative of ground parameters and this led the researcher to perform an unsupervised classification. The data mining process usually consists of three sequences: (1) pre-processing or data preparation; (2) modelling and validation; and (3) post-processing or deployment (Traore *et al.* 2017). Firstly, the data may require some cleaning and transformation according to some constraints imposed by some tools, algorithms, or users. Data has to be free of noise and some transformations are required for visualising very large data sets. Secondly, the making of a choice or the development of a model that better reflects the application behaviour has to done. In other words, once a model is chosen or developed, its efficiency and the accuracy of its predictive results should be evaluated. These two operations failed in this study. Finally, the third step consists using the model, evaluation and validation in the second phase in order to effectively study the application behaviour. Usually, the model output requires some ''post-processing'' in order to exploit it (Knoth and Pebesma 2017; Traore *et al.* 2017; Watmough *et al.* 2017; Xue *et al.* 2017).

Classification parameters are usually generalised across large spatial extents when using remotely sensed data derived from Landsat and MODIS. However, the challenges associated with using Very High Resolution (VHR) data may be that VHR sensors allow for small land parcels and ground features detection and classification not ideally suitable for monitoring complex landscapes. However, VHR data are also characterised by a series of challenges (Watmough *et al.* 2017). The H-resolution problem occurs when a single ground feature's characterisation is done by multiple image pixels thereby increasing the likelihood of the pixels comprising a single ground feature that have different spectral reflectance values. This problem, combined with the often low number of spectral bands available on VHR sensors, reduces the spectral separation of different ground features in VHR satellite sensor data. This is because it is more likely that pixels comprising one ground feature will share spectral characteristics with pixels comprising different ground features (Watmough *et al.* 2017), a view also confirmed by Knoth and Pebesma (2017) and Xue *et al.* (2017).

5.5.2 Factors that affect Water Savings

A number of factors that affect water savings in the study area were observed. These include:

Water allocation method: It is better to allocate water a volumetric analysis than to allocate water on a "standard volume (quota) per unit area (i.e. m^3/ha/annum) and on an "irrigation area" which is seen as a major disincentive that leads to negation of saving on irrigation water as efficient water management and proper scheduling are compromised.

Lack of DWA support: There is little or minimal involvement of the DWA in monitoring WD/WCM through encouragement and auditing. It is generally assumed that the involvement of the DWA can yield fruitful audit results.

Governance relative to statutory requirements of Irrigation Boards (IBs) and WUAs: Anomalies are common owing to the use of IBs (i.e. using old legislation) and WUAs (i.e. using new legislation). Legalities relating to these different governance structures, especially with regard to non-uniformity, lead to several non-compliance issues impeding irrigation efficiency.

Poor condition of bulk infrastructure: Most WUAs have been in existence for some time now such that the infrastructure is now old and require enormous overhaul capital inputs.

Inadequate/inappropriate water measuring devices: A major irrigation constraint is the lack of appropriate water measuring devices that leads to poor irrigation efficiency in the WUAs and IBs.

Lack of incentives to save water: Most farmers in the area feel that cutting on water usage de-values attached prices to their lands and so do not save water. In addition, the WUAs do not save on irrigation water as they often have to sell extra water to irrigators to meet their running budget costs (DWA 2013a; Komakech *et al.* 2012).

5.5.3 Incentives to improve Irrigation Water Efficiency

The use of tangible incentives might improve the efficiency of irrigation water use and management in the study area. The suggested incentives include:

Use of high tech irrigation scheduling tied to overseas destined products which need specific documented proof (see water footprint). This in turn minimises on electricity costs.

Promoting water markets.

Careful irrigation scheduling may lead to the irrigation of an adjacent area through allocated irrigation water.

The provision of a guaranteed long term irrigation water supply.

Charges made to WUAs should tally with the actual water allocated to irrigators rather than the total-area-based allocation (DWA 2013a).

5.5.4 Specific Opportunities for Irrigation Water Savings

Irrigation water savings can be achieved by addressing unregistered irrational water use. This involves (i) the expansion of unregistered diffuse irrigation away from the main stream of the Orange River and outside of controlled irrigation areas. A better control will yield significant water savings. Savings can also be achieved through (ii) the expansion of unregistered irrigation in irrigation areas. Coverage for WUAs should be for the entire basin as this is likely to discourage the "illegal use" of water which would be seen as "stealing own water." Another foreseeable benefit can be achieved through the accurate measurement of allocations as the volumetrically accurate allocations can lead to or encourage realistic water savings such as that observed in the Orange - Riet WUA.

There also exist likely benefits from the proper purchasing of water entitlements. It is possible that a reduction in water use could be accomplished when the Minister levies additional water allocations on all water users, in terms of Section 57 of the NWA, thus encouraging water users who are willing to sell to do so by tendering. However, great caution should be observed not to de-value the land, compromise viability of IBs and WUAs, which could lead to the loss of jobs by farm-workers and reduced levy income.

The introduction of an application of Irrigation "Best Practice" could be advantageous. All users, IBs, WUAs and individual irrigators, can advocate for best practices by (i) applying the DWA guidelines, (ii) putting in place policies, rules/regulations and abiding by them, (iii) making constant reference to water supply and monitoring bench marks, (iv) advocating proper auditing, accounting and disposal, (v) and indulging in best operational management practices. The best operational management practices involve the implementation of bulk infrastructure repair and maintenance, water quality measurement and monitoring, effective water allocation measurement and monitoring, operating under prescribed time management plans, seeking technical and advisory support on on-farm irrigation and curbing unlawful water withdrawals.

Some of the best management practices which were carried out by irrigators and yielded approximately 20% water saving include: (i) On-farm water measurement, (ii) using water efficient irrigation systems, (iii) implementing scheduled irrigation to prevent irrigating above crop requirements, and (iv) using proper reticulation systems and storage dams that could minimise losses (DWA 2013a: 24).

5.5.5 Irrigation Water Savings Estimates

According to the DWA (2013: 26) a 10% saving of 237 million m^3/annum could be achieved in the entire Orange River basin from a total irrigation demand of 2 366 million m^3/a, within a ten-year period. In total 34 520 direct jobs could be supported by irrigated agriculture and provide R1 912.1 million/annum in payments to low income households. This translates to R55 000 per household per annum, if on average two people per household are employed. Of these 34 520 direct jobs, 10 097 are permanently employed and 24 423 are seasonal workers (DWA 2013a). The agricultural production related to these savings include table-grapes and grapes (dry) at 35% and 33% respectively, potatoes at 6%, wheat at 6%, grape (wine), and pasture (lucerne) ate around 5% and deciduous fruit and drybean ate 3% each, while vegetable production accounts for only 1% (DWA 2013a).

Nationally, irrigated agriculture contributes R8 110 million (nearly 5%) to the total Gross Domestic Product (GDP) with that from the study area contributing slightly less than 50% of this and thus making a major contribution towards poverty alleviation through the provision of wages to low income households (DWA 2013a). Observations show that grapes (dry) (raisins) sustain 33% of the jobs with a 26% contribution to low income households where a large number of the employees are seasonal. The grape sector sustains about 72% of the employment and pays 52% of the total payments to low-income households. The plant sectors' contribution to employment generation is such that the various grape types account for 48%; wheat, maize and pasture (lucerne) account for 12% each, potatoes generate 7% of the overall employment in the study area, while wine grapes, deciduous fruits, vegetables and drybean account for the remainder. The capital generated by the irrigation activities is estimated at about R15 900 million (DWA 2013a).

The above analysis illustrates the value of the Orange River irrigation water and the significant contribution it makes to the growth of South Africa with regard to the GDP and job creation. Irrigation also makes a major contribution to poverty alleviation through the wage payments to low income households and the creation of direct employment opportunities in the area (DWA 2013a). The results from the Upper Orange River sections 1 – 14 show the volume of water use in million cubic metres per annum (Mm/a) and irrigation in hectares (ha). Usually results from different studies also produce different results in this area as evidenced in the comparative studies carried out by DWA (2013a) that produced the Main Report, Validation and Verification (VV) (i.e. Qualifying_Final and Current) reports in which the MR results show the area (99 647ha) having used 846 Mm/a for irrigation. In addition, the VV $_{Qualifying\_Final}$ study which considered an average area = 100 896ha used 869.02 Mm/a of irrigation water and the $VV_{Current}$ had an area equivalent to 119 687ha and used 1031.21 Mm/a of irrigation water.

The current study's computed results indicate that an average water quota is at 11 560 m^3/h/a while water allocation is at 1 221 m^3 x 10^6/a. It is also against this background that some notable and serious disparities that were obtained in this study show similarities to those provided by DWA (2013a) during a comparative summary of irrigation areas and volumes of irrigation water utilised in the Upper Orange River basin. These results relate to (a) the Main Report (January 2013 to August 2013), and (b) the 2010 validation data also known as "Qualifying_final", and (c) the so-called "Current" water use which equates to irrigation areas (and estimated water use associated with these area) as observed from satellite imagery and validated on the ground. It is of importance to note that these "Current" areas have not yet been verified as "lawful" irrigation water use. The "Current" irrigation areas were not validated on the ground. Nonetheless, the "Current" water use is inclusive of unregistered unlawful use, groundwater used for irrigation, areas incorrectly identified from satellite imagery as irrigation, and irrigation from farm dams which could be opportunistic in nature in that farmers take advantage of wet years when local surface water is available for irrigation (DWA 2013a).

To indicate the kind of mis-reporting on the actual farming operations in the study area, a set water demand management practices associated with irrigation indicate as though the year on year operations are similar and that all years receive equal supplemental water from rains. The operations are reportedly portrait to be unaltered throughout time. This illegal use of water continues even where crops under cultivation do not necessarily have similar crop water requirements. At times even when a seasonal crop is cultivated it is mis-reported that water quotas or allocation schedules have to remain unchanged. The area under cultivation for this area is also declared consistently unaltered such that Figures 14 - 19 show only the slight differences they indicate. This generally leads to conflicts amongst all stakeholders with respect to access to water. As it could be viewed from this study, it then remains apparent that increasing conflicts over water access and overexploitation of scarce water resources are indicators of management failures and undesirable state of water governance. The observation schedule infact helped here in that farmers maintain initially high quotas and when they need to sell their farms a low allocation means a cheaper farm! Much of the information is withheld by farmers to protect the value of their farms so observations reveals all that hidden information.

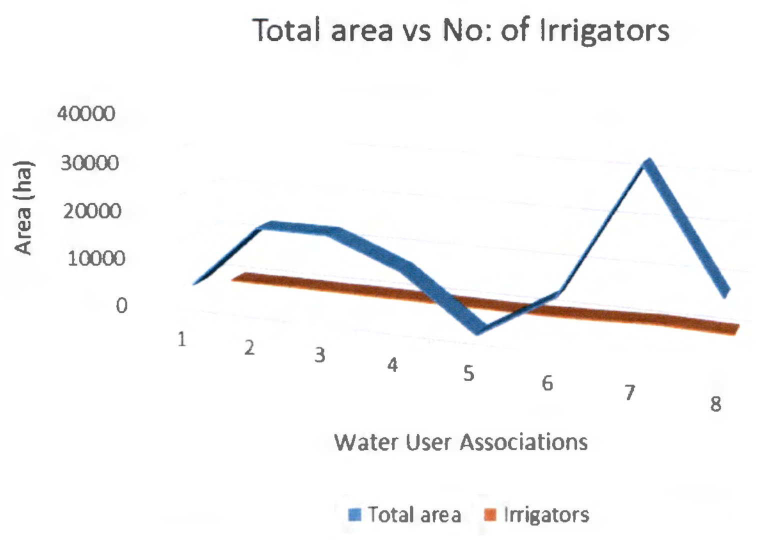

Figure 14: Total area vs Number of Irrigators

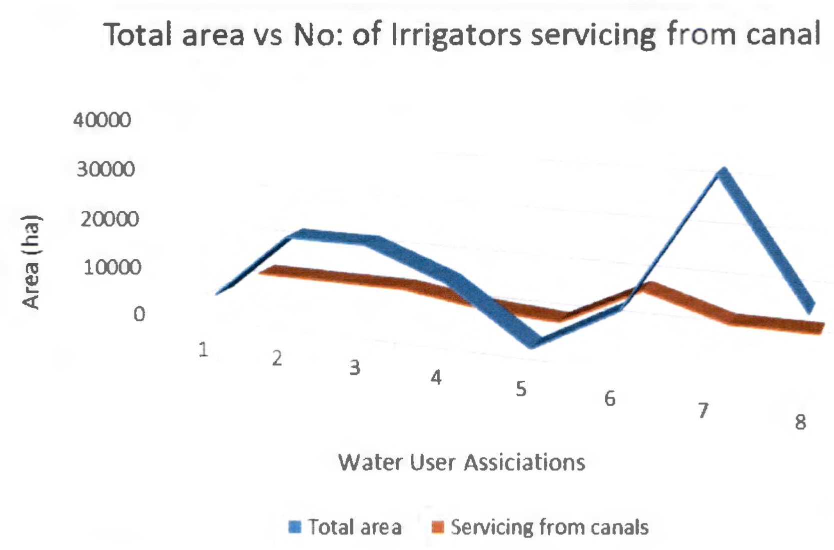

Figure 15: Total area vs Number of Irrigators servicing from canal

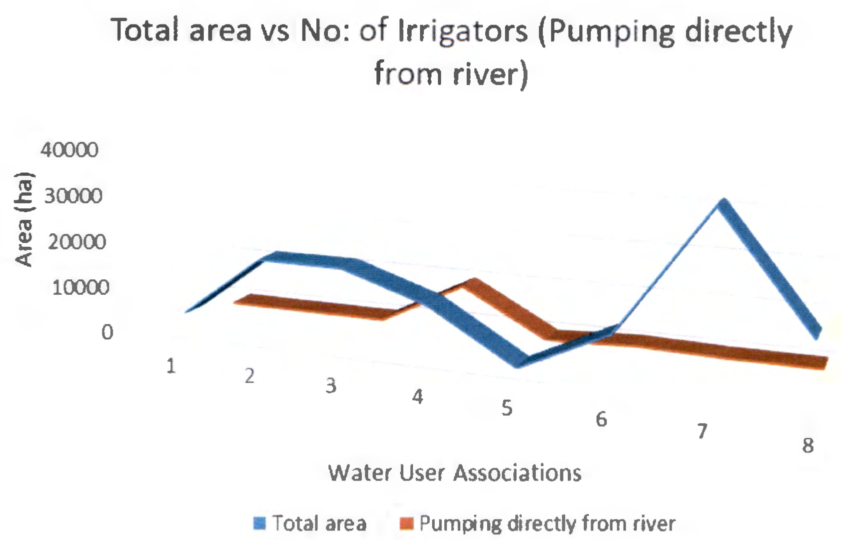

Figure 16: Total area vs Number of Irrigators (Pumping directly from river)

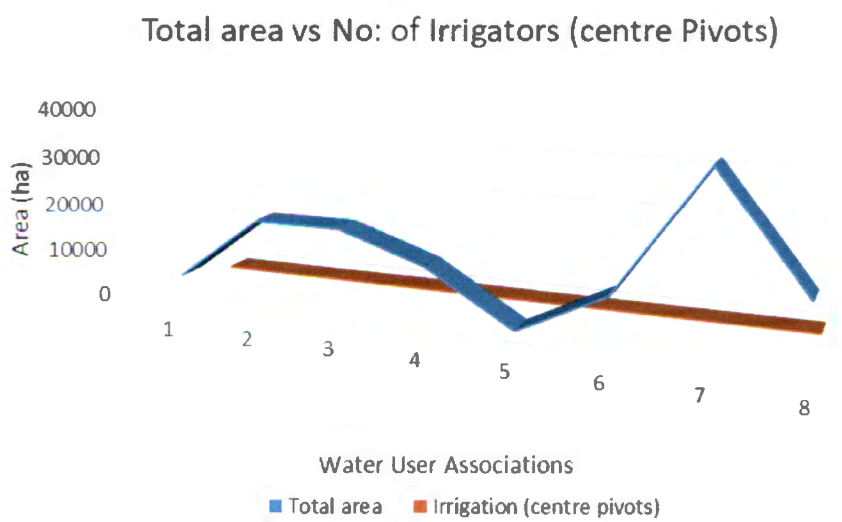

Figure 17: Total area vs Number of Irrigators (Centre pivots)

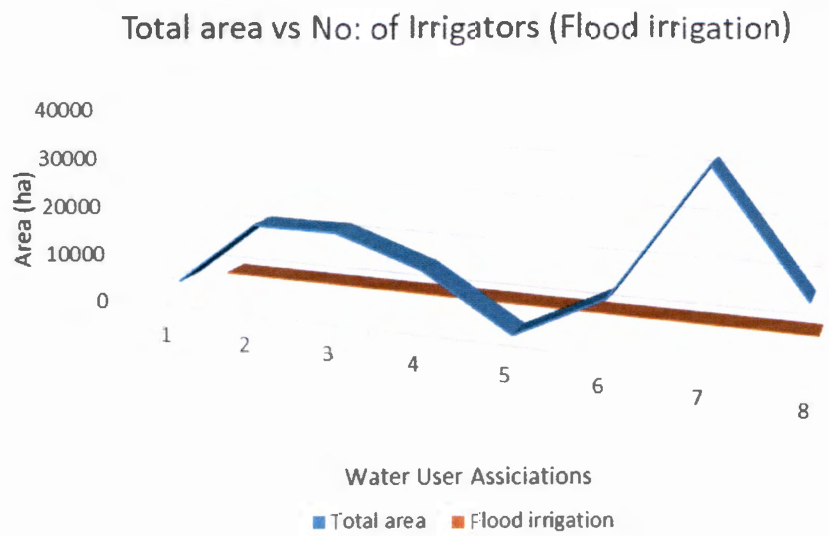

Figure 18: Total area vs Number of Irrigators (Flood irrigation)

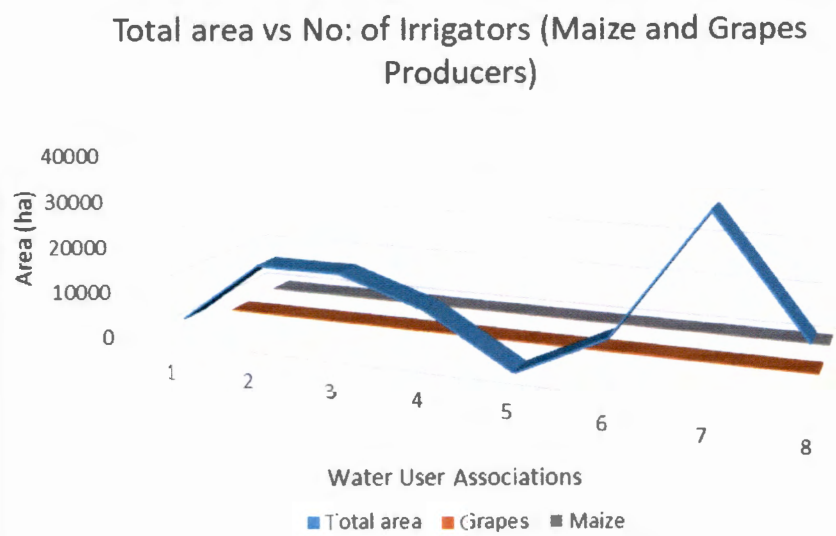

Figure 19: Total area vs Number of Irrigators (Maize and Grapes Producers)

5.5.6 Evaluation of Methodology and Limitations

The pre-conceived assumption was that the irrigated area in arid and semi-arid region could be identified in summer by the significant reflection of infrared or by detecting the wetland when crops have been recently irrigated. Anterior studies have already approved this hypothesis (Möller *et al.* 2017, Geurmazi *et al.* 2016). Ground truth data from the test sites was used to improve the identification of the different classes and incorporate the error matrix. In this study, a set of three satellite images were used: the first was the November 2011 corresponding to pre-drought conditions, the second one for November 2014 which indicates the transition towards the onset of the drought season, and the third for November 2015 was for the drought period itself. The results affirm that the images used can provide a significant consistence with the ground observation for the mapping of irrigated area, although Gao *et al.* (2017) confirm that there is a limitation of Landsat imagery with regard to the differentiation of the vegetation species when they are spectrally similar as noted with grapes and vegetables in this study.

Accordingly, the concept of Water Demand Management (WDM) has significantly evolved. Its current definition encompasses five main goals: (1) reducing the quantity and quality of water required to accomplish a specific task; (2) adjusting the nature of the task so that it can be accomplished with less or lower quality water; (3) reducing losses in movement from the source through use to disposal; (4) shifting the time of use to off-peak periods; and (5) increasing the system's ability to operate during droughts (Ponte *et al.* 2016). In this context, the effectiveness of a WDM system depends heavily on demand forecasting. This is not only about minimising the water used to meet demand as accurate forecasts are associated other benefits such as the reduction of energy consumption in water catchment, purification and distribution processes. This reality highlights the importance of water demand forecasting, which can be divided into:

Very long-term forecasting (decades), which crucially determines the design of the water supply system, e.g. tank capacities and pipe dimensions.

Long-term forecasting (years), which allows managers to develop plans on how to manage water demand and make adjustments in the distribution system.

Mid-term forecasting (months), used to adjust previous planning, through comparing actual and planned data, as well as to determine the price of water.

Short-term forecasting (days), which involves the implementation of supply plans and the setting up of the necessary systems.

Very short-term forecasting (hours), which results in water conveyance, from tanks to points of consumption when required, in the right quantity and pressure.

The completed validation data shows that the "qualifying final" irrigation areas and irrigation water use on the regulated Irrigation Schemes in the Upper Orange River catchment are essentially unchanged, as noted in the August 2013 report figures. The "qualifying_final" for diffuse irrigation areas have increased marginally by about 9% on average, with the largest increases occurring in the Kraai River catchment (25%) and upstream of Krugersdrift Dam (17%). The large variances in diffuse irrigation between the "Qualifying_final" irrigation areas and the "Current" areas are however most noteworthy (DWA 2013a).

The whole of the Upper Orange has witnessed an increase of 18 791ha or 43% (43 431ha to 62 222ha) in the area of diffuse irrigation. The main contributing reaches are Reach 1 and 2 (Caledon u/s and d/s of Welbedacht dam) – 8 175ha; Reach 3 (Orange main stream u/s Aliwal North d/s Oranjedraai – 1 322 ha; Reach 5 (Kraai River) – 3 437ha; and Reach 10 (Krugersdrift dam to Tweerivier gauge - Modder River) – 1 444 ha. As indicated in section 5.7.5, it is possible that this increase may represent opportunistic irrigation in wet years, but in any event the increases are significant and could have a major impact on water availability in the catchment as a whole in the future (DWA 2013a). It is highly apparent that municipal authorities in different areas use the same method to allocate water in the study area and that water allocations by different users have unacceptable levels of inconsistencies.

5.6 Summary

The results in this study revealed that there are different methodological approaches which produce different results because irrigators often use different datasets for a particular reference year. This creates a remarkable difference in determining future amounts of irrigation water use.

The SEEA-W can be considered a useful methodology for the standardisation of concepts and methods in water accounting that provide a conceptual framework for organising economic and environmental information in alignment with Water Framework Directive objectives. Nevertheless, the level of detail expected of the data requirements is very demanding. In addition, the accuracy of the analysis differs from territory to territory depending on the data availability.

Transboundary basins, such as the Upper Orange River basin, need coordination between countries, in the case of this study between South Africa and Lesotho, to integrate information on water balance, otherwise the differences on data availability may result in different water balances for each part. The water balances were computed from the inter-annual averages of this period. Additional water balances were estimated with different levels of disaggregation: temporal, spatial, and by water uses. The two temporal resolutions, monthly and yearly, which were used were adequate for the water balance. Monthly disaggregation enabled the identification of significant intra-annual variability in the Upper Orange River basin. However, it was observed that yearly-aggregated balances would better support the decisions of water authorities and other stakeholders the the planning and management of water resources.

Misleading aspects have been found with regard to the spatial scale when elaborating SEEA-W physical accounts. While the analysis conducted for the complete territory was found to be adequate, the division into smaller units highlighted relevant drawbacks. Each division introduced "artificial divides" among spatial units which were not well defined in the physical tables. Flow exchanges between the different units must be considered in order to balance the asset accounts properly. New terms are proposed for inclusion in SEEA-W tables to avoid confusion with similar concepts of water exchange. Finally, the disaggregation of a basin into smaller units is not recommended for all the cases unless the basin has a high spatial variability (e.g. very large basins or territories with very high orographic differences). Most elements or hydrological processes of the SEEA-W tables are very difficult to fill out on the basis of measured data, especially for large basin case studies such as evapotranspiration, soil water, and exchanges between water bodies. As a result, the use of hydrological and hydraulic models is highly recommended.

The next chapter proposes the development of a modified model from a couple of existing models.

CHAPTER 6

PROPOSED WATER DEMAND MANAGEMENT MODEL FOR THE UPPER ORANGE RIVER BASIN

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6. Theoretical Background

Proper water resources management and planning that ensure sustainable use of watershed resources is not feasible without accurate and reliable models. A modified model is proposed in this chapter. This proposed modified model draws on strengths from several existing models in the hope of producing a better one. The highly stochastic nature of hydrological processes and the development of models with capabilities to provide descriptions of complex phenomena is a growing area of research. Nonetheless, the provision of knowledge into the modelling of complex phenomena that draws on an overview of literature and expands research horizons has the potential to enhance the potential of accurate modelling.

Models provide smoother responses than real-world systems. In general modelling is aimed at ensuring minimum uncertainty through the most achievable parameterisation. Numerous attempts are ascribed to the determination of the categories whose strengths and weaknesses are often under discussion. A general observation is that a particular strength or weakness of a model is relatively subjective, for the strength of a model to one modeller could be that very model's weakness to another. It is, therefore, necessary to discuss the application of the WRYM and WRPM, especially in relation to the management of the upper Orange-Senqu River Basin's water resources. The reasons under consideration have been pre-selected on the basis of the perceived water resources planning requirements of South Africa.

6.1 Assessment of DWAF's modelling methodologies

The assessment of modelling methodologies that are in current use is reported in the context of key characteristics. These characteristics are:

- Assessment of the river flow gauging calibration for accuracy, with the assessment of the reliability of the records and gauge re-calibrations being carried out if necessary.

- Selection of river-flow gauges for model calibration purposes and the configuration and calibration of the Pitman monthly basin model at each gauge.

- Acquisition of rainfall data for all stations in the area of interest, classification and infilling of these records on the basis of suitable groups and the generation of long term basin rainfall records for basins upstream of calibration points and other points of interest.

- Use of model parameters that are calibrated in the generation of runoff sequences at all points of interest.

- Production of monthly naturalised and denaturalised flow sequences whilst accounting for the developmental influences in the basins. Using statistically derived curves to determine the effects of alien vegetation.

- Generation of stochastic hydrology for the system model and testing the generated sequences for integrity. The use of WRYM and its routines is ideally suited for this task.

- The WRYM or WRPM can be used to model operational hydrology. The estimation of yield quantities can be obtainable using both stochastic and historically generated flows.

- Disaggregation of the monthly flow data, if needed, in the production of the daily flow sequences to meet the instream flow requirements (IFR) studies (older methodologies did not have this component within them as the IFRs did not exist in the previous NWA).

- Determination of spillway flood flow sizing at proposed dam sites and at IFR sites. It is used for reliable streamflow gauging in areas with a depth duration frequency analysis.

- Modelling of water quality is done with the WRYM or with other models, which use outputs from other models such as the WRPM.

Several advantages can be achieved through the multi-level and multidisciplinary modelling approach, although this has attracted significant criticism in contemporary literature (Kotir *et al.* 2017). A major concern is that linkages have to be pre-determined in the development of models from an integrated modelling approach. This suggests that an integrated model can only be considered as good as its sub models. However, an integrated modelling approach is equally problematic as the models used and in the linkages between the different sub models and their integration into the main overall model. This points to the view that, within disciplines, a particular phenomenon may require some sort of degree of confidence such that linking models may remain highly conjectural. The modelling approach in many ways does not consider the linkages and often compromises the validity of results.

Added to this concern of disregarding the linkages and the often compromising of the validity of results is the detailed requirement in the implementation of the NWA (1998). The Pitman–WRYM combinations which offer the monthly modelling approach have limitations in offering the required solutions. While a finer scale modelling is associated with the complexity for many of the tasks needed, the upward aggregation of variables from daily to monthly, is a more accurate technique than that of disaggregating monthly to daily flows. This is because many inaccuracies can be introduced in the disaggregating monthly to daily flow technique.

Globally, there has been a dramatic shift towards the use of finer resolution models for exercises such as scoping or broad level assessments that have less information as a requirement. The inhibition of model precision and reduction of the accuracy of upward aggregation is usually a constrained data limitation. It is of concern that modelling accuracy still has limitations, despite recent advances in RS technology, GIS and database development that increase the accuracy and validity of data for many finer resolution process and physical based models. Data required for calibration models, particularly for the measurement of streamflow, tend to inhibit the use of coarse resolution calibration models. In addition, the data needs for physical process based models such as land-use and soils information become increasingly more accurate and accessible, and thus make the use of physical process based methodologies tend to be more attractive.

Calibration and statistical methods, including those in the preceding description, have now become less attractive since they are black box approaches and unable to make the assumptions explicit. The result is such that modelling efforts generally tend to have less credibility when in the use of the stakeholder community and during the associated comprehension of the results. Although physical based process models have more complicated algorithms and are generally more time consuming to set up, the inputs and outputs are generally easier to understand. These physical based models represent real world quantities, while calibration models and statistical methods are, in general, situation specific and their results are non-transferable to other areas. The implication is that the testing of different scenarios and extension of derived estimates at ungauged sites can result in large inaccuracies as a result of the use of these calibration and statistical methods.

6.2 Key findings identified in the study

A number of key findings that were identified in the study that are incorporated in model design. It was found out in the findings such as the ones below that:

- The main users of water in the basin are the water service providers, district and local municipalities. The findings also showed a considerable mismatch between allocated quotas and actual water withdrawals in the study area. It was also noted that consistent government monitoring was lacking. The setting up of relevant state institutions might be understood as an outcome of the government efforts to address emerging challenges with respect to increasing water demand and multi-use. However, some negative outcomes accompany this institutional set-up as they weaken social norms and threaten sound water management. The experiences from the irrigation schemes, therefore, highlight the need to include locally evolved institutions and the re-crafting formal institutions.

- It is important to measure water usage at the distributor and farm level. This fundamental step ensures the successful implementation of a whole range of practices which can lead to improved water conservation and water demand. Directly linked to this issue is the measurement the way in which water is paid for, with the researcher proffering the view that a volumetrical payment leads to the establishment of a whole range of incentives that will encourage farmers to use their allocations of water more efficiently. Although the identification and description of best management practices can be done individually, there is need for concerted and holistic approaches to scheme and farm management. These could bring about the full realisation of benefits of each best management practice. It is also necessary to establish an irrigation database that can bring about significant changes in the irrigation practices that are taking place and these can include additional areas that would be under irrigation.

- The inability to perform proper water accounting results from (i) water allocation methods – which may be inefficient, chaotic, unsystematic, (ii) lack of the DWA support, (iii) a disjuncture between Governance and the statutory requirements of Irrigation Boards (IBs) and WUAs, (iv) poor condition of bulk infrastructure, (v) inadequate/inappropriate water measuring devices and (v) lack of incentives to save water.

It is imperative that the quantification of the water consumption of large areas such as the Upper River basin and particularly within the irrigated agricultural areas is important for water resources planning, and the mitigation of impacts of reduced streamflow, establishment of hydrologic water balances, water rights management and water regulation. The aspects addressed in section 6.2 are lacking in the two models which are WRYM and WRPM that are predominantly used in South Africa. In an attempt to address these shortcomings it was necessary to modify these existing models and to incorporate aspects from other models which may improve their application and efficiency.

The preference for a modified model is made on the basis that the current models are to some extent addressing the modelling requirements for the region but not to the required level adequacy. It is against this back-drop in modelling capabilities that a modified model is proposed. For instance ecological reserve, alien vegetation and hydropower power generation are not accounted for in both models. In addition, the majority of farmers irrigate on the basis of an allocation of irrigation water per ha and technical irrigation scheduling is an exception rather than the rule. These aspects are of critical relevance to water conservation and water demand management in the irrigation sector, hence the modification of the model.

6.3 Assessment of models used by the DWAF

The two main network simulation models that are used in South Africa for water resource analysis are the WRYM and the WRPM. Table 11 summarises some of the parameters discussed herein.

6.3.1 Water Resources Yield Model

The design of the WRYM (Figure 14) facilitates an assessment of the long-term yield capabilities of a system for a given operating policy. The WRYM is a general simulation model that has multi-purpose and multi-reservoir capabilities, and these are useful in analysing a system at a constant development level where the systems demands are assumed constant throughout the simulation period. The WRYM has been set up as a current state model to incorporate several processes such as:

- Naturalised streamflow
- Irrigation (i.e. diffuse and or flood) and afforestation demands from the various basins
- Reservoir storage and releases
- Precipitation on reservoirs and evaporation from reservoirs
- Outlets from reservoirs via physical discharge controls
- Monthly-based specified inflows from adjacent subsystems
- Water flow in channels such as streams, irrigation diversions, normal diversions, minimum flows, pumping, power generation and hydropower releases
- Channel losses
- Aquifers.

Table 11: The Comparison of the WRYM and WRPM models

Model	**WRYM**	**WRPM**
Calibration or physically based	Calibration	Calibration
Applicable to SA conditions	Yes	Yes
Finest temporal scale	Monthly	Monthly
Individual water availability	No	No
Model under development	No	No
Operational hydrology	Yes	Yes
Spatial scale	System	System
System yield	Yes	Yes
Transparency and credibility	Low	Low
User friendly	No	No
Water quality modelling	Limited	Limited
Water quantity modelling	Yes	Yes

The WRYM model has the capability to simulate a wide range of operating policies that govern the allocation of water in a multi-purpose and multi-reservoir system. The WRYM model enables the user to define operating policies that govern the allocation of water by altering the penalty structure associated with channels and reservoirs in the data sets used to run the model. The WRYM assumes that a flow network is representative of a water resource system. The network analysis for each time period can be carried out and solved by way of an efficient network solver (through techniques in linear programming) with the careful selection of penalty structures. The network solver can compute a particular network problem using a minimum cost approach, where appropriate costs (penalty structures) are considered under allocation to channels and reservoirs in a manner that accounts for the relative "value" of water in each storage zone. The penalty structure is also based on the selection that dictates the most attractive route (i.e. minimum penalty) for transference of water from the storage areas to the areas of demand.

6.3.2 Water Resources Planning Model

The WRPM has a more complicated structure than the WRYM (Figure 20 - 23). The design allows for more detailed operation runs to be carried out. The model is capable of accomplishing limited dynamic demands that increase over time as well as change system configurations. It can only be used as a planning tool in the assessment of the likely implementation dates of new schemes or resources and also as an operating tool that assists in the month-to-month operation of a system. It is based on the same optimisation techniques such as the WRYM and uses penalty structures to route water through the system.

Both models utilise monthly input except that weekly data can be used in the WRPM. The penalty structure modelling technique in which the user attributes certain penalties is used in both models (i.e. streamflow quantities or dam levels with a derived, usually arbitrary, relative cost associated with them) to different water users and dams in the system. The water is then routed through the system in accordance with the least penalty concept. The models are highly dependent on user defined penalty structures which need to be defined relative to each other to describe the system operation properly, thus they are highly dependent on the users' interpretation of the system. This means that the structure defined in the system can vary depending on the user and means that two different modellers can obtain different results. This system leads to lack of transparency, consistency and credibility with the stakeholders.

The monthly estimates may be too coarse for those required by the CMA to develop the CMS and assess individual license applications. A large amount of pre-processing needs to be performed as the model requires monthly denaturalised or naturalised flow to generate the stochastic flow sequences. The model results also require a large amount of post processing and are not in an easily translatable format since they are usually in the form of yield reliability curves. This again leads to considerable lack of transparency. Some concern has been raised about methods for testing the total system yield for failure (DWA 2012e). It is possible in the current structure of testing the model to have a failure with regard to individual demand while the system or sub system is operational. This is due to the fact that the WRYM model works from a single main yield channel.

Hence, it is possible that, under particular circumstances, the subsystem yield is satisfied while an individual demand linked to the main channel can fail. This can lead to problems in the equity criteria and requires large amounts of post processing analysis as individual water availability is not tested automatically. These models are the DOS based systems that also include difficult configuration and set up (Table 12). An attempted improvement of setup is accomplished via a more user friendly interface known as the SAWRAM for the WRYM. Here, some subjective assumptions are made in setting up the model with regards to the penalty structures. The high amount of pre and post processing also makes the model tedious to run and produces results that are difficult for stakeholders to accept.

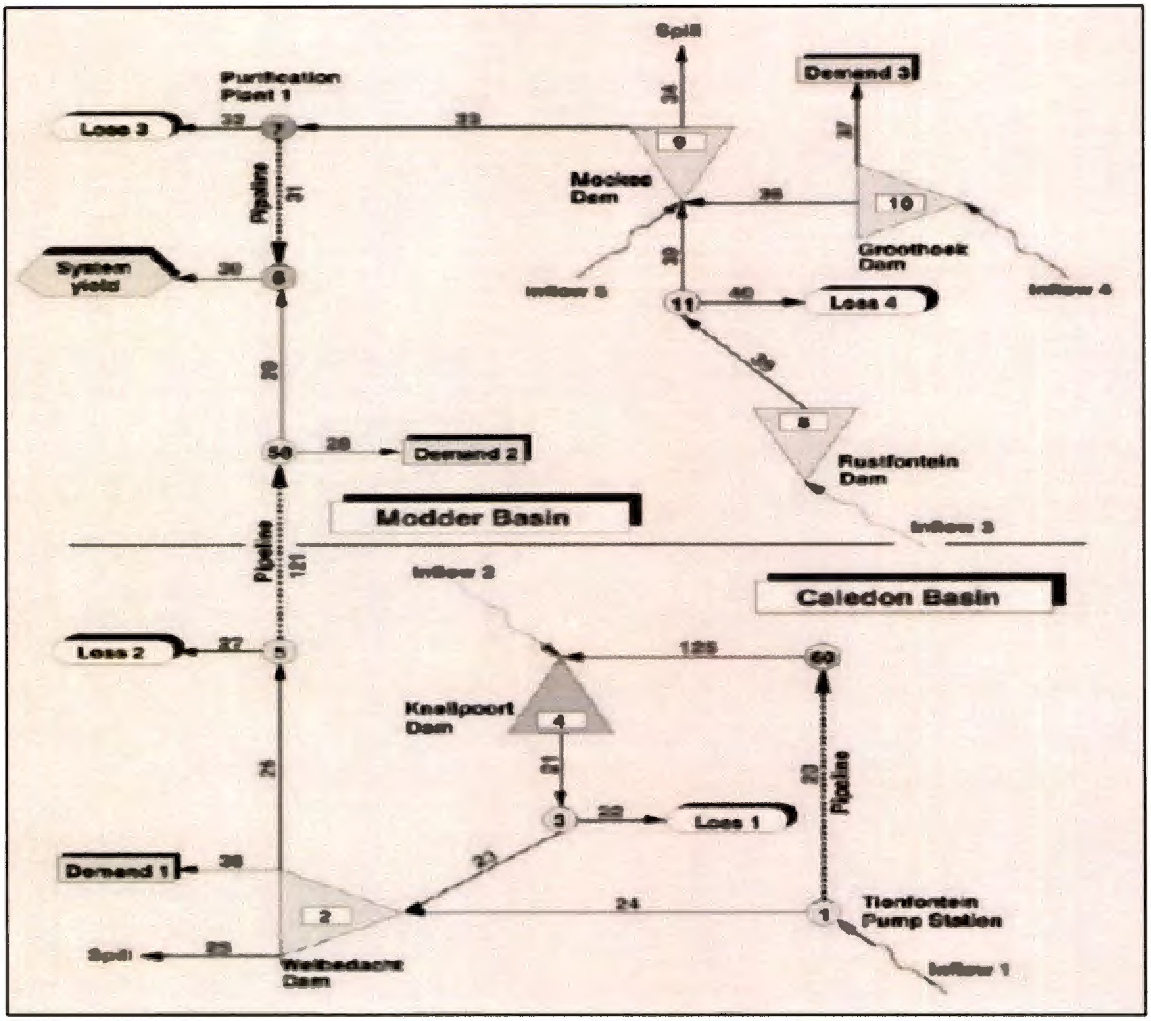

Figure 20: Typical WRYM Configuration, Caledon- Modder Sub-System

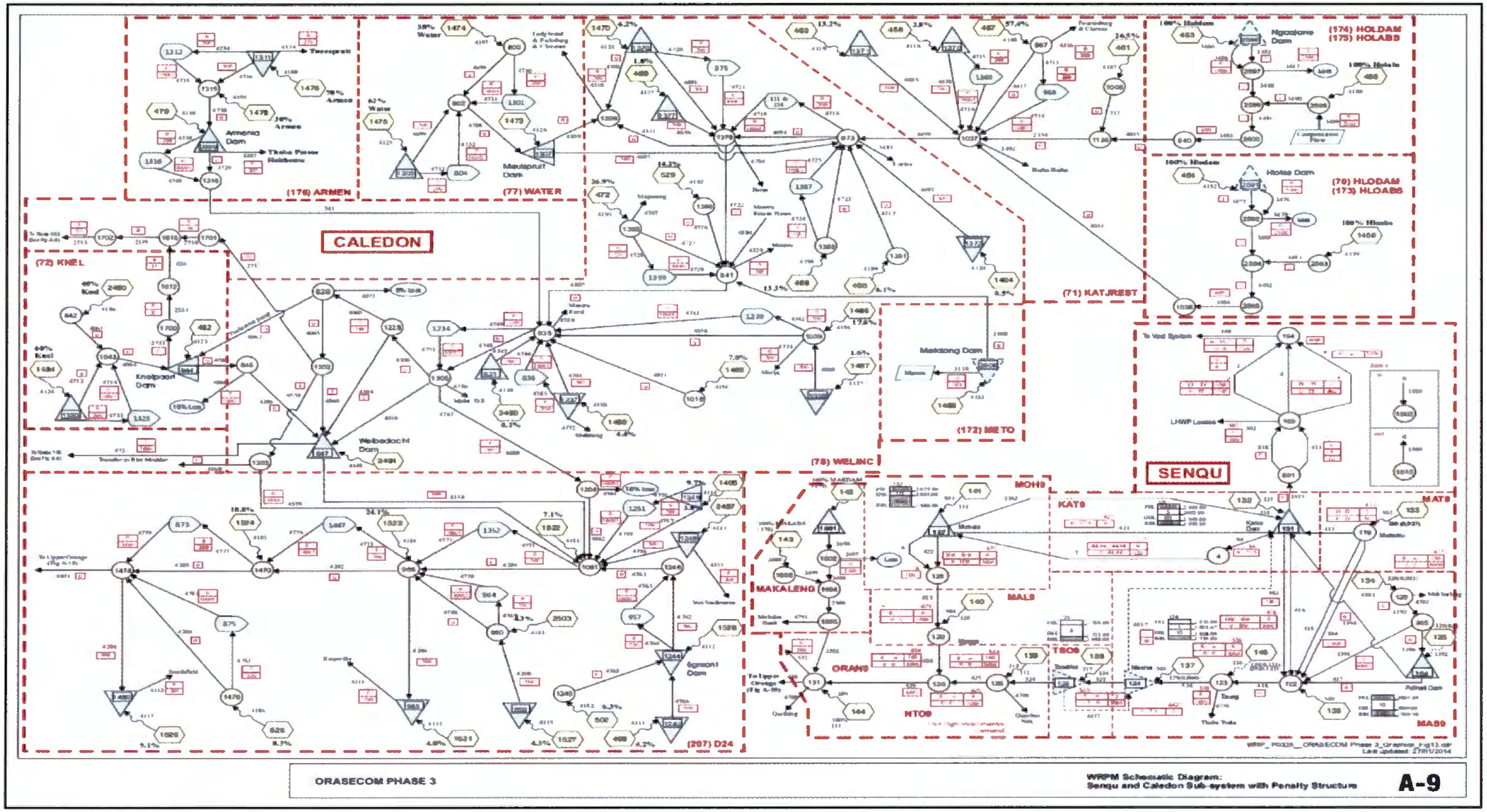

Figure 21: The WRPM Schematic Diagram – Senqu and Caledon Sub-system with Penalty Structure

(Seago and Maré 2014: 64)

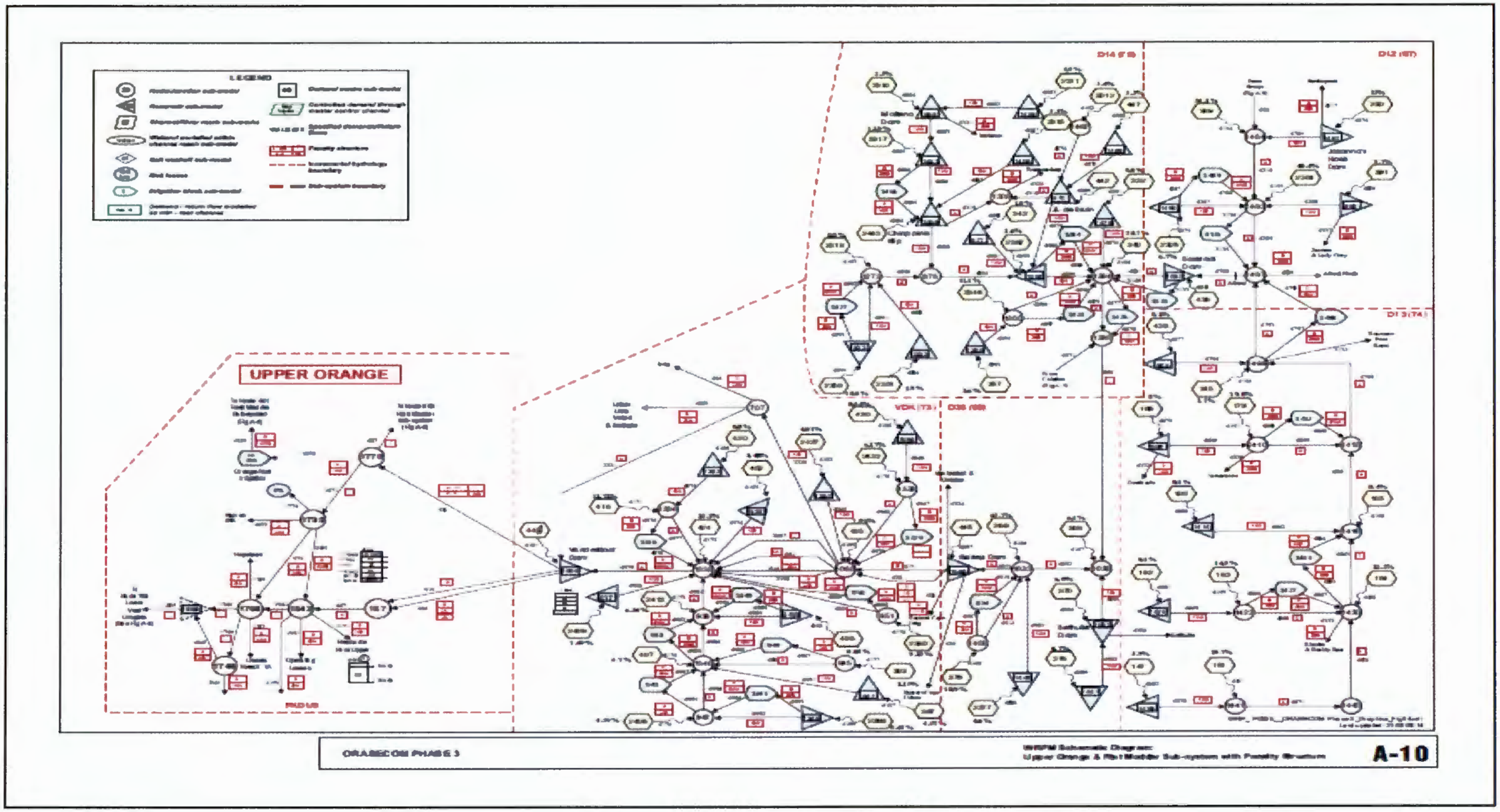

Figure 22: The WRPM Schematic Diagram – Upper Orange and Riet-Modder Sub-system with Penalty Structure

(Seago and Maré 2014: 65)

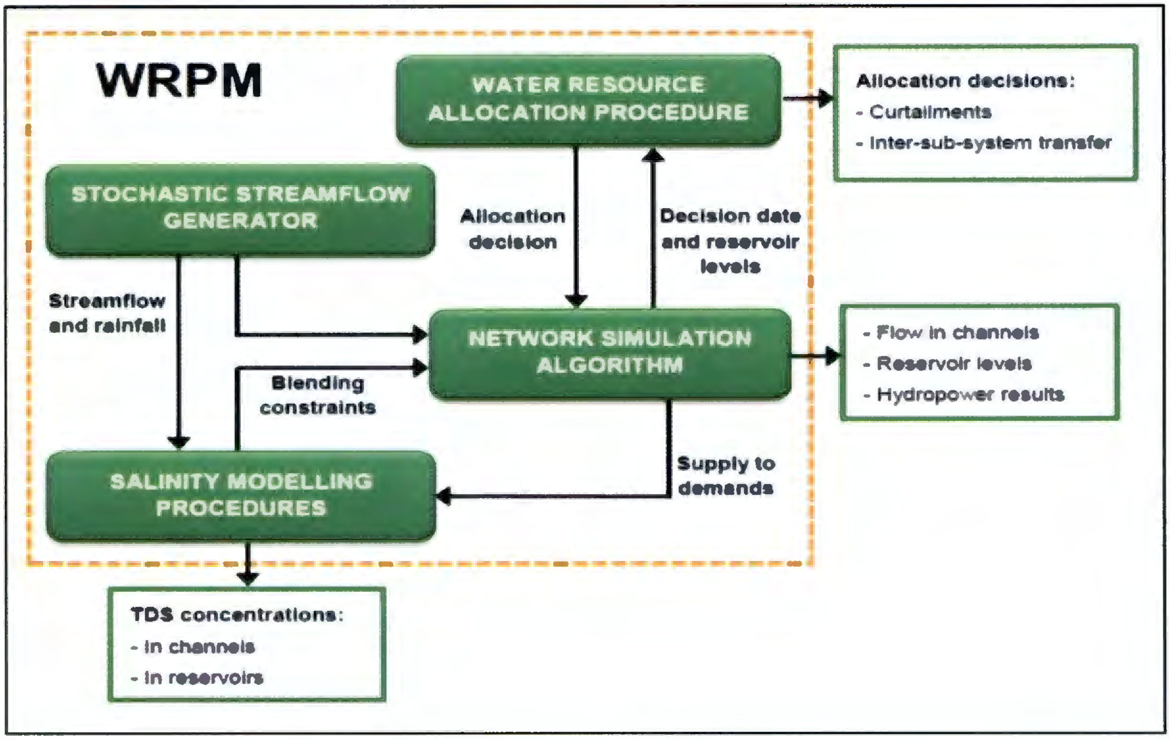

Figure 23: Linkages between components of the WRPM

(Blersch 2014: 68)

6.4 Limitations of the WRYM and WRPM

These models have several limitations. Firstly, modelling is only possible at a monthly time step. Secondly, hydrological (rainfall-runoff) modelling is not built in, so extensive pre-processing is required to generate inflow files and demands. Thirdly, it does not have river routing capabilities and hydraulic analysis. Figures 24 – 27 details all the hydrological zones present in the entire Upper Orange River basin.

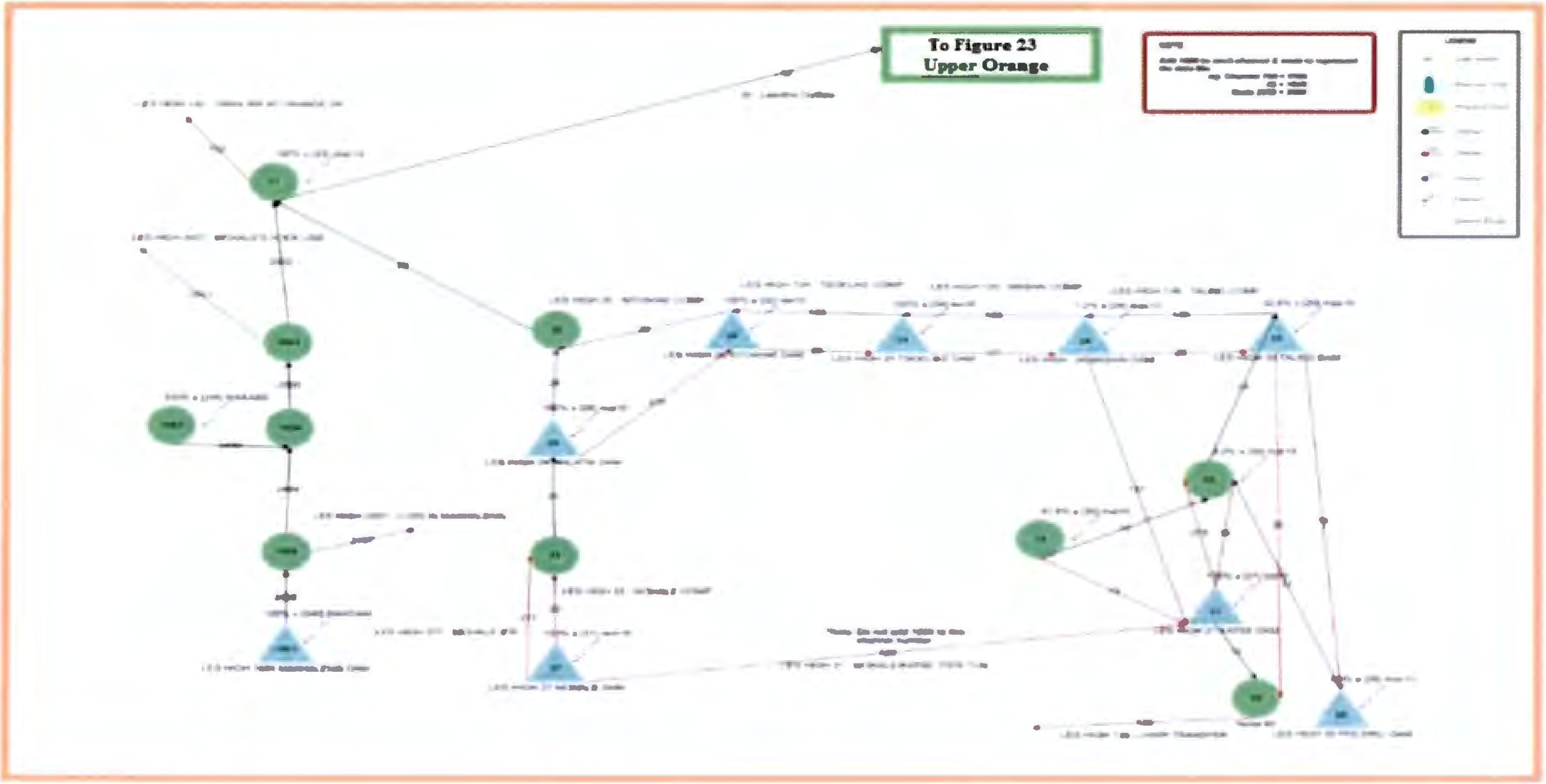

Figure 24 Senqu Hydrological Zone

(ORASECOM 2011: 87)

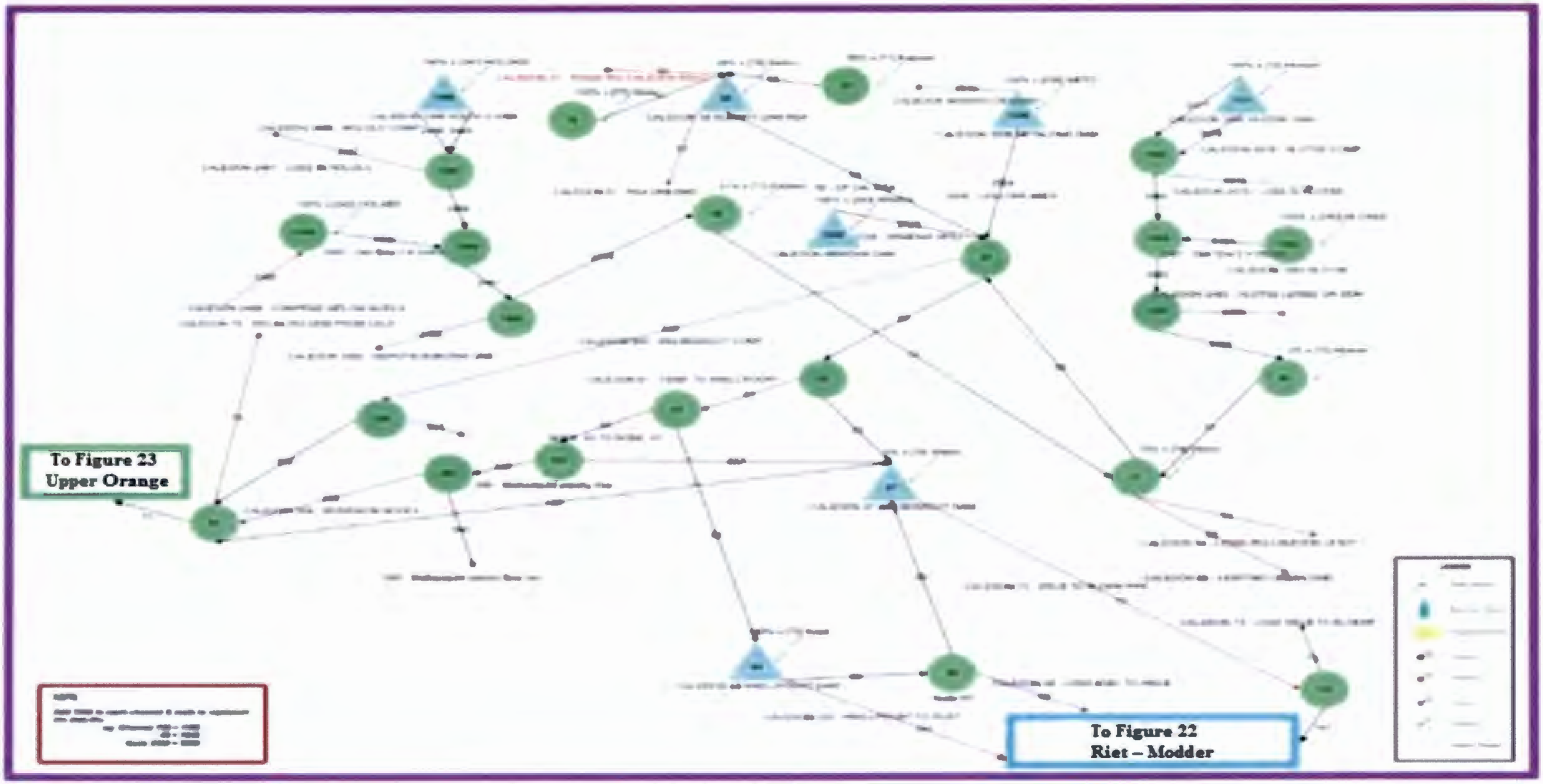

Figure 25 Caledon Hydrological Zone

(ORASECOM 2011: 88)

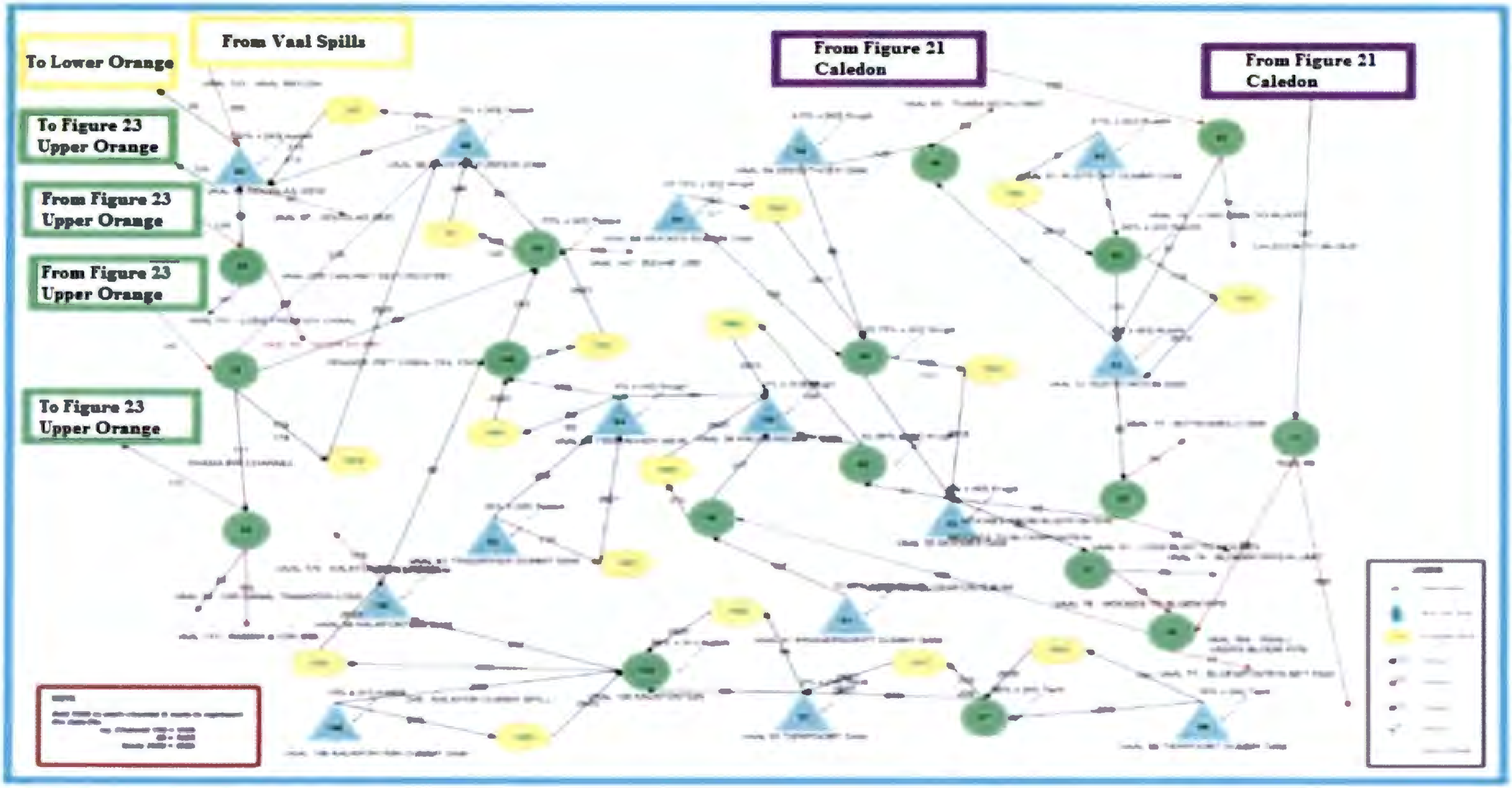

Figure 26 Riet – Modder Hydrological Zone

(ORASECOM 2011: 89)

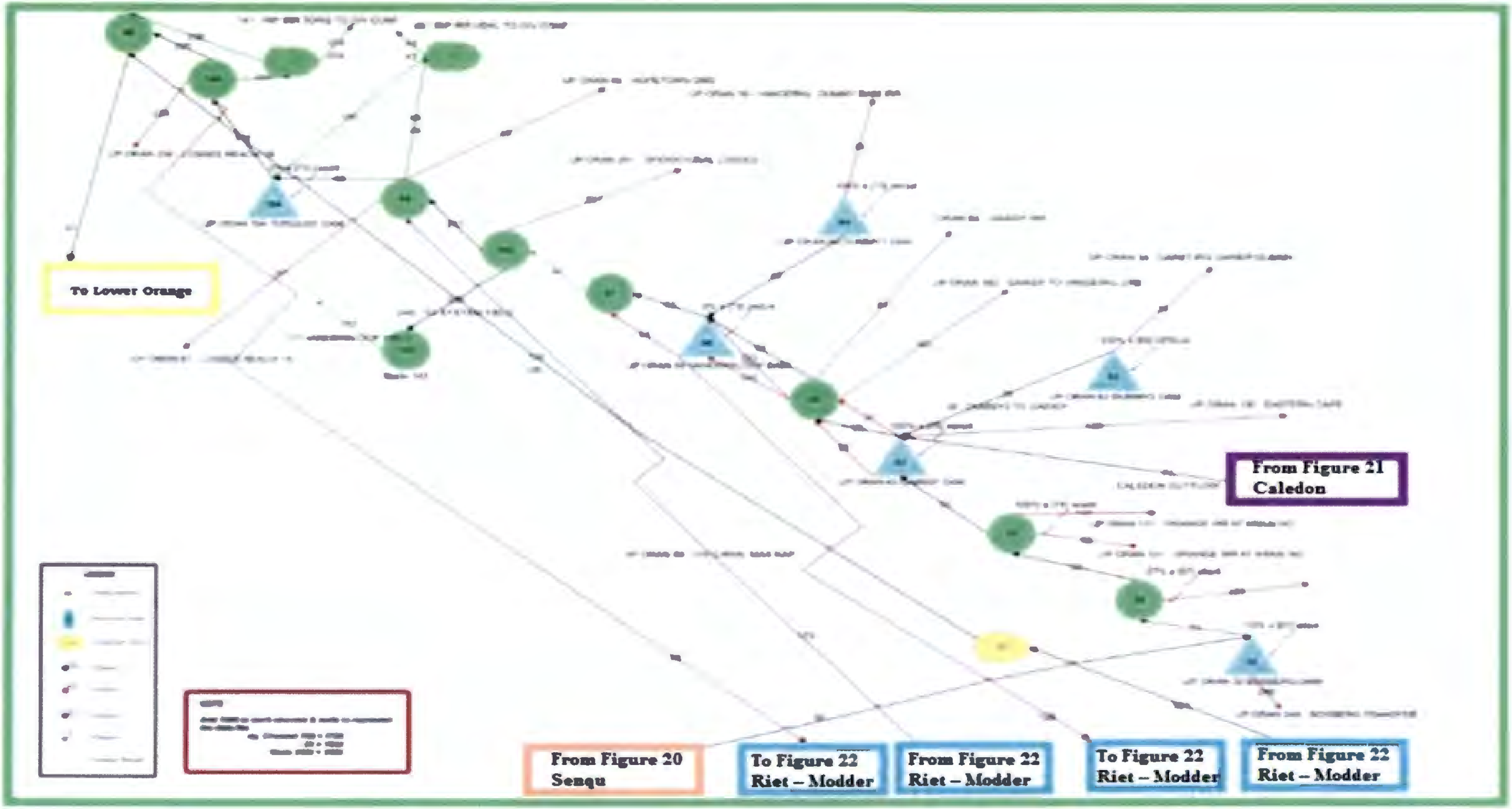

Figure 27 Upper Orange Hydrological Zone

(ORASECOM 2011: 90)

Table 12: Summary of types of channels used in the WRYM

Channel type	No of arcs	Use	Data File
General	1	River reaches or flow routes with no capacity constraint	F03.DAT only
In-stream flow requirements	2	Environmental water requirements based on rule curves	F14.DAT
Flow constraint	1 or 2	Physical flow constraints in channel /control structures	F04.DAT
Diversion	2	River diversion structure/ abstraction works	F10.DAT
Hydropower	2	Power generating capacity of a hydropower plant	F07.DAT F08.DAT
Loss	2	Flow-related losses such as seepage and evaporation	F11.DAT
Master control (yield)	2	Imposing target drafts to determine system yield	F13.DAT
Minimum flow	2	Channels which must maintain a minimum flow such as releases from reservoirs	F11.DAT
Multi-purpose min-max	1	Channel with restricted capacity	F12.DAT
Pumping	2	Hydraulics of pump stations and pipelines	F03.DAT only
Specified demand	2	Specified abstractions, such as irrigation, which vary on a monthly and annual basis	F03.DAT only
Specified inflow	2	Monthly time series of inflows – typically from a separate system	F03.DAT only
Water requirements and return flows		2 or more	

6.4.1 General Characteristics of Each Model

Both the WRYM and WRPM are monthly time step models with features that are ideal for handling the characteristics of the Orange-Senqu River and its tributaries (i.e. lengthy droughts (>15 years), scarce and/or often unavailable data, etc.), have a fully modularised network which can be sequentially solved, and have been in use in southern Africa for more than three decades. The WRYM model has a structured database, including a number of data input files. It also has pre-processor functionality. There is an ability to store metadata as well as reports. These functions are, to a lesser extent, available in the WRPM through the data input files, which are edited using a text editor. Plans are in progress to incorporate a user interface for the WRPM that is similar to that of the WRYM, which will render assistance with information and data management.

The WRYM has the ability to present tables and graphs of most input and output data. This is, however, not output via GIS, and cannot present animations. A weakness of the WRPM output is the large result file sizes, which are difficult to work with and take up a significant amount of computer space. In addition, all graphical outputs for the WRPM require preparation using post processors with graphs needing preparation using an outdated dos utility. These post processors do not operate correctly on all computers, especially the newer computers, and the graphs prepared appear outdated. The ability to prepare output results within the WRPM is, however being addressed and will, in the future, be possible in a way similar to the current WRYM approach.

One of the largest weaknesses of both models is the lack of user friendliness, though again this may be seen as a somewhat subjective category. There are very few warning messages should data not be correctly input, and if this is the case and the model does not run as the error messages are often very cryptic. This is currently being addressed, along with the new user interface of the WRYM. There are at present no wizards or expert systems to assist users with configuring the model. The WRPM, in its current state, is fairly “unfriendly”. Data input files have a very rigid structure and format, and any misalignment of data could cause incorrect results. As already indicated earlier in this section, the models do not use any GIS type interfaces which could assist in setting up networks and in making the models more understandable to decision-makers.

The WRYM has a basic network visualiser and the ability to interrogate input and output data via this visualiser. This functionality has not yet been included in the WRPM. However, there are plans to do so in the future. There are presently no GIS capabilities in either of both models, and all maps relating to study areas must be prepared outside the models. This functionality could, in the future, greatly assist with presenting results to the public who sometimes battle to relate a network diagram to the physical environment. For example, the ability to click on a satellite image of a reservoir (possibly linked to Google Earth) and view all the details would be of great value to the models.

Support is provided by means of e-mail and telephonic support, as well as an available online change request system. All the latest versions of software, documentation and example datasets are provided by the Online User Support System. Only a few people provided the support, and it can be difficult to reach these support personnel at times.

Another weakness to the models is that maintenance and regular upgrading are costly and require a high level of skill that is not readily available. Inter-operability is an important aspect when evaluating systems, since it effects how flexible the modelling system is in adding new methods without major investment. Both models currently only have data Com Object functionality. They also do not have any costs involved with issues such as initial outlay and licenses. A new security measure has, however, been incorporated into the WRYM and it requires the user to input license codes when the model is installed on a new computer. This process in not user-friendly and can be improved upon.

6.4.2 Hydrological Features

Rainfall is input to the WRYM and WRPM models in the form of a historic monthly rainfall file that covers the record period. This file, which prepared externally to the model, is used to compute the rainfall on a reservoir's surface. Evaporation is input by means of twelve monthly evaporation values. Some model users have, in the past, used incorrect evaporation values, as the models require different forms of evaporation in various data files. For example, the reservoirs require a lake evaporation value, whereas the data files relating to irrigation demands require A-pan or S-pan evaporation and crop/pan factors. In the case of the WRPM, the user is also required to input rainfall data in a few different places such as in mining and irrigation files. An enhancement to the model could be achieved by making this input to take place once in order to avoid mistakes, and having all rainfall or evaporation dependent on where the particular demand or reservoir is located.

The strength of both models is their ability to facilitate the simulation of irrigation requirements and return flows. The requirements are based on crop types and the user can modify irrigation systems and input information regarding losses and efficiency. Return flows can be modelled using a simple approach of percentage of irrigation demand, or using soil moisture conditions. A possible enhancement that could be made to the models is on the ability to include crop yield modelling, with specific reference to planning and costs. The ability to facilitate the simulation of groundwater interaction via soil moisture storage is not available.

The estimation of groundwater use and its effects on surface water availability is carried out explicitly inside both models. The ability to facilitate the simulation of groundwater effects in stochastic mode is still under development. While both models have the ability to facilitate the simulation of groundwater effects, they place more emphasis and focus on surface water resources. Additional ground water functionality can be an added development that leads to the enhancement of both models.

The WRYM does not have the ability to facilitate the simulation of water quality. The WRPM has Total Dissolved Solids (TDS) and Sulphate modelling capabilities, with the unique feature of modelling river basin salt build-up. This important feature enables the analysis of water quality operating rules (dilution and/or blending, as well as controlled releases of polluted water from mines) and water quality management interventions (such as re-use and desalination). The water quality modelling in the WRPM is fully integrated with the risk-based methodology. This provides the unique ability to undertake probabilistic projection analysis, where an assessment of the implication of water quality management options on water availability is made possible.

These three demands, known as streamflow reduction (SFR) activities, are important in water resources modelling in southern Africa. All three are water users, as they reduce the amount of runoff from rainfall that is available for dam storage and other users. The models have been recently enhanced with a new approach to facilitate the simulation of SFR activities. The approach eases the simulation of scenarios on the basis of removal or increment of the

SFRs as the area is now input along with a millimetre reduction file. The user can enhance the modification of the area as required.

A simple method that can be used to simulate urban demands and return flows is available in both models. This method does not, however, include the ability to incorporate increases in demand as a result of population growths and economic activities within the model. Demands are computed externally and input as current and projected volumes. The WRPM permits the user to put in a priority classification for all demands which are used to determine curtailments, should the short term yield capabilities that are cannot sufficiently supply all demands.

Both models can facilitate the simulation of wetlands. The Wetland sub-model algorithm is based on the assumption that a wetland has a nominal storage capacity and surface area, which can be exceeded. The nominal value refers to the wetland storage, below which there is no linkage to the river channel. The flow from wetland to river channel is governed by the storage state of the wetland and is proportional to the storage volume over and above the nominal capacity. The flow from a river channel to wetland occurs when the river flow is above a prescribed threshold. The surplus flow is then apportioned between the river channel and the wetland inflow channel. Both models can facilitate the simulation of mining activities and their quantitative and qualitative (WRPM only) effect on water resources. These include opencast mines, slurry ponds, underground sections and other features.

Ecological requirements are an ever increasing concern in southern Africa, and thus should be considered as a prerogative for water resources studies. Both models can ably facilitate the prioritisation of ecological requirements, which are input as lookup tables. A required environmental flow is obtained, based on the natural simulated flow obtained at a certain point by the model. The weakness of the WRYM and WRPM relates to the large amount of pre-processing that is required to develop the lookup tables based on the outputs of other models used to determine ecological flows. This process could be streamlined to enhance the models.

6.4.3 River and Infrastructure Features

Both models can facilitate the simulation of abstractions and inflows as well as diversion structures. A major strength of both models is that they are able to facilitate the simulation of multiple reservoirs. A past weakness has been the many different data files required to specify all the various aspects of a reservoir. This has been streamlined in the WRYM, where all input data required by one reservoir is located in the same place. This still requires adjustment in the WRPM. Some of the data is duplicated to simulate the quantity and quality side of a reservoir in the WRPM and the model would be enhanced by changing this. A fair amount of pre-processing focuses on the determination of reservoir starting storage levels, based on starting volumes, and this could also be simplified if the user is allowed to input a percentage for each reservoir.

The WRPM has the ability to simulate hydropower, a characteristic deemed a necessity for the Orange River. This is, however, only available for reservoirs and the model is unable to facilitate the simulation of run-of-river hydropower. The other abilities to consider here include: Pumping features- Both models are able to facilitate the simulation of both the energy requirements of pumping stations and pipelines and the associated hydraulic characteristics; and definition of complex operating rules between all channels and other infrastructures, including physical flow constraint and reservoirs. Both models use penalty structure definitions and constraints on reservoirs and channels in order to define complex operating rules. The models have the inherent inability to optimise operating rules automatically; and Infrastructure cost computations (operating, hydropower and other).

As the core function of these models is not of a financial nature, the ability to solve or deal with calculations on infrastructure costs are not catered for and are therefore unavailable.

6.4.4 Risk-based Analysis

The level and explicit stochastic risk-based analysis of both the WRYM and WRPM is a major and is unique strength of the models when compared with other similar types of models. The advantage of stochastic hydrology, as opposed to historical hydrology, is that the reliability of supply, expressed in annual return periods or exceedance probability percentages, can be determined. In addition, the range of generated possible streamflow sequences are likely to encompass even the most severe events resulting from possible climate changes, which is an important factor in water resources planning.

Both models are advantaged to solve rigorous risk analyses, on the basis of a multi-site stochastic streamflow algorithm. This enables the development of operating rules, evaluation of infrastructure maintenance schedules, undertaking planning of new infrastructure, and the design and implementation of drought curtailment rules.

The stochastic streamflow generator used in South Africa is a powerful tool with the ability to preserve the basic statistical properties of individual flow records, as well as cross correlations between flow records. The modelling technique used in the package involves an examination of the annual streamflow totals for each hydrological record, in order to determine their marginal distribution and time series structure. On re-generation, the stochastic annual totals are disaggregated in a manner that preserves the correct temporal distribution.

A unique feature of the analysis methodology is the capability of the WRPM to facilitate the simulation of drought curtailments for water users receiving water from the same resource yet have different risk requirements (profiles). This methodology makes it possible to evaluate and implement adaptive operating rules that accommodate changing water requirements, as well as planned additions to the water resource infrastructure in a single simulation model. By combining these simulation features into one model, the WRPM has the ability to undertake risk-based projection analyses that evaluate all components in a fully integrated system that derives operating rules and assesses future developments in a dynamically changing water resource system.

6.4.5 Other Functionality

The following functions are presently unavailable in the WRYM and WRPM and can be under investigation for the enhancement of the models' capabilities: (i) linkages to real-time systems; (ii) water accounting and water rights; (iii) aquaculture; (iv) recreation and: (v) sedimentation.

6.5 Modelling Formulation

The methodology entails four major components: interval crop - water production functions (Allen *et al.* 1998), interval linear fractional irrigation allocation model (Chadha and Chadha 2007), the solution method (Dai and Li 2013), and the incorporation of the Water Demand Management into a Cooperative Water Allocation Framework (Xiao *et al.* 2016). Each of these components is similarly discussed as in an efficient irrigation water allocation model under uncertainty by Li *et al.* (2016a) and Xiao *et al.* (2016). In this study, three types of water resources, which are river water, surface drainage water and groundwater, are the major water supplies that meet the regional water demands of the various agricultural, industrial, tourism-related, residential, and municipal sector users. Depending upon the use pattern, surface water is deliverable directly to consumers or after passing through a water treatment plant. River water can be provided to agricultural irrigation and industry production. Pumped groundwater has to be disinfected prior to delivery to all users. Piped water is transferred between end-users though capacities are limited (Dong *et al.* 2014).

The major crops in this study region are maize, table-grapes, potatoes, and lucerne, with food-processing and small mining activities and industries make up the local industry. An overview of the components and factors that need to be taken into account is given in Dong *et al.* (2013) and these are also under consideration for the proposed modified model on the Upper Orange River Basin study. These elements are considered with the objective to maximise the total system benefit and in a case similar to the water and agricultural use planning model (WFUPM) (Dong *et al.* 2014: 988). This covers several benefits including irrigated agricultural, industrial, residential, tourism-related water supply benefits, minus the costs for water delivering and pumping, and treatment of wastewater. It may be worthwhile to make a comparison of this model with the frame-work of the of the solution method of the Interval Linear Fractional Irrigation Allocation Model (ILFIWA) shown in Figure 28 (Li *et al.* 2016a).

It is specific and follows:

$$Maxf^{\pm} = f_{BC}^{\pm} + f_{BI}^{\pm} + f_{BT}^{\pm} + f_{BT}^{\pm} - f_{CW}^{\pm} - f_{CE}^{\pm} \tag{63}$$

Benefit for irrigation agriculture

$$f_{BC}^{\pm} = \sum_{l=1}^{3}\sum_{t=1}^{3}(PC_{it}^{\pm} \cdot Y_{it}^{\pm} - CC_{it}^{\pm})A_{it}^{\pm} \tag{64}$$

Water supply benefit for industrial activities

$$f_{BI}^{\pm} = \sum_{k=1}^{2}\sum_{t=1}^{3} \mathrm{QI}_{kt}^{\pm} \cdot \mathrm{Z}_{it}^{\pm} \tag{65}$$

Water supply benefit for tourism-related purposes

$$f_{BT}^{\pm} = \sum_{t=1}^{3} \mathrm{QT}_{t}^{\pm} \cdot Z_{t}^{\pm} \tag{66}$$

Water supply benefit for residential purposes

$$f_{BT}^{\pm} = \sum_{t=1}^{3} \mathrm{QR}_t^{\pm} \cdot \mathrm{ZR}_t^{\pm} \tag{67}$$

Cost for water delivering and pumping

$$f_{CW}^{\pm} = \sum_{t=1}^{3} (\mathrm{QS}_t^{\pm} \cdot \mathrm{WS}_t^{\pm} + \mathrm{QG}_t^{\pm} \cdot \mathrm{WG}_t^{\pm} + \mathrm{QR}_t^{\pm} \cdot \mathrm{WR}_t^{\pm}) \tag{68}$$

Cost for treatment of wastewater

$$f_{CE}^{\pm} = \sum_{t=1}^{3} (\mathrm{QWT}_t^{\pm} \cdot \mathrm{DWT}_t^{\pm} \cdot \mathrm{ZT}_t^{\pm} + \mathrm{QWM}_t^{\pm} \cdot \mathrm{DWM}_t^{\pm} \cdot \mathrm{ZM}_t^{\pm} + \mathrm{QWR}_t^{\pm} \cdot \mathrm{DWM}_t^{\pm} \cdot \mathrm{ZR}_t^{\pm} + \sum_{k=1}^{2} \sum_{t=1}^{3} \mathrm{QWI}_{kt}^{\pm} \cdot \mathrm{DWI}_t^{\pm} \cdot \mathrm{Z}_{it}^{\pm} \tag{69 - 70}$$

6.5.1 Constraints

Balance for agricultural use

$$MINA_t \le \sum_{i=1}^{3} A_{it}^{\pm} \le MAXA_t, \forall t \tag{71}$$

Balance for water resource availability

$$\mathrm{WS}_t^{\pm} \le \mathrm{MS}_t^{\pm}, \forall t \tag{72}$$

$$\mathrm{WG}_t^{\pm} \le \mathrm{MG}_t^{\pm}, \forall t \tag{73}$$

$$\mathrm{WR}_t^{\pm} \le \mathrm{MR}_t^{\pm}, \forall t \tag{74}$$

$$\sum_{i=1}^{2} \mathrm{RWC}_{it}^{\pm} \cdot \mathrm{A}_t^{\pm} + \sum_{k=1}^{2} \mathrm{ZI}_{it}^{\pm} + \mathrm{ZT}_{it}^{\pm} + \mathrm{ZM}_{it}^{\pm} + \mathrm{ZR}_{it}^{\pm} + \mathrm{RWG}_{it}^{\pm} \cdot \mathrm{GA}_{it}^{\pm} \le \mathrm{WS}_t^{\pm} + \mathrm{WG}_t^{\pm} + \mathrm{WR}_t^{\pm}, \forall t \tag{75}$$

Balance for water supply

$$\sum_{i=1}^{2} \mathrm{RWC}_{it}^{\pm} \cdot A_t^{\pm} \ge \mathrm{MA}_t^{\pm}, \forall t \tag{76}$$

$$\sum_{k=1}^{2} \mathrm{ZI}_{it}^{\pm} \ge \mathrm{MI}_t^{\pm}, \forall t \tag{77}$$

$$\mathrm{ZT}_{it}^{\pm} \ge \mathrm{MT}_t^{\pm}, \forall t \tag{78}$$

$$\mathrm{ZM}_{it}^{\pm} \ge \mathrm{MM}_t^{\pm}, \forall t \tag{79}$$

$$\mathrm{ZR}_{it}^{\pm} \ge \mathrm{MR}_t^{\pm}, \forall t \tag{80}$$

Balance for treatment of wastewater

$$\mathrm{DWT}_{kt}^{\pm} \cdot ZI_{it}^{\pm} + \mathrm{DWT}_{t}^{\pm} \cdot \mathrm{ZT}_{t}^{\pm} + \mathrm{DWM}_{t}^{\pm} \cdot \mathrm{ZM}_{t}^{\pm} + \mathrm{DWR}_{t}^{\pm} \cdot \mathrm{ZR}_{t}^{\pm} \leq \mathrm{TWC}_{t}^{\pm}, \forall t \quad (81)$$

6.5.2 Environment Constraints

$$\sum_{i=1}^{3} \mathrm{NA}_{t}^{\pm} \cdot \mathrm{A}_{it}^{\pm} + \left(\sum_{k=1}^{2} \mathrm{NI}_{kt}^{\pm} \cdot \mathrm{ZI}_{kt}^{\pm} + \mathrm{NT}_{t}^{\pm} \cdot \mathrm{ZT}_{t}^{\pm} + \mathrm{NM}_{t}^{\pm} \cdot \mathrm{ZM}_{t}^{\pm} + \mathrm{NR}_{t}^{\pm} \cdot \mathrm{ZR}_{t}^{\pm} \right) (1 - \mathrm{NRE}_{t}^{\pm}) \leq \mathrm{TN}_{t}^{\pm}, \forall t$$

(82)

$$\sum_{i=1}^{3} \mathrm{PA}_{t}^{\pm} \cdot \mathrm{A}_{it}^{\pm} + \left(\sum_{k=1}^{2} \mathrm{PI}_{kt}^{\pm} \cdot \mathrm{ZI}_{kt}^{\pm} + \mathrm{PT}_{t}^{\pm} \cdot \mathrm{ZT}_{t}^{\pm} + \mathrm{PM}_{t}^{\pm} \cdot \mathrm{ZM}_{t}^{\pm} + \mathrm{PR}_{t}^{\pm} \cdot \mathrm{ZR}_{t}^{\pm} \right) (1 - \mathrm{PRE}_{t}^{\pm}) \leq \mathrm{TP}_{t}^{\pm}, \forall t$$

where f = expected net system benefit (R); t = time period, t = 1, 2, 3; i = type of crop, i = 1, 2, 3 (where i = 1 for maize, 2 for potatoes, 3 for table-grapes); k = type of industry, k = 1,5 2 (where k = 1 for mining industry, 2 for food industry); $\mathrm{A}_{it}^{\pm}$ = area allocated to crop i in period t (km^2); $\mathrm{CC}_{it}^{\pm}$ = cost for cultivating crop i in period t (Rkm^{-2}); $\mathrm{DWI}_{kt}^{\pm}$ = unit wastewater discharge by industry k in period t (tm^{-3}); $\mathrm{DWM}_{t}^{\pm}$ = unit wastewater discharge by municipal sector in period t (tm^{-3}); $\mathrm{DWR}_{t}^{\pm}$ = unit wastewater discharge by household in period t (tm^{-3}); $\mathrm{DWT}_{t}^{\pm}$ = unit wastewater discharge by tourism industry in period t (tm^{-3}); $\mathrm{MA}_{t}^{\pm}$ = water demand of agriculture in period t (m^3); $\mathrm{MG}_{t}^{\pm}$ = the maximum allocated amount of groundwater in period t (m^3); $\mathrm{MI}_{t}^{\pm}$ = water demand of industry in period t (m^3); $MAXA_t$ = the maximum area allocated to crop i in period t (km^2); $MINA_t$ = the minimum area allocated to crop i in period t (km^2); $\mathrm{MM}_{t}^{\pm}$ = water demand of municipal sector in period t (m^3); $\mathrm{MR}_{t}^{\pm}$ = the maximum allocated amount of river water in period t (m^3); $\mathrm{MR}_{t}^{\pm}$ = water demand of household in period t (m^3); $\mathrm{MS}_{t}^{\pm}$ = the maximum allocated amount of surface drainage water in period t (m^3); $\mathrm{MT}_{t}^{\pm}$ = water demand of tourism in period t (m^3); $\mathrm{NA}_{t}^{\pm}$ = nitrogen percent content of the soil in period t (%); $\mathrm{NI}_{kt}^{\pm}$ = unit nitrogen discharge by industry k in period t (tm^{-3}); $\mathrm{NM}_{t}^{\pm}$ = unit nitrogen discharge by municipal sectors in period t (tm^{-3}); $\mathrm{NR}_{t}^{\pm}$ = unit nitrogen discharge by household in period t (tm^{-3}); $\mathrm{NRE}_{t}^{\pm}$ =nitrogen removal efficiency in period t (%); $\mathrm{NT}_{t}^{\pm}$ = unit nitrogen discharge by tourism in period t (tm^{-3}); $PA_t^{\pm}$ = phosphorus percent content of the soil in period t (%); $PC_{it}^{\pm}$= price of crop i in period t (Rkg^{-1}); $PI_{kt}^{\pm}$ = unit phosphorus discharge by industry k in period t (tm^{-3}); $PM_t^{\pm}$ = unit phosphorus discharge by municipal sectors in period t (tm^{-3}); $PR_t^{\pm}$ = unit phosphorus discharge by household in period t (tm^{-3}); $PRE_t^{\pm}$ = phosphorus removal efficiency in period t (%); $PT_t^{\pm}$ = unit phosphorus discharge by tourism in period t (tm^{-3}); $QG_t^{\pm}$ = cost for cultivating green field in period t (Rkm^{-2}); $QG_t^{\pm}$ = cost for pumping and delivering the ground water in period t (Rm^{-3}); $QI_{kt}^{\pm}$ = unit benefit of water allocated to industry k in period t (Rm^{-3}); $QR_t^{\pm}$ = cost for pumping and delivering the river water in period t (Rm^{-3}); $QR_t^{\pm}$ = unit benefit of water allocated to household in period t (Rm^{-3}); $QS_t^{\pm}$= cost for pumping and delivering the surface drainage water in period t (Rm^{-3}); $QT_t^{\pm}$ = unit benefit of water allocated to tourism in period t (Rm^{-3}); $QWI_{kt}^{\pm}$ = treatment cost of wastewater from industry k in period t (Rt^{-1}); $QWM_t^{\pm}$= treatment cost of wastewater from municipal sector in period t (Rt^{-1}); $QWR_t^{\pm}$ = treatment cost of wastewater from household in period t (Rt^{-1}); $QWT_t^{\pm}$ = treatment cost of wastewater from tourism in period t (Rt^{-1}); $RWC_{it}^{\pm}$ = unit irrigation demand for crop i in period t (m^3km^{-2}); $RWG_{it}^{\pm}$ = unit irrigation demand for green field in period t (m^3km^{-2}); $TN_t^{\pm}$ = the maximum allowed amount of nitrogen discharge in period t (kg); $TP_t^{\pm}$ = the maximum allowed amount of phosphorus discharge in period t (kg); TWC_t = total wastewater treatment capacity in period t (tonne); $WG_t^{\pm}$ = allocated amount of groundwater in period t (m^3); $WR_t^{\pm}$ = allocated amount of river water in period t (m^3). $WS_t^{\pm}$ = allocated amount of surface drainage water in period t (m^3); $Y_{it}^{\pm}$ = yield of crop *i* in period t ($kgkm^{-2}$); $ZI_{kt}^{\pm}$ = water allocated to industry k in period t (m^3); $ZM_t^{\pm}$ = water allocated to municipal sectors in period t (m^3); $ZR_t^{\pm}$ = water allocated to household in period t (m^3); $ZT_t^{\pm}$ = water allocated to tourism in period t (m^3).

Several constraints are formulated to restrain the entire model under the purpose of maximising system benefit in order to generate optimal system solutions. In particular agricultural use, including the planting areas of maize, potatoes, and table-grapes, should be limited to available agricultural resources. All kinds of water resources have their own availabilities in every period due to the natural and policy limitations. Water supplies to each end-user should be commensurate with their operational demands. The wastewater discharged to the central treatment plant should not exceed its fixed capacity.

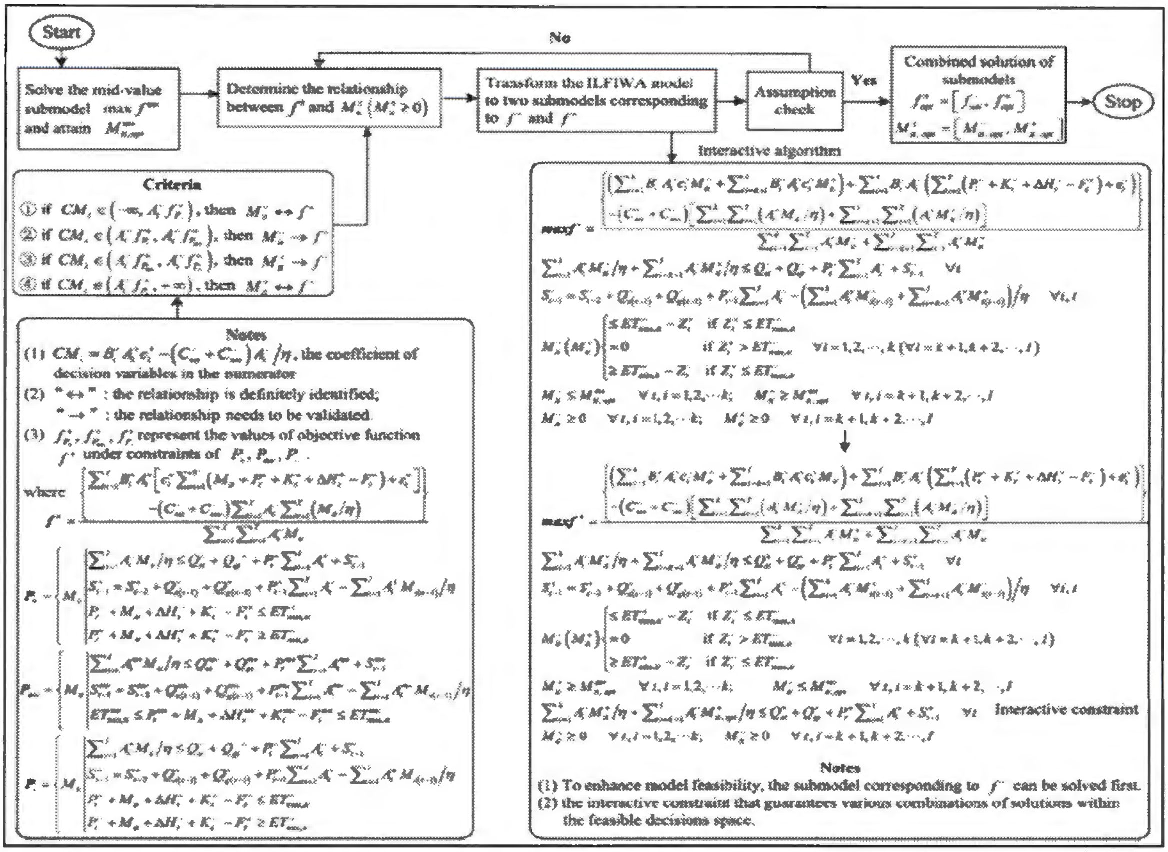

Figure 28: The Solution Method flowchart of Interval Linear Fractional Irrigation Allocation Model (ILFIWA) model

(Li *et al.* 2016a: 50)

6.6 Development of the Orange-Senqu River Irrigation Model© (OSRIM©)

This model which is obtained after a modification is named the Orange-Senqu River Irrigation Model© (OSRIM©). It is currently under intellectual property registration with the South African Patents Office in Pretoria. The copyright information of this model is obtainable from the office referred to in the preceding section. It will be referred to hereafter as the OSRIM throughout this thesis and other texts. The development of OSRIM is based on the functionalities in this chapter whilst cognisant of the fact that it is mainly a predictive systems dynamic model.

The current river-basin scale management, particularly in developing countries, has become increasingly challenging due to the complexities arising from the functioning of hydrological cycles, socio-economic factors, and diverse stakeholder perspectives, needs, values, and concerns associated with the use of water for various purposes (Martin *et al.* 2016; Gain and Giupponi 2015). In particular, complex interactions and dynamic feedbacks between socio-economic and environmental systems make it difficult to understand the potential consequences of decisions (Kotir *et al.* 2017; 2016).

System feedbacks have been identified as one of the key attributes that influence sustainability in most human-environmental systems (Liu *et al.* 2015b; Levin *et al.* 2013), yet limited attention has been given to feedback processes and long-term dynamics in those systems (Schlüter *et al.* 2014; Levin *et al.* 2013; Sterman 2012). It has been argued within water resources management systems that our inability to develop sustainable solutions is grounded in the lack of understanding of the interconnections and dynamics of different sub-systems (Sivapalan 2015; Davies and Simonovic 2011).

Consequently, many researchers (Kotir *et al.* 2017; Sahin *et al.* 2016; Sivapalan 2015; Gain and Giupponi 2015; Liu *et al.* 2015a; Gohari *et al.* 2013; Mirchi and Watkins 2013; Davies and Simonovic 2011 and Simonovic 2009) have stressed that decision-making in water resources management systems should be based on a holistic view given the magnitude of complex dynamics, feedback processes, and interdependencies between the biophysical and socio-economic processes. Water planners require anticipation for adaptation to management practices and infrastructure development and this can be achieved through the development of a systemic approach that depicts the natural and socio-economic factors and processes that determine the future dynamics of river basins (Girard *et al.* 2015). The combined effects of system dynamics need to be considered in order to achieve improved management decisions and intentions that could lead to the reduction of the possibilities of unintended consequences and adverse side-effects of policy decisions (Tomaszkiewicz *et al.* 2017; Sivapalan 2015; Kelly *et al.* 2013 and Simonovic 2009).

The categorisation of water resources modelling is based on three main modelling processes and these are:

1) Yield modelling: objectively for the individual determination of yields of river sub-basins for input into planning model;

2) Rainfall-runoff modelling: objectively for the production of naturalised hydrology extending for the whole historical record period on the basis of observed rainfall and streamflow data for input into planning and yield models; and

3) Planning and operations modelling: objectively for the operation and management of river basins via the IWRM based on characteristics of individual river sub-basin yields.

The commonly used models for the systems analyses in South Africa are as follows:

- WRYM: Used for the determination of river sub-basin yields,
- WRPM: Used for the configuration of the future management of the Integrated Orange-Senqu River basin.

A predictive model facilitates an accurate estimation of water demand. It is a robust demand-forecasting model that renders assistance to managers in designing a more environmentally sustainable water distribution systems and ensures proper management of available water resources in a more efficient manner (Kotir *et al.* 2017; Tomaszkiewicz *et al.* 2017; Kotir *et al.* 2016; Kelly *et al.* 2013; Levin *et al.* 2013). Together with a water demand management strategy, these models assist managers in overcoming operational problems, such as specific instances that are common during peak demands that include low pressure, and issues that relate to management of assets, such as the non-replacement of assets or replacement by lower capacity assets reaching the end of their economic life (Shabani *et al.* 2016: 100). This observation has also been made by Carboni *et al.* (2016); Kotir *et al.* (2016); Wanjiru *et al.* (2016) and Yang *et al.* (2016).

A system dynamics model is ideally suited for integration of demand, supply and financial dimensions (Sahin *et al.* 2016). It is in line with these considerations that the development of OSRIM can account effectively for the essential features of a real-life system, since its behaviour under stress will likely be similar to the behaviour of the prototype models. Essential variables for model operation were identified by reviewing locally-based literature for region specific inputs and examining world literature for more generic variables and their behaviour (Kotir *et al.* 2017; Sahin *et al.* 2016).

System rules and norms in the proposed OSRIM were informed from and by the Upper Orange River Water Strategy Reports and concepts from other reviewed literature (Figure 29).

The system assumes three facets of operation with regard to avoiding water shortages: (a) increased supply capacity with rain-independent supply; (b) changing demand management practices; and (c) optimising asset management. The model also accounts for the representation of anticipated externally driven changes to the underlying system along the progression of time. It also calls for an incorporation and minimisation of potential methods of the negative impacts of reform on the socio-environmental system.

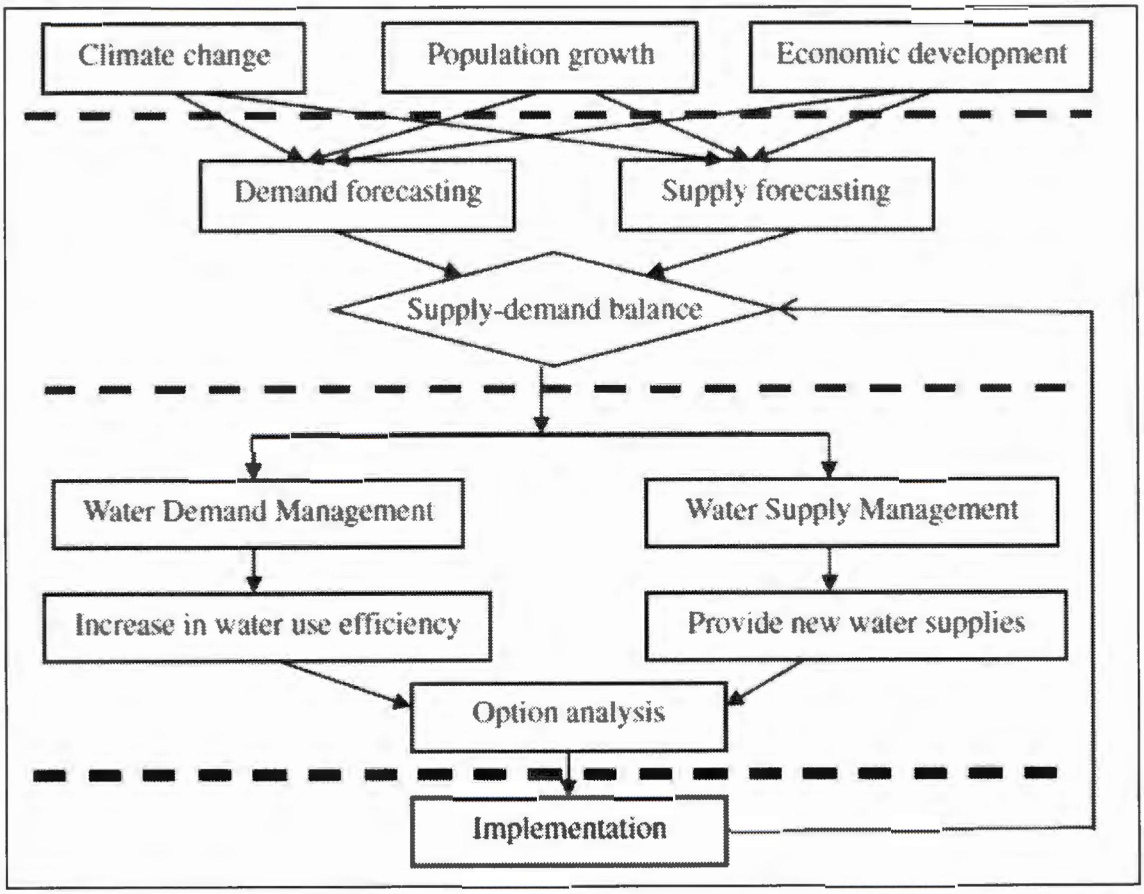

Figure 29: The Water Management System Framework together with the Adaptation to a changing Environment

(Wang *et al.* 2016b: 86)

Climate change impacts on water resources and is commonly mitigated through short but systematic reviews of knowledge gathered by researchers in different parts of the world. Similarly, the current study reviewed relevant studies from recent years in order to get an understanding of the direct and indirect impact of changing patterns of temperature and rainfall on water demand within the agriculture, industry, domestic affairs and ecology sectors. In some cases, published data may need to be re-analysed for the purposes of a better understanding of the changes reported on (Wang *et al.* 2016).

Environmental conditions that become drier and warmer as a result of climate change can aggravate further the water crisis in regions of the world that are already facing water shortages due to growths in the economy and population. Increased water demand might lead to conflicts between different water users and alter in-stream requirements for retaining ecosystem sustainability. Managing water resources has become an important priority and a major challenge across the world, as the growing and conflicting demand for water appears as a major deterrent to economic development. Therefore, adaptation through water management practices is essentially required in the mitigation of the negative impacts of climate change. Water management strategies are categorised into three broad classes, namely, the supply side management, demand side management and business-as-usual management (Wang *et al.* 2016).

6.6.1 Climate Change and Water Demand

It is widely documented that water demand is likely to increase as a result of changes in precipitation amount and distribution, and in temperature regimes. Numerous research has been carried out on water demand and in the estimation of the influence of climate variables (Helman *et al.* 2017; Gudmundsson *et al.* 2016; Wang *et al.* 2016c; Allen *et al.* 1989). A variety of methods for understanding the impact of climate variables, such as rainfall, relative humidity, air temperature, wind speed, sunshine duration, on annual, seasonal, monthly, weekly, and daily water demands have been proposed, and these include the use of system dynamics (Sun *et al.* 2016b), linear regression (Fang and Lahdelma 2016), artificial neural networks (Ehsani *et al.* 2016; Tiwari *et al.* 2016), the Box and Jenkins model (Brentan *et al.* 2016; Sebri 2016), and other methods (Dutta *et al.* 2016; Zhuo *et al.* 2016). The results of these analyses reveal that water use and climatic conditions are significantly correlated and hence influence water demand. An interpretation and summarisation of the results obtained by various authors regarding the impact of climate change on water demand are also briefly discussed in this chapter in support of the OSRIM inception.

The Mohale Dam (Phase 1B) in Lesotho started transferring water to the Katse in 2003. The yield of Mohale Dam is 9.6 m^3/s. The Matsoku Weir (also Phase 1B) started transferring water to the Katse as well in 2001. A new dam, the Mashai Dam in Lesotho, which is part of Lesotho Highlands Phase 2, may come into operation in 2020. New dams, the Tsoelike (Phase 3) and Ntoahae (Phase 4), are also planned for future implementation. This will significantly address anticipated decline introduced by climate change and will enhance better water demand.

6.6.2 Irrigation Water Demand

A number of studies have been carried out to determine the impact of climate change on irrigation water demand in various geographical and climatic regions (Mukwada *et al.* 2019; Dong *et al.* 2016; Wang *et al.* 2016b; Alcamo *et al.* 2007; Vörösmarty *et al.* 2000). Ideally the use of water balance models and of the Penman-Monteith equation seems highly applicable for the assessment of the impact of climate change on irrigation demand. The OSRIM and WFUPM are thus no exception in pursuance of this. OSRIM also assumes that the change in evapotranspiration due to the change in temperature can be computed according to the Penman-Monteith model (FAO-PM) as:

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_2 - e_2)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (83)$$

where ET_0 is the reference evapotranspiration (mm/d), R_n is the net radiation over the grass (MJ x m^{-2} x d^{-1}), G is the soil heat flux density (MJ x m^{-2} x d^{-1}), Δ is the slope of the saturation vapour pressure curve at the mean daily air temperature (kPa/°C), γ is the psychrometric constant (kPa/°C), u_2 is the wind speed measured at 2m above the ground (m/s), e_o is the saturated vapour pressure of the air (kPa), and e_a is the mean actual vapour pressure of the air (kPa).

In addition, water balance models as well as OSRIM and the sister model WFUPM can be applied in the estimation of how irrigation demand changes when both temperature and rainfall change. The irrigation demand of crop land can be computed using the water balance model below:

$$I_N = ET_c - P_e + \Delta W + G \quad (84)$$

where I_N is the net water demand of the crop (mm), ET_c is the reference crop evapotranspiration (mm), P_e is the effective precipitation (mm), G is the groundwater recharge during the growth of the crop (mm), and ΔW is the soil moisture storage capacity (mm).

It can be concluded that irrigation water demand will certainly increase due to increases in evapotranspiration and reductions in soil moisture that occur under warmer climatic conditions. Irrigation water withdrawals account for almost 90% of global consumptive water use and 70% of global water withdrawals (Wang *et al.* 2016b). Therefore, as predicted from the OSRIM and WFUPM, increased demand for irrigation will certainly intensify water competition among different sectors.

6.6.3 Industrial Water Demand

Industrial water demand encompasses water needs for fabrication, processing, washing, dilution and cooling. However, the majority of water withdrawn by industry is used for the cooling process. Major changes in industrial water consumption even in OSRIM are the result of changes in the amount of water needed for cooling (Wang *et al.* 2016b). Demand for cooling water in the once-through cooling system has been computed as:

$$Q = KW \cdot h \cdot 3.6 \cdot \frac{1-\eta_e}{\eta_e} \cdot (1-a) \cdot \frac{1}{\rho \cdot c \cdot AS} \tag{85}$$

where Q is the cooling water demand (m^3), KW is the installed capacity (kW), h is the operation hours (h), 3.6 is the factor used to convert kWh to megajoules, η_e is the electric efficiency (%), η_t is the total efficiency (%), a is the share of waste heat not discharged by cooling water (%), c is the specific heat capacity of water (MJ/t.K), ρ is the water density (t/m^3), and AS is the permissible temperature increase of the cooling water (k).

In industry, the calculation of maximum permissible water withdrawal can be:

$$Q_{max} = \frac{KW_{max} \cdot \lambda \cdot 3.6 \cdot (1-\alpha)\ (1\eta_t)}{4.2 \cdot \eta_e \cdot AS_{max}} \tag{86}$$

where Q_{max} is the maximum permissible water withdrawal (m^3), AS_{max} is the maximum permissible temperature increase (*K*).

Cooling water demand is dependent on local climate conditions, and especially on water temperatures. The direct relationship between cooling water demand and temperature means that water demand in power plants and manufacturing facilities will increase due to increases in temperature. Supplementary water supplies are a noble requirement in order to compensate for decreased efficiencies of cooling systems due to these rises in temperature (Wang *et al.* 2016b). However, the impact of climate change on water demand in agriculture will be larger than the demand in industry.

6.6.4 Domestic Water Demand

Domestic water demand includes water needs for all residential purposes, including in-house water use for drinking, preparing food, bathing, washing clothes and dishes, and the flushing of toilets, as well as outdoor water use for gardening, lawn watering and other activities. All these uses are incorporated in the OSRIM and are carefully addressed in the plenary of the WFUPM. The climatic elasticity of water use is used to compute domestic water demand (Wang *et al.* 2016b). The temperature elasticity of water use is used in the estimation of impacts of temperature on water demand in the equation:

$$e_t = -\Delta Q/\Delta T \quad (87)$$

where ΔQ is the percentage change in water demand and ΔT is the percentage change in temperature. Similarly, the impact of precipitation on water demand is estimated using the precipitation elasticity of water demand:

$$e_t = -\Delta Q/\Delta P \quad (88)$$

where ΔQ is the percentage change in water demand and ΔP is the percentage change in precipitation.

Domestic water demand will increase as a result of increased evapotranspiration caused by higher temperatures. However, changes in domestic water demand may not be significant in some regions, due to an increase in precipitation (Wang *et al.* 2016b). Overall changes in domestic water demand will depend on how well increased rainfall balances with water losses from increased evapotranspiration due to higher temperatures.

6.6.5 Ecological Water Demand

Ecological water demand includes water demand for environmental and ecological system protection purposes. Usually, when supplies become scarcer, major adjustments in water use are required in order to maintain the minimum in-stream flows needed for the protection of endangered species and the recreational benefits of an area. This forms a strong basis for which OSRIM was proposed. This is as result of the observable lack of ecological water requirements the world over. Ecological water demands are computed by adding in-stream and out-stream water demands. There is no well-accepted method of estimating in-stream ecological water demand (Wang *et al.* 2016b). Out-stream water demand for environmental protection is usually computed as:

$$ET_c = \alpha D \tag{89}$$

where ET_c is the out-stream water demand for environmental protection (mm), α is a parameter (mm/hPa), and D is the aerial saturation deficiency (hPa). A comprehensive factor reflecting temperature change and air humidity can be obtained as:

$$e = e_0 - e_a \tag{90}$$

where e_a is the mean actual vapour pressure of the air (kPa) and e_0 is the saturated vapour pressure of the air (kPa), which can be defined as:

$$e_0 = e_1 \cdot 10^{\frac{8.5t}{273+t}} \tag{91}$$

where t is air temperature and e_1 = 6.11 hPa.

A potential increase of in-stream water demand due to increases in ecosystem demands and recreational uses within climate change scenarios is likely. The water demands of endangered species and other fish and wildlife could increase along with ecosystem impacts due to warmer air and water temperatures, as well as the resulting hydrologic impact such as runoff timing. Changes in the quantity, quality, and timing of runoff, stemming from greenhouse gas warming, would affect in-stream water uses as the maintenance of ecosystems are likely to be a daily occurrence (Wang *et al.* 2016b). These changes might also directly or indirectly affect in-stream water demands. Furthermore, an increase in air temperature would also lead to an increase in water temperature, which in turn will have a direct impact on cyanobacteria growth and water demand.

6.7 The Framework of the Orange-Senqu River Irrigation Model (OSRIM)

The framework of the OSRIM is presented in the context of the hydrological zones that form the Upper Orange River basin by sub-basins of the Senqu, Upper Orange, Caledon and Riet-Modder hydrological zones.

Three things are worth-noting about the various *water user associations* and / or sectors mentioned in chapter 4:

Ecological Reserve (environmental-in-stream flow requirements). This water is not consumed.

Alien vegetation has not been included in the above though the provision of water for its existence should be allowed for.

Hydropower. This water is not consumed apart from losses. It should be noted that hydropower is a secondary determinant of the weekly releases from Gariep and Vanderkloof dams, irrigation requirements are the primary concern.

The researcher shares similar views with Gogate *et al.* (2017) and Wurbs (2017) stating that the incorporation of environmental flows in water allocation is minimally addressed the world over. This forms the basis for the researcher's strong view and the urgency to develop a framework that holistically integrates these models as there is a need to move from the traditional single-discipline approach to a more multi- or interdisciplinary approach. This view is also strongly asserted Gogate *et al.* (2017), Khan *et al.* (2017) and Tundisi and Tundisi (2017).

Figure 30 outlines the undertaken modification of the structure leading to the OSRIM with a water demand management plan (based on Xiao *et al.* 2016; Chen and Wei 2014 and Hipel *et al.* 2013).

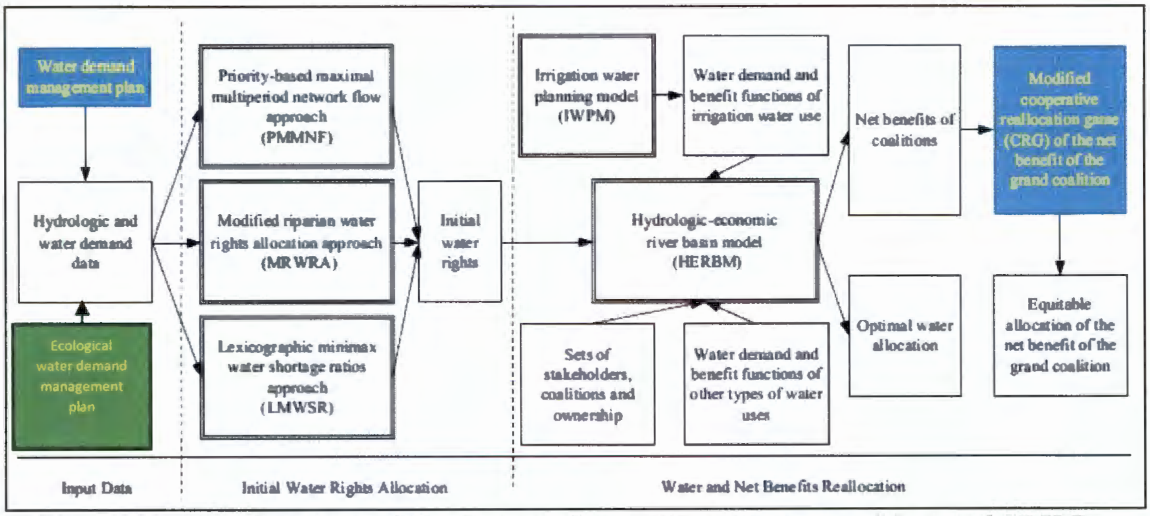

Figure 30: The Structure of the Orange-Senqu River Irrigation Model (OSRIM)

The simulation models provide the answer to the '*What if?*', while, the optimisation models were used to find the answer to the '*What is the best*?' under a particular set of conditions. Simulation models are widely used for the management of water demand problems as they typically assist in finding the solution of a particular water management option due to their predictive capability (Singh 2016: 1436). Optimisation models include techniques such as linear programming (LP) models, non-linear programming (NLP), dynamic programming (DP) and genetic algorithm (GA) (Singh 2016). However, the combined use of simulation and optimisation models is necessary (Singh 2016: 1436) in order to obtain a suitable solution to the problems.

6.8 Limitations

Limitations in model design that are addressed by the OSRIM are outlined in section 6.8.1 while the limitations of the study are dealt with in section 6.8.2.

6.8.1 Limitations in model design addressed by the OSRIM

This section addresses the limitations which resulted in the development of OSRIM. All of these are aspects are inherent enhancements that can be incorporated into the proposed OSRIM (Figure 31). These models have several limitations. Firstly, modelling is only possible at a monthly time step. Secondly, hydrological (rainfall-runoff) modelling is not built in, hence extensive pre-processing is required to generate inflow files and demands. Thirdly, it does not have river routing capabilities and hydraulic analysis.

The limitations of both models are addressed in this section. Both models provide estimates that may be too coarse for those required for CMA. These models' other requirement is that a large amount of pre- and post-processing needs to be performed when using them. They use DOS based systems that are difficult to configure and set up. The pre- and post-processing requirements also make the models tedious to run and thus results are not easily accepted by stakeholders. Although there are plans in progress to incorporate a user interface for the WRPM similar to that of the WRYM, which will render assistance with information and data management, this is still an outstanding limitation to date. In addition, both models can present tables and graphs of most input and output data, yet it produces no output via GIS, and cannot present animations. A weakness of the WRPM output is the large results file sizes, which are difficult to work with and take up a significant amount of computer space. All graphical outputs for the WRPM also require preparation using post processors and graphs are prepared using an outdated dos utility. These post processors do not operate correctly on all computers, especially newer computers, and the prepared graphs appear outdated.

One major weakness of both models is the lack of user friendliness. The models are have very few warning messages in the event of an incorrect data input, and should the model not run, the error messages that are given are often very cryptic. The models do not use any GIS type interfaces which could assist in setting up networks and in making the models more understandable to decision-makers. Currently, there is no visual basic interface in the WRYM but there are plans to do so in the future. A weakness of the models is that maintenance and regular upgrading are costly and require a high level of skill that is not readily available. Both models only have data Com Object functionality and do not have any costs involved with initial outlay and licenses. Some model users have, in the past, used incorrect evaporation values, as the models require different forms of evaporation in various data files.

An enhancement to the model pertaining to irrigation, rainfall and evaporation rates is inaccurately achieved and this is done merely to avoid mistakes, and all rainfall or evaporation is dependent on where the particular demand or reservoir is located. A possible enhancement that could be made to the models is the ability to include crop yield modelling, with specific reference to planning and costs. The ability to facilitate the simulation of groundwater interaction via soil moisture storage is not available. The WRYM does not have the ability to facilitate the simulation of water quality. A simple method of simulating urban demands and return flows is available in both models. This method does not, however, include the ability to incorporate increases in demand owing to population growths and economic activities within the model. A weakness of both the WRYM and WRPM is the large amount of pre-processing that is required to develop the lookup tables based on the outputs of other models that are used to determine ecological flows. This process could be streamlined to enhance the models. Simulation of hydro-power generation is lacking. This is, however, only available for reservoirs and the model is unable to facilitate the simulation of run-of-river hydropower.

The functions that are unavailable include: (i) linkages to real-time systems; (ii) water accounting and water rights; (iii) aquaculture; (iv) recreation and: (v) sedimentation.

The basis for which OSRIM was proposed in line with Xiao *et al.* (2016) is to address the viewed shortcomings in the preceding section. These are areas for which OSRIM is deemed to capitalise on and render an improvement. OSRIM is intended to accomplish a wide array of dynamic demands (increase over time) as well as changing system configurations. This will ensure its use beyond the planning tool assessment status for the likely implementation dates of new schemes or resources and also as an operating tool that assists in the month-to-month operation of any system.

6.8.2 Limitations of the study

A number of limitations, as also noted by Agide *et al.* (2017), lead to an inference of evidenced disparities. These limitations include: 1) the low-quality data that is often flawed and disinformative (Kauffeldt *et al.* 2013) and often provide a falsified sensation of data that could be considered rich; 2) mismatch between field irrigation water demand and water diversion, where water shortage is one of the main constraints to irrigated agriculture as raised by the irrigation water users in several of the study irrigation schemes; 3) high water losses in the conveyance and distribution systems, where poorly constructed, maintained and leaky conveyance and distribution systems contribute to the largest share of water losses particularly on semi-modern schemes; and 4) the high head, middle and tail water delivery inequity levels that are related to the nonexistence of flow control structures and the weakness of institutional setups for water management. The observed trend is not limited to the study area alone but has been noted by, among others, Chiang *et al.* (2017), Guo (2017), Swain (2017), Wada *et al.* (2017) and Zhong *et al.* (2017).

6.9 Summary

The section addressed the development of the modified model OSRIM which is a result of both the water demand and global hydrological model. The model's structure consists of well-organised arrays of physical laws and empirical observations that are presented in mathematical terminology and in such combinations that are able to produce a set of results on the basis of a set of known and/or assumed conditions. The application of models such as the OSRIM, in hydrology, accurately represent real world decision tools in the planning, design and operation of hydrologically related systems and structures.

As a result, the OSRIM provides an evaluation of the performance of the integrated modelling approach in terms of simulated irrigation water withdrawal and consumptive water use from the surface waters of the Upper Orange River and associated groundwater resources. It also potentially assists in setting up preliminaries for the quantification of the impact of human perturbation, irrigation water use and reservoir regulation, on the region's water resources in a consistent manner.

The next chapter draws conclusions and makes recommendations for future research and that of practice associated with the use of OSRIM.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7. Introduction

The fundamental components of the water balance, precipitated water, consumed water, water withdrawals, and non-consumed water were quantified as well as the associated variegated definitions and sub-groups found in widely used water assessment frameworks such as Water Accounting Plus (WA+), Water Footprint, and System of Environmental-Economic Accounts for Water (SEEA-Water). The relationship between precipitation and/or withdrawals to the consumptive water use through evapotranspiration was observed based on an assessment of monthly or weekly surface runoff, drainage and groundwater recharge dynamics or deficit due to irrigation, return flows, inundation and their reuse. The functions of the proposal of OSRIM followed the same pathway proposed by Simons *et al.* (2016: 2).

Models provide smoother responses than real-world systems. Modelling is generally aimed at ensuring the minimum model uncertainty through the most parsimonious parameterisation. Numerous discussions have gone into determining the strengths and weaknesses and yet it is clear that opinions regarding a particular strength or weakness of a model are relatively subjective. The strength of a model to one modeller could be that very model's weakness to another. It is mandatory to discuss the purposes of the WRYM and WRPM, especially as they relate to the management of the water resources of the Orange-Senqu Basin. The points identified in the first paragraph have been selected based on the perceived water resources planning requirements of South Africa which resulted in the development of the OSRIM.

It is important to realise that the institutions involved in water demand management and planning have been developed independently over many decades to establish complicated and intricate sector specific methodologies, instruments and frameworks. The number of stakeholders involved at all levels of society means that the transformation from isolated single sector thinking to a joint integrated structure requires much more than simply linking models. Further research and investigation is crucial towards documenting and providing the evidence needed to raise awareness of the required changes. The real challenge lies in translating these issues into political systems, regulations and governance. The increasing number of studies, projects and events at international political forums, scientific institutions and multilateral organisations concerning sustainability, integrated systems and holistic approaches, is an encouraging indicator of movement in the right direction. It is clear that integrated, holistic management approaches are key to sustaining the kinds of lifestyle patterns and population increases that are predicted in the face of diminishing natural resources and climate change (Kolokytha *et al.* 2017). While it is clear that water demand management is highly interdependent, there are also strong dynamic links with other sectors such as agriculture, land use, environment, climate change, industry, politics and international relations. Finally OSRIM will include aspects such as (i) water accounting and water rights; (ii) linkages to real-time systems; (iii) aquaculture; (iv) recreation; and (v) sedimentation. A section on recommendations for further studies and that of practice associated with the use of OSRIM is also provided.

7.1 Research Contribution of the Study

Water demand management is not only an effective system engineering on different industries, different companies, different departments, but also is the future trend, If it could be promoted and used as presumed in this study, enormous economic, social and environmental benefits can be brought. This study has shown that water administrators and water users, water operators need to participate the action, especially those who need water to mobilize the whole society to participate in the implementation policy by guidance, administrative and economic incentives to achieve the formation of long-term mechanism step. We should learn to grasp and use new opportunities brought by current socio-economic and innovative technological development, promote water demand management actively. As envisaged in the current study water demand management alleviates the current contradiction between water supply and demand effectively, and provides a good reference to address water use with low efficiency and the water crisis. Therefore, it should be promoted vigorously.

The ecological water requirements are not sufficiently addressed globally. It is a point of concern that concessions often made in attempts at increasing water supply owing to the high water demand seriously undermine the need to cater for ecological requirements. The reality, however, is that a disregard of the ecological needs means that all downstream users and the river system itself will be adversely affected. The overall health of the river may plummet into an irreversibly hard and unacceptable situation. This observation motivates this current study ensures that ecological water requirements addressed and allocated adequately together with the shortfall of Principle C3 of the South African Water Act of 1998 and in turn form a strong and essential basis for which OSRIM was proposed. As it is sad to note, as a concluding remark that the previous South African regime did not recognise aquatic ecosystems at all (Chikodzo *et al.* 2017).

The study highlights the need for a shift from scheduled irrigation to technical irrigation owing to climate change induced fluctuations on water demand management. Its advocacy is primarily aimed on ensuring adherence to proper allocations for consumptive water use whilst incorporating ecological water requirements. These proper allocations are likely to minimise the impact on downstream users, alien vegetation and also hydro-power generation for this shared trans-boundary water resource. Gogate *et al.* (2017) and Wurbs (2017) are of the view that the incorporation of environmental flows in water allocation is minimally addressed the world over. This together with the urgency to develop a framework that holistically integrates the WRYM and WRPM models formed the basis for this research as there is a need to move from the traditional single-discipline approach to a more multi- or interdisciplinary approach (Khan *et al.* 2017, Tundisi and Tundisi 2017). Filling this gap is of significance to water users, water resource managers, planners and the whole public domain in their development and implementation of strategic plans seeking to conserve and use water wisely and sparingly.

The role of OSRIM is likely to enhance the adaptive capacity of implementing agencies at the state or local level through the formulation of policies that facilitate the translation of capacity into action and creating networks to share knowledge and information. It will raise awareness and acknowledgement of different stakeholders in view of the impact of the likely climate change on water management and their desire to engage constructively in order to represent valuable opportunities for the creation of an enabling mechanisms for the adaptation and improvement of water management in the Upper Orange River and South Africa as a whole. Its application may well extent beyond this region to a global context. OSRIM will provide new understanding of the inter-institutional dynamics between the key institutions involved in climate change adaptation and a novel opportunity to understanding the weak linkages between specific key institutions. It will reduce uncertainties that have a complex multi-layered system of water governance needed to address the institutional and systemic challenges that hinder the smooth coordination and accessibility to data, information and the competing priorities of infrastructural and technological developmental priorities.

7.2 Conclusions

Serious disparities that were obtained in this study show that the two models used in South Africa do address water demand management adequately so the researcher proposes the use of a re-formulated model, namely OSRIM to provide a summary of irrigation areas and volumes of irrigation water utilised in the Upper Orange River basin. Water resources are not evenly distributed in time and space. Major spatial variability observed in this study area through the difference between levels of aridity where almost no precipitation falls and relatively humid regions where several millimetres of rain can fall annually. Even smaller spatial scales than the study area level can experience great variability in the availability of water: some areas within the same river basin may be subject to water scarcity, while others may be subject to a slight abundance of water. The temporal distribution of water resources depends on the characteristics of the water cycle. Periods of high rainfall alternate with dry periods, where on a yearly basis, dry summer months are followed by wet winter months. The frequency of the water cycle varies with climatic regions, and the inter-annual and year-to-year variability can be significant (UNDS 2012: 36). All these are catered for in the OSRIM.

The lack of consistency between water allocations and observations is perhaps not surprising, because stronger anthropogenic climate change started relatively recently. The current study's computed results indicate that an average water quota is at 11 560 m^3/h/a while water allocation is at 1 221 $m^3 \times 10^6$/a. It is also against this background that some notable and serious disparities that were obtained in this study show similarities to those provided by DWA (2013a) during a comparative summary of irrigation areas and volumes of irrigation water utilised in the Upper Orange River basin.

In the meantime, the summarised theoretical considerations relevant to WDM and vehemently addressed in the OSRIM are:

Arid regions have aquatic ecosystems that are generally sensitive. The implication is that a sustainable management of these fragile resources should be based on a firm understanding (and quantification) of the notion of a "threshold".

As countries in arid regions develop, mobilisation for increasingly more water resources is often necessary. This is termed supply-sided management.
As a result of supply-sided management, the successful transition to the demand-management era requires proper and strong political institutions that are supported by the political will and legitimacy to make the necessary policy changes while still surviving as a political entity.
Human perceptions are derived from socio-cultural conditions, which makes them difficult to change.
Mobilisation of any water beyond this threshold will have long-term debilitating effects on the environment, the economy and socio-political spheres of life. Sustainability therefore becomes an important element of the overall policy objective.
National crises in the forms of droughts allow for the hydro-political agenda to be re-negotiated. This is usually in the form of an introduction of notions of sustainability, which are linked to a strategy of demand-management.
One factor making demand-management complex is the fact that it is based on the need to change human perceptions about water.
One of the existing perceptions suggests that, at the economic level, water has a unique characteristic in the form of a high differential between the average price and the marginal price.
Policy requirements are aimed at attaining a clear objective. Attempts to launch policies that are beyond the scope of a regime are therefore not good, thus reinforcing the need to have a strong political institutional base for the implementation of demand-management.
The nature of supply-sided projects is elevated to increased levels of complexity. The projects work to the point where a threshold is crossed after which they fail to meet the growing demand, as is typically experienced during periods of drought.
Tariff structures alone are a necessary but insufficient instrument to achieve effective WDM.
The initial stages of demand-management are politically stressful as they involve the re-allocation of resources away from political constituencies that were previously privileged.

Water Accounting Plus (WA+) is a novel analytical framework that summarises complex hydrological processes and water management issues in vast river basins by means of four simple sheets. It is easy to implement and understand. The WA+ framework provides strategic insights on the possibilities to secure water resources availability and resilience to droughts and climate change, while maintaining biodiversity, preventing land degradation and conserving water for committed outflow. The WA+ framework evaluates the impact of interventions such as deficit irrigation, water re-allocations, altered cultivation practices and artificial recharge, cropping pattern change and deforestation. It also can be applied in the introduction of biofuel crops, modernisation of irrigation, reduced groundwater withdrawals, urban expansion, wastewater treatment, water productivity improvement, water retention and storage.

Communications and decision-making has the potential for improvement, provided that the framework is supported by larger international academic and donor organisations. The dissemination of the WA+ principles to the responsible water professionals is also an elementary prerequisite for making the framework commonly known. A consideration of the results obtained here indicates that it is possible to engage further and require an evaluation of this example of demand-management that has been studied in South Africa (Mantel *et al.* 2015). The deficits are likely to be exacerbated by the inclusion of environmental flows (not included in the previous models).

The strength of this research lies in its observation of the significant pressure that is growing on many of the world's river basins and how this makes it increasingly critical to balance the competing needs among different water use sectors and ecosystems. Marginalised action on environmental flow requirements that is likely to be addressed by the OSRIM have been offset and limited by (1) lack of understanding of environmental flow benefits, (2) uncoordinated management of water resources, (3) low priority given to environmental flows in allocation processes, (4) limiting environmental flows to low flow requirements, (5) not paying attention to the impact of too much water, and (6) the difficulties of coordinating complex environmental flows

7.3 Recommendations

Further studies should examine the performance of the ET_{act} products for different geographical regions, climate zones and land use types, in order to ultimately facilitate the coupling between these products and global hydrological models. A trade-off between water use, yield and economic water productivity is advisable in water scarcity conditions; thus, the adoption of "moderate" to "mild" supplemental irrigation is necessary since on the overall the farming business can have enhanced profitability though the requirement for appropriate irrigation management support may need additional capital investment. This can be done in conjunction with: (i) an assessment of the impact of alternative sowing dates and irrigation schedules for the contrasting dry and wet years; (ii) measurement of yields, water use and productivity for the contrasting dry and wet years; and (iii) further assessments of the impact of sowing dates and supplemental irrigation schedules under drought conditions.

The Orange-Senqu system's water is regulated by more than thirty-one major dams and a highly complex and integrated water resource system with numerous large inter and intra-basin transfers. This makes the basin notably much interconnected. At present an incomplete inventory of water users in the Upper Orange River Basin arises due to the vast nature of the basin. Most irrigated land is privately owned and as such access is highly problematic. The sensitive nature of the research makes accessibility even restricted because results could largely influence the allocation schedules of irrigation water. Until recently, there has been no established standard methodology for the collection of data on irrigation water applied to crops, water use by crops and crop yields. There is also a diverse array of instruments used to support water conservation/water demand management. It is recommended that divulging correct ground information could be rewarded by incentives.

It is also recommended that a model, such as the of the Orange-Senqu River Irrigation Model (OSRIM), which can be linked with ease to an irrigation scheduling model such as the SIMDualKc (Paredes *et al.* 2017; Rosa *et al.* 2012), be used to establish the most appropriate schedules that will be of help to farmers. Moreover, real-time irrigation scheduling is desirable, especially after using ensemble seasonal weather forecasts following from this research. Medium to long-term forecasts can make an allowance for the prediction of the yield in advance and help update these predictions during the advancement of the cropping season. Beneficial to this is that irrigation management will be adjusted to real time conditions.

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Appendix 1 – Questionnaire (Interview)

Date of survey:____________________

Time of survey:____________________

Area surveyed:____________________

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
MAFIKENG CAMPUS

Section A: General Information:

1. Water management setting:

1. National Department ☐
2. Water Management Agency (WMA) ☐
3. Municipal Water Allocation Entity ☐
4. Other ☐

2. a) Person interviewed:

A. Head of CMA ☐
B. Engineer ☐
C. Head of department ☐
D. Supervisor ☐
E. Technician ☐
F. Artisan ☐

b) Education:

A. Post Graduate ☐
B. Graduate ☐
C. Senior Secondary ☐
D. Junior Secondary ☐
E. Primary Education ☐

3. a) Age ☐ **b) Sex** ☐

Section B: Policy and Water Allocation Information:

(Indication: 1 = No, 2 = uncertain, 3 = Yes)*

1. Are you aware of any policy on water allocation?

1	2	3

2. How much water are you allocated water for extraction?

1 = < 10 million m^3/a,

2 = 10 - 20 million m^3/a

3 = > 20 million m^3/a

1	2	3

3. Is water allocated for industries adequate?

1	2	3

4. How much water is allocated for industries from your entity?

1 = < 10 million m^3/a,

2 = 10 - 20 million m^3/a

3 = > 20 million m^3/a

1	2	3

5. Is water allocated for irrigation adequate?

1	2	3

6. How much water is allocated for irrigation from your entity?

1 = < 10 million m^3/a (i.e. < 1000 ha)

2 = 10 - 20 million m^3/a (i.e. 2000 – 3000 ha)

3 = > 20 million m^3/a (i.e. > 3000 ha)

1	2	3

7. I s water allocated for domestic use adequate?

1	2	3

8. How much water may be used for domestic use from your entity?

1 = < 10 million m^3/a

2 = 10 - 20 million m^3/a

3 = > 20 million m^3/a

1	2	3

9. Is water allocated for recreational purposes adequate?

1	2	3

10. How much water may be used for recreational tourism activities?

1 = < 10 million m^3/a

2 = 10 - 20 million m^3/a

3 = > 20 million m^3/a

1	2	3

11. Do you treat enough water each day?

1	2	3

12. How much water do you treat per day?

1 = < 10 million m^3/day

2 = 10 - 20 million m^3/day

3 = > 20 million m^3/day

1	2	3

13. How much water is generally piped to various users per day?

1	2	3

1 = < 10 million m^3/day

2 = 10 - 20 million m^3/day

3 = > 20 million m^3/day

14. Are you aware of any licenses awarded by your entity?

1	2	3

15. How many functioning water licenses has your entity given to date?

1 = < 100

2 = 100 - 200

3 = > 200

1	2	3

16. How many water licenses have been revoked so far and why?

1 = < 100

2 = 100 - 200

3 = > 200

1	2	3

17. Have you ever been restricted from using water by DWAF or any authority? If so when and why?

....

18. What measures do you have in place that could help you no experience the same scenario again?

....

Section C: Financial Information:

1. Is money allocated for water extraction enough?

1	2	3

2. How much money water is allocated for water extraction?

   1 = < R100 million

   2 = R100 – R200 million

   3 = > R200 million

1	2	3

3. Is money allocated for water treatment enough?

1	2	3

4. How much money is allocated for water treatment?

   1 = < R100 million

   2 = R100 – R200 million

   3 = > R200 million

1	2	3

5. Is money allocated for water chemicals sufficient?

1	2	3

6. How much money is allocated for water chemicals?

   1 = < R100 million

   2 = R100 – R200 million

   3 = > R200 million

1	2	3

7. Which chemicals do you use for water treatment?

   i. Nothing = 1 ☐

   ii. Sand (Filter) = 2 ☐

   iii. M30 = 3 ☐

   iv. $Al_2(SO_4)_3$ = 4 ☐

   v. Cl_2 = 5 ☐

   vi. Any other (specify) = 6 ☐

....

8. Is money allocated for chlorination and/or residual lime treatment enough?

1	2	3

9. How much money is allocated for final chlorination and/or residual lime treatment?

1 = < R100 million

2 = R100 – R200 million

3 = > R200 million

1	2	3

10. Do you do sufficient water metering?

1	2	3

11. How much money is allocated for metering?

1 = < R100 million

2 = R100 – R200 million

3 = > R200 million

1	2	3

12. Is your water network up to standard?

1	2	3

13. How much money is allocated for pipeline repair-works?

1 = < R100 million

2 = R100 – R200 million

3 = > R200 million

1	2	3

Section D: Technical Information:

1. Do you enough engineers?

1	2	3

2. How many engineers do you have in your entity?

1 = < 10

2 = 10 – 20

1	2	3

3 = > 20

3. Do you have enough technicians?

1	2	3

4. How many technicians do you have in your entity?

1 = < 10

2 = 10 – 20

3 = > 20

1	2	3

5. Do you have enough artisans?

1	2	3

6. How many artisans do you have in your entity?

1 = < 10

2 = 10 – 20

3 = > 20

1	2	3

7. Do you have enough support staff?

1	2	3

8. How many support staff do you have in your entity?

1 = < 10

2 = 10 – 20

3 = > 20

1	2	3

9. Please indicate their respective qualifications in the space below.

....

....

....

....

....

....

....

10. How often do they attend workshops and/or in-house training during the last 5 years?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

11. When last did they attend any of the above?

....

12. What amounts of staffing levels are you looking at in order for you to function optimally?

A. Engineers:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

B. Technicians:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

C. Artisans:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

13. Any other contributing factor relating to above?

....

....

....

Section E: Resource Information:

1. How many air compressors?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

2. How many computers?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

3. How easy is it to obtain inventory data on a computer about water users serviced from a particular point?

....

4. How many instruments (i.e. repair, pipe-wrenches, spanners, etc.)?

A. Repair:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

B. Pipe-wrenches:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

C. Spanners:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

5. How many instruments (i.e. surveying equipment including GPSs, etc.)?

A. Surveying:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

B. GPSs:

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

6. How many water delivery main trunks are there in this area?

1 = < 2
2 = 2 – 4
3 = > 4

1	2	3

7. How much manpower (i.e. labourers do you often have)?

1 = < 2
2 = 2 – 4

1	2	3

3 = > 4

8. How many updated maps of the area are at your disposal?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

9. How many modes of transport (i.e. Vans, Trucks, Cars, Canoes, etc.)?

A. Vans:

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

B. Trucks:

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

C. Cars:

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

D. Canoes:

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

10. How many pump-stations are there in the area that is non-functional and operational?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

11. How many TLBs are operational in your entity?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

1	2	3

12. How many emergency water supply trucks could be made available in case of an emergency?

1 = < 2

2 = 2 – 4

3 = > 4

Section E: Human Capacity Information:

1. How many people operate the accounts section of this entity?

1 = < 2

2 = 2 – 4

3 = > 4

1	2	3

2. How easy is it to obtain any information about any of the water users?

....

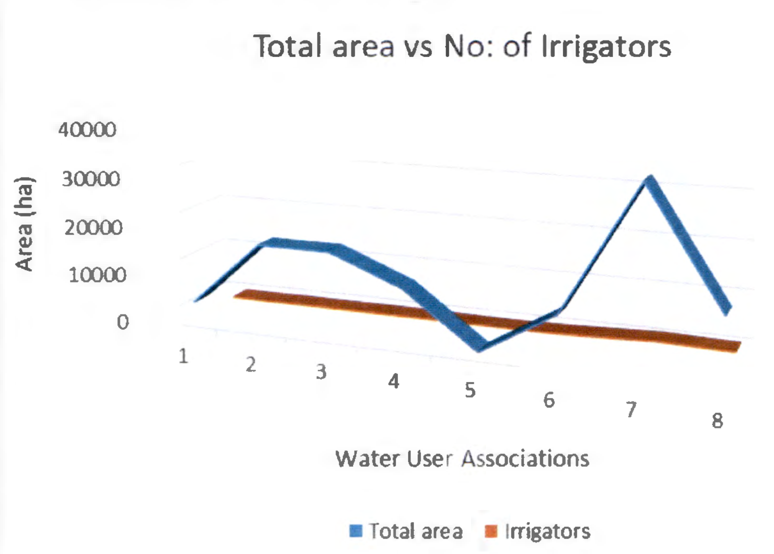
3. How easy is it to obtain inventory data on a computer about water users serviced from a particular point?

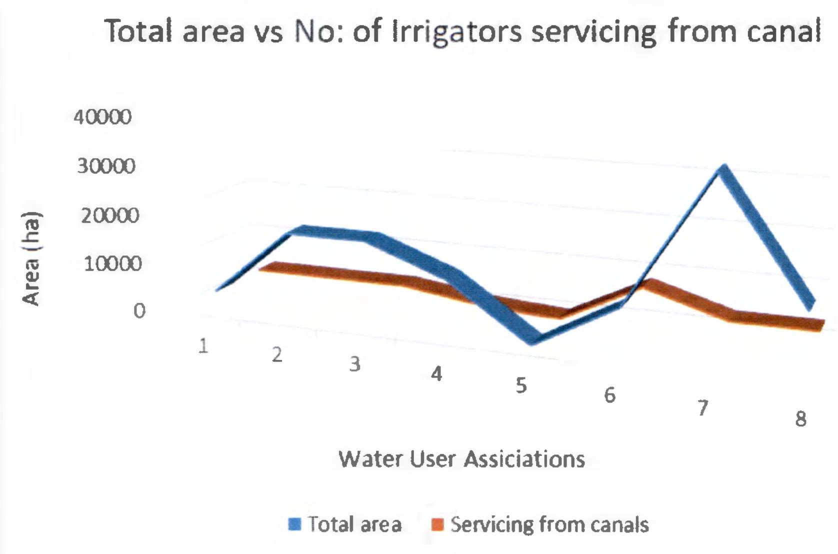
....

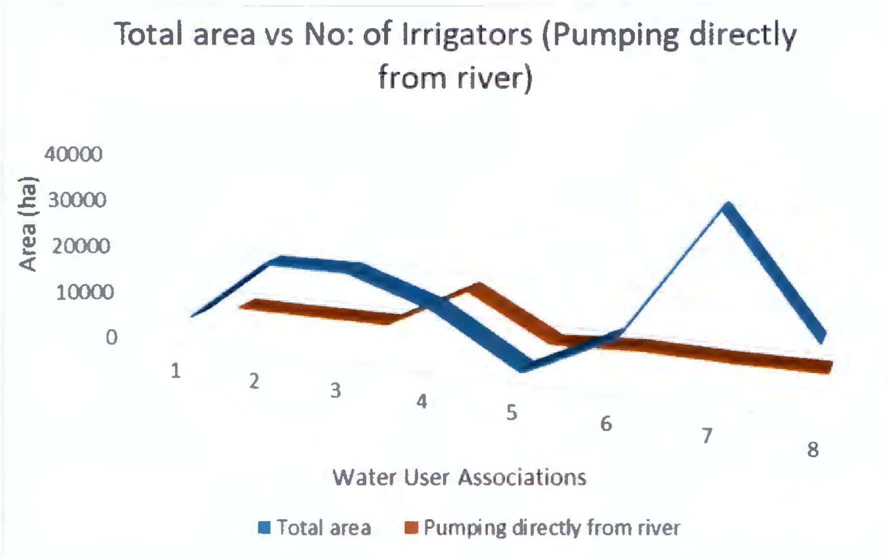
....

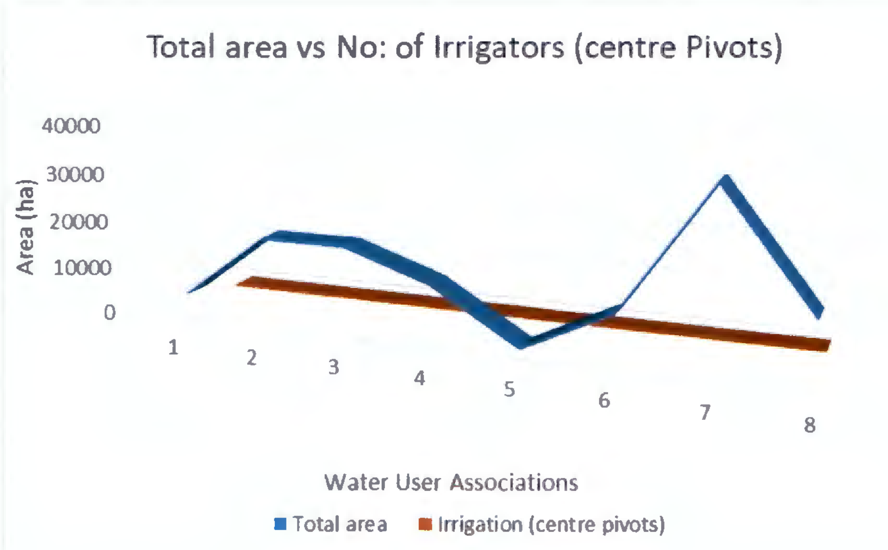
Thank you for your co-operation

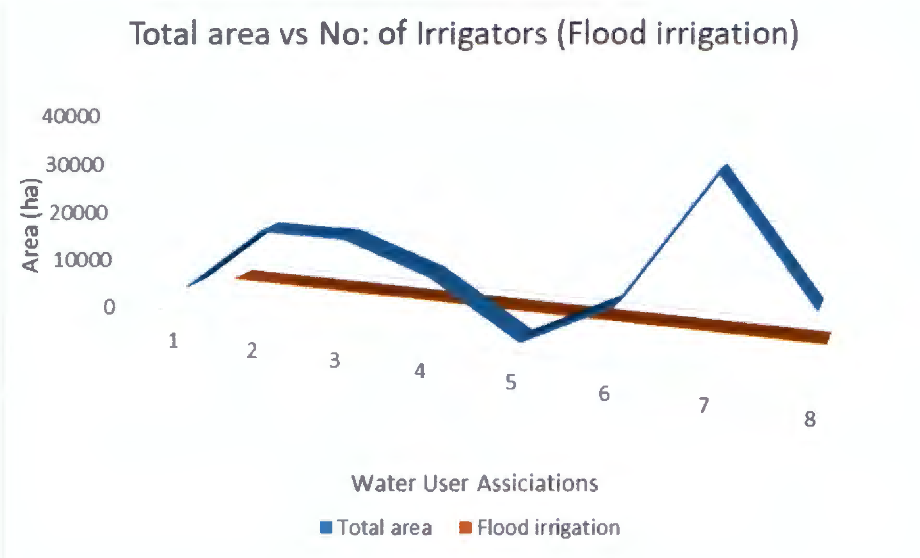
Appendix 2 – Statistical Tables and Graphs

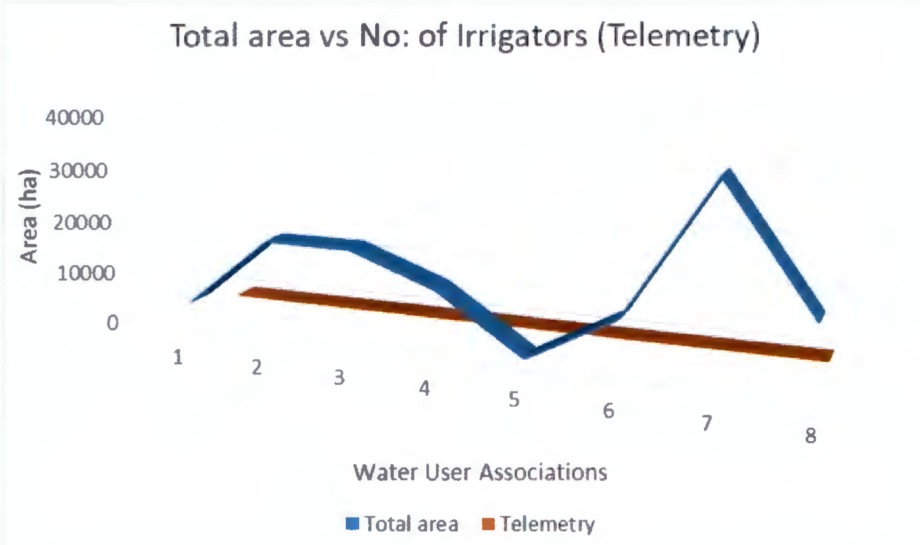


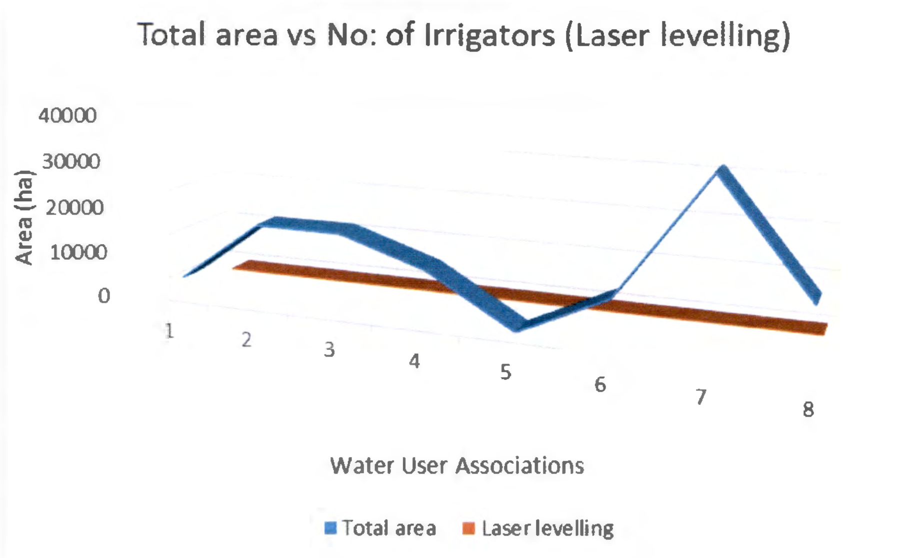


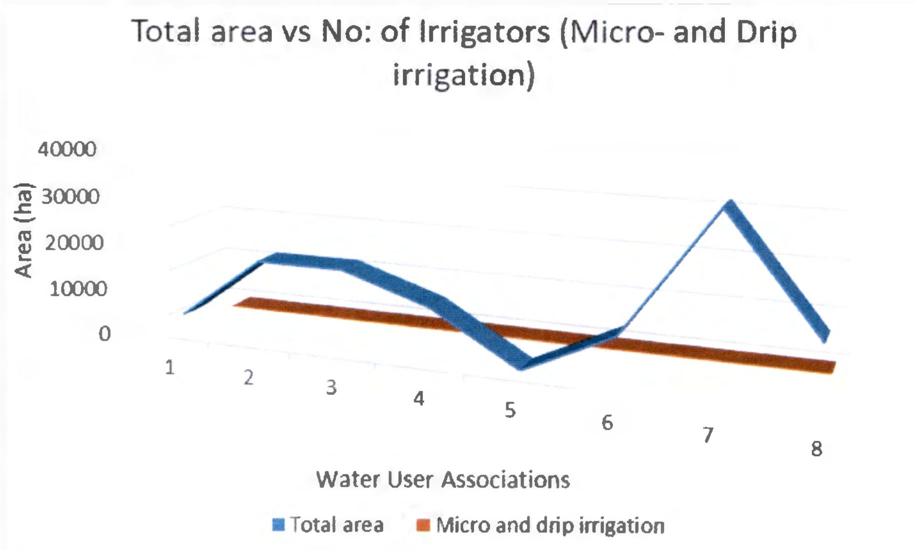

Total area vs No: of Irrigators (Pumping directly from river)
40000
30000
20000
10000
0
Area (ha)
1
2
3
4
5
6
7
8
Water User Associations
Total area
Pumping directly from river

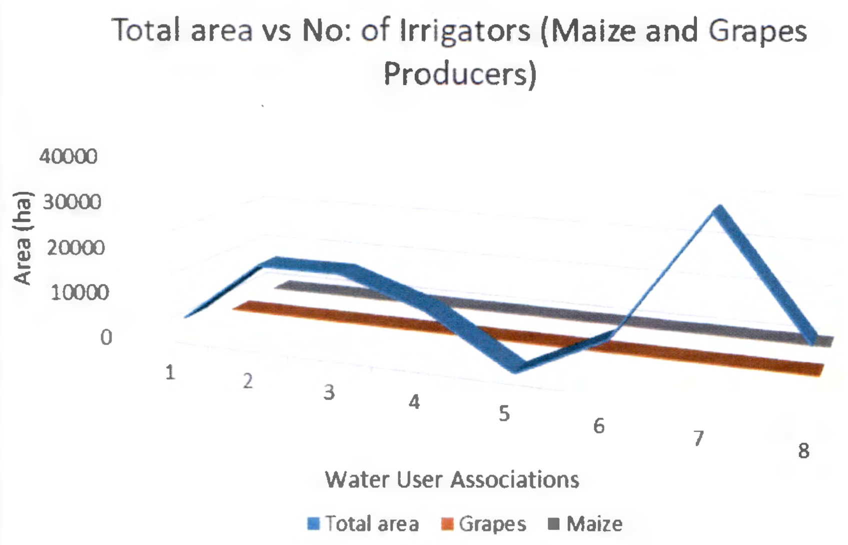

Total area vs No: of Irrigators (centre Pivots)
40000
30000
20000
10000
0
Area (ha)
1
2
3
4
5
6
7
8
Water User Associations
Total area
Irrigation (centre pivots)


Total area vs No: of Irrigators (Flood irrigation)
40000
30000
20000
10000
0
Area (ha)
1
2
3
4
5
6
7
8
Water User Assiciations
Total area
Flood irrigation


Total area vs No: of Irrigators (Telemetry)
40000
30000
20000
10000
0
Area (ha)
1
2
3
4
5
6
7
8
Water User Associations
Total area
Telemetry


Total area vs No: of Irrigators (Laser levelling)
40000
30000
20000
10000
0
Area (ha)
1
2
3
4
5
6
7
8
Water User Associations
Total area
Laser levelling


Total area vs No: of Irrigators (Micro- and Drip irrigation)
40000
30000
20000
10000
0
Area (ha)
1
2
3
4
5
6
7
8
Water User Associations
Total area
Micro and drip irrigation



Descriptive Statistics

	Mean	Std. Deviation	N
Water Allocation	13038.750	8362.5362	8
Total area	13237.375	10856.8211	8
Irrigators	302.625	286.9061	8
Servicing from canals	3301.750	2406.5469	8
Pumping directly from river	1644.563	3365.7053	8
Irrigation (centre pivots)	72.500	34.1216	8
Flood irrigation	10.000	12.9945	8
Telemetry	.125	.3536	8
Laser levelling	.000	.0000	8
Micro and drip irrigation	4.875	7.4726	8
Grapes	10.000	28.2843	8
Maize	26.375	19.9853	8
Wheat	17.125	18.4425	8
Lucerne	15.625	12.2350	8
Cotton	2.250	6.3640	8
Other crops	16.125	9.8914	8
Old Infrastructure	-1.250	3.5355	8
Industrial and Domestic Supply	-1.250	3.5355	8

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Industrial and Domestic Supply, Servicing from canals, Telemetry Total area, Maize, Pumping directly from river, Micro and drip irrigation[b]	.	Enter

a. Dependent Variable: Water Allocation

b. Tolerance = ,000 limit reached.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	1.000[a]	1.000	.	.	1.000	.	7	0	.

a. Predictors: (Constant), Industrial and Domestic Supply, Servicing from canals, Telemetry, Total area, Maize, Pumping directly from river, Micro and drip irrigation

b. Dependent Variable: Water Allocation

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	489524087.500	7	69932012.500	.	.[b]
	Residual	.000	0	.		
	Total	489524087.500	7			

a. Dependent Variable: Water Allocation

b. Predictors: (Constant), Industrial and Domestic Supply, Servicing from canals, Telemetry, Total area, Maize, Pumping directly from river, Micro and drip irrigation

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	-2.274E-12	.000		.	.		
	Total area	.155	.000	.201	.	.	.280	3.568
	Servicing from canals	2.120	.000	.610	.	.	.693	1.443
	Pumping directly from river	.366	.000	.147	.	.	.727	1.375
	Telemetry	-3.282E-12	.000	.000	.	.	.571	1.750
	Micro and drip irrigation	543.025	.000	.485	.	.	.210	4.773
	Maize	51.073	.000	.122	.	.	.756	1.323
	Industrial and Domestic Supply	486.941	.000	.206	.	.	.787	1.270

a. Dependent Variable: Water Allocation

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics		
						Tolerance	VIF	Minimum Tolerance
1	Irrigators	.[b]	.	.	.	.000	.	.000
	Irrigation (centre pivots)	.[b]	.	.	.	.000	.	.000
	Flood irrigation	.[b]	.	.	.	.000	.	.000
	Grapes	.[b]	.	.	.	.000	.	.000
	Wheat	.[b]	.	.	.	.000	.	.000
	Lucerne	.[b]	.	.	.	.000	.	.000
	Cotton	.[b]	.	.	.	.000	.	.000
	Other crops	.[b]	.	.	.	.000	.	.000
	Old Infrastructure	.[b]	.	.	.	.000	.	.000

a. Dependent Variable: Water Allocation

b. Predictors in the Model: (Constant), Industrial and Domestic Supply, Servicing from canals, Telemetry, Total area, Maize, Pumping directly from river, Micro and drip irrigation

Collinearity Diagnostics[a]

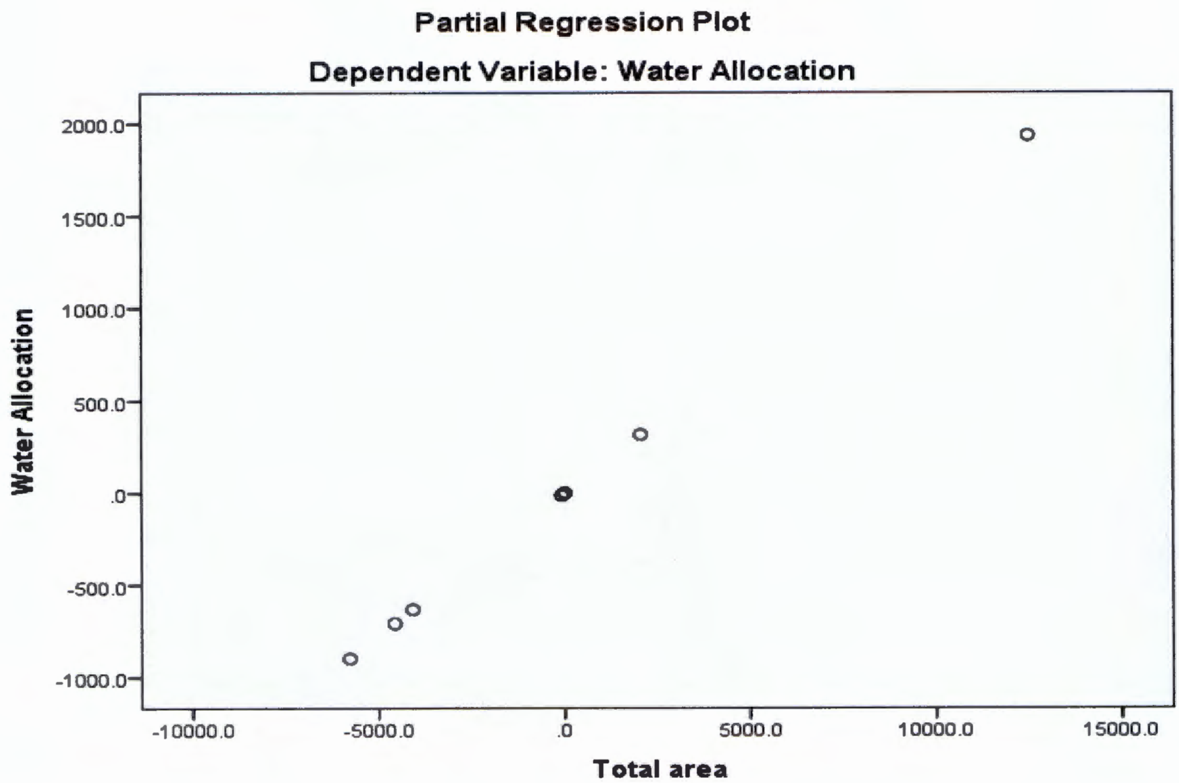
del	Dimension	Eigenvalue	Condition Index	Variance Proportions							
				(Constant)	Total area	Servicing from canals	Pumping directly from river	Telemetr	Micro and drip irrigation	Maize	Industrial and Domestic Supp
	1	4.233	1.000	.01	.00	.01	.01	.00	.00	.01	.
	2	1.157	1.913	.00	.00	.00	.16	.07	.03	.01	.
	3	1.045	2.013	.00	.00	.01	.16	.25	.00	.02	.
	4	.768	2.347	.00	.01	.00	.00	.09	.03	.01	.
	5	.381	3.334	.03	.05	.19	.18	.09	.05	.03	.
	6	.255	4.071	.00	.02	.21	.46	.01	.00	.45	.
	7	.109	6.232	.62	.06	.20	.03	.15	.08	.45	.
	8	.052	9.051	.34	.86	.37	.00	.33	.81	.03	.

)ependent Variable: Water Allocation

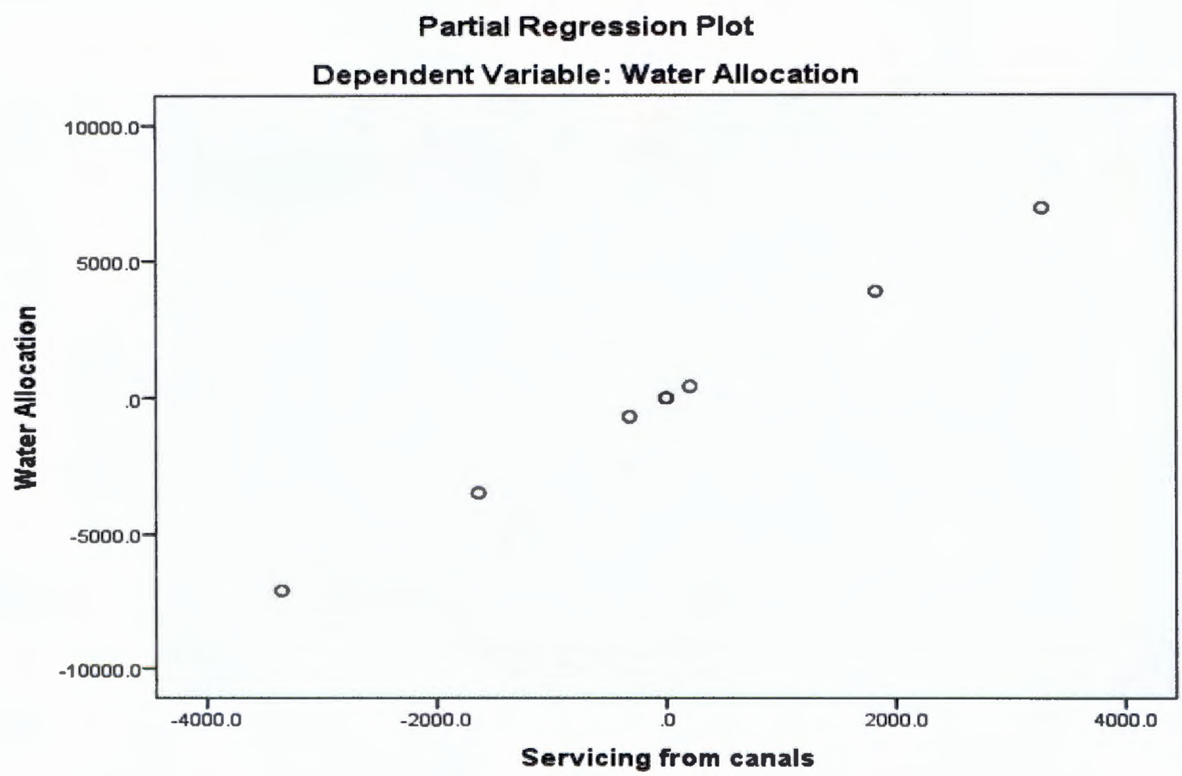
Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	.000	25310.000	13038.750	8362.5362	8
Residual	.0000	.0000	.0000	.0000	8
Std. Predicted Value	-1.559	1.467	.000	1.000	8
Std. Residual	.	.	.	.	0

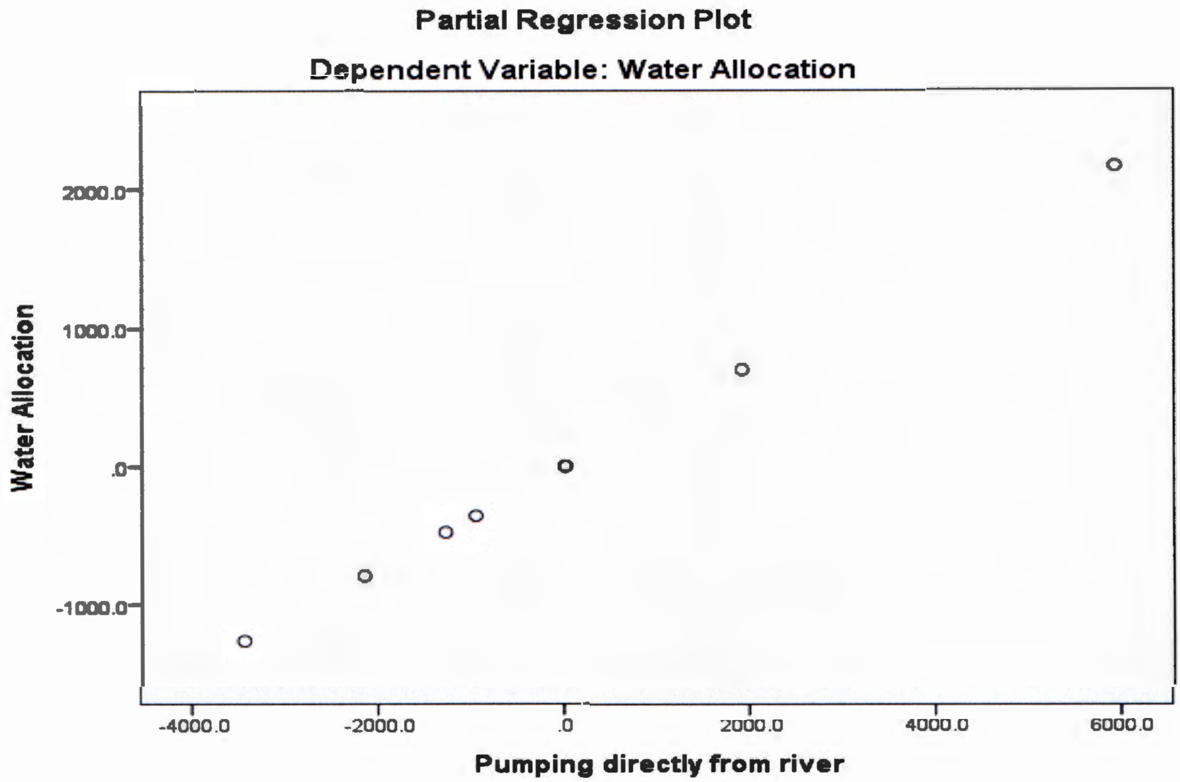
a. Dependent Variable: Water Allocation

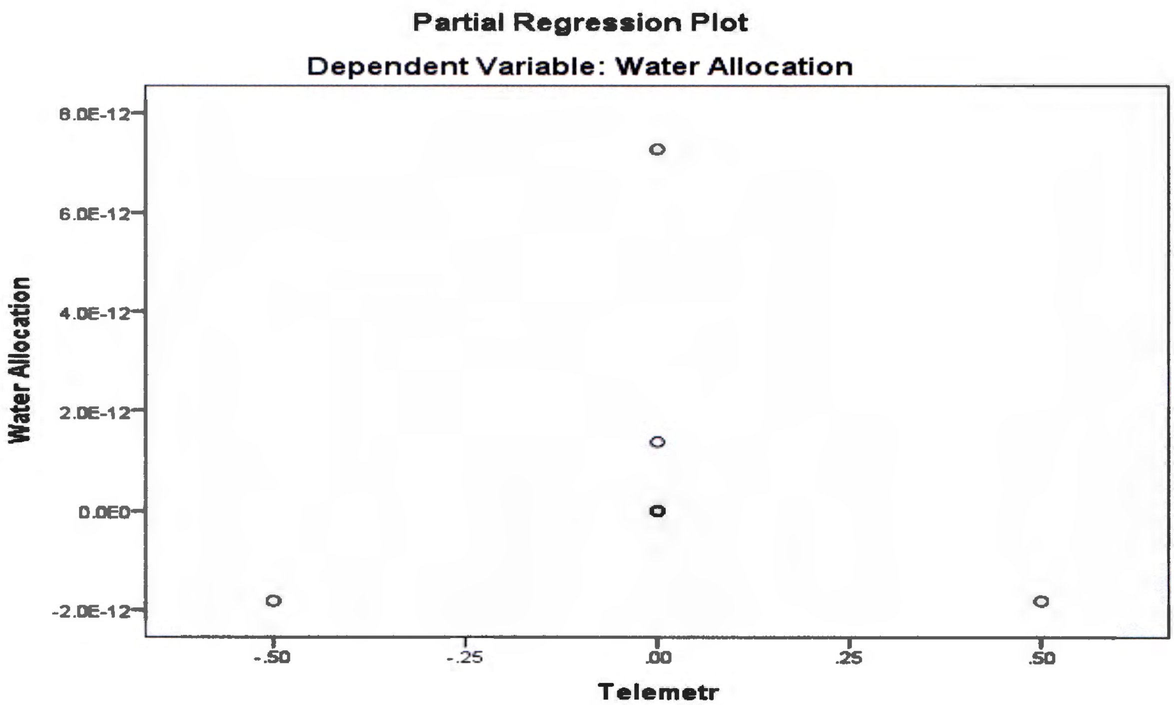


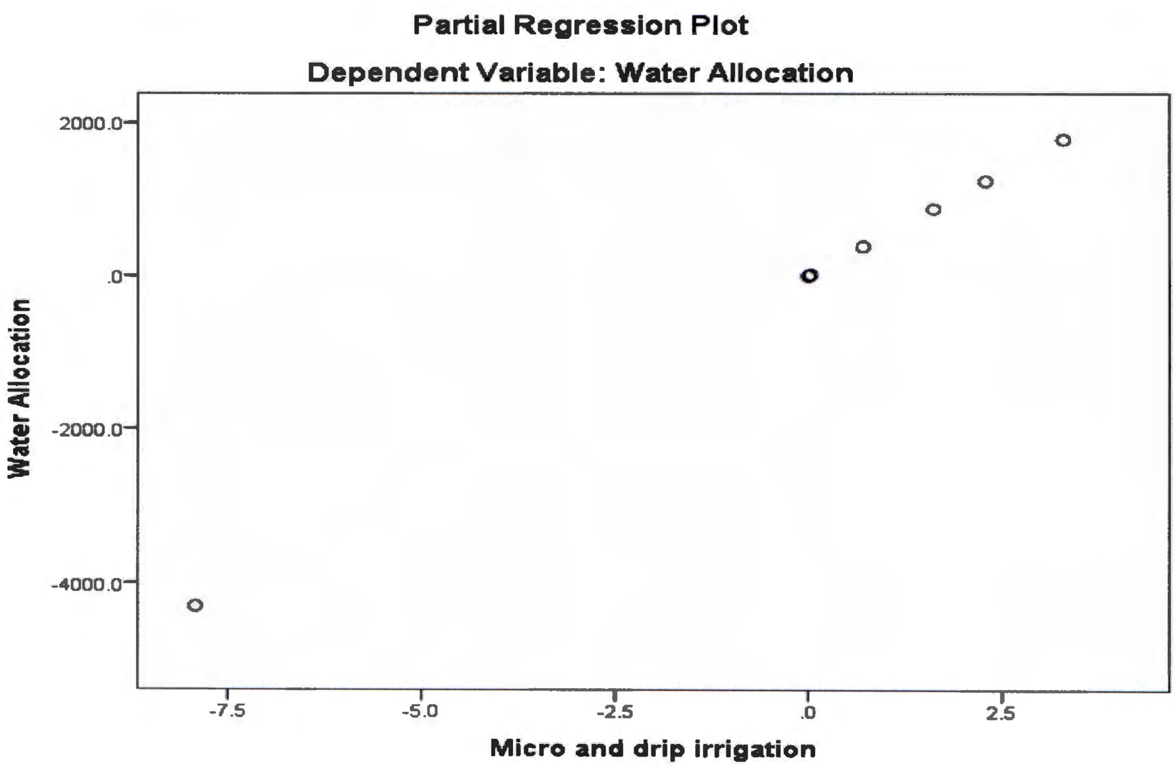
Partial Regression Plot
Dependent Variable: Water Allocation
2000.0
1500.0
1000.0
500.0
.0
-500.0
-1000.0
Water Allocation
-10000.0
-5000.0
.0
5000.0
10000.0
15000.0
Total area

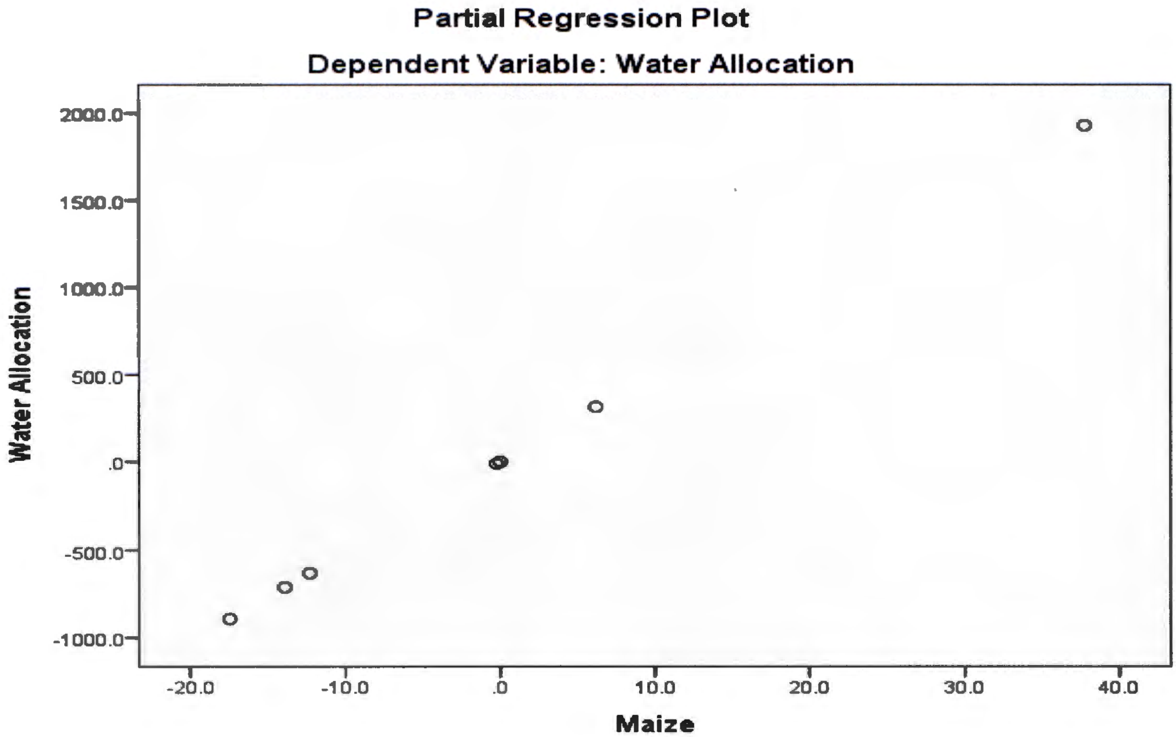


Partial Regression Plot
Dependent Variable: Water Allocation
10000.0
5000.0
.0
-5000.0
-10000.0
Water Allocation
-4000.0
-2000.0
.0
2000.0
4000.0
Servicing from canals


Partial Regression Plot
Dependent Variable: Water Allocation
Water Allocation
2000.0
1000.0
.0
-1000.0
-4000.0
-2000.0
.0
2000.0
4000.0
6000.0
Pumping directly from river


Partial Regression Plot
Dependent Variable: Water Allocation
8.0E-12
6.0E-12
4.0E-12
2.0E-12
0.0E0
-2.0E-12
Water Allocation
-.50
-.25
.00
.25
.50
Telemetr


Partial Regression Plot
Dependent Variable: Water Allocation
2000.0
.0
-2000.0
-4000.0
Water Allocation
-7.5
-5.0
-2.5
.0
2.5
Micro and drip irrigation


Partial Regression Plot
Dependent Variable: Water Allocation
Water Allocation
2000.0
1500.0
1000.0
500.0
.0
-500.0
-1000.0
-20.0
-10.0
.0
10.0
20.0
30.0
40.0
Maize

Appendix 3 – Publications and Conferences

The chapters of this thesis are based on the following publications and presentations that have been presented at various conferences:

Publications:

Mukwada, G., Manatsa, D., Mahasa, P., Taylor, S., Guy, R. Combating food shortages in a rapidly changing mountain climate: The case of Lesotho. *Land Use Policy* - Accepted.

Mahasa, P. S., Palamuleni, L. G. & Ruhiiga, T. M. 2015. Uncertainties in Techniques used to determine areas under Irrigation in the Upper Orange River Basin. *Hydrology: Current Research* **6**: 213. doi:10.4172/2157-7587.1000213.

Mahasa, P. S., Palamuleni, L. G. & Ruhiiga, T. M. 2015. The Upper Orange River Water Resources affected by Human Interventions and Climate Change. *Hydrology: Current Research* **6**: 212. doi:10.4172/2157-7587.1000212.

Conferences:

Water Demand Management in the Upper Orange River Basin, South Africa. ***Track Three: Sustainable Development on Environmental Sciences.*** International Conference on Disaster Risk Management for Sustainable Development (DRMSD 2017). NSD 2017 International Conference, Rochester Institute of Technology, Dubai (RIT). August 23rd - 25th 2017.

Water Demand Management in the Upper Orange River Basin, South Africa. ***Internationalisation of Higher Education for Sustainable Development (IHESD): Environmental Issues.*** The 4th International Interdisciplinary Conference (4IIC 2017), Kyambogo University, Uganda in Collaboration with Chukwuemeka Odumegwu Ojukwu University Nigeria; University of Eldoret Kenya; and Mount Kenya University, Kenya. August 1st - 4th 2017.

Irrigation Implications for the Upper Orange River through Remote Sensing and Evapotranspiration. ***The 3rd International Conference on Water Resource and Environment (WRE 2017),*** Qingdao, China. June 26th - 29th, 2017.

Remote Sensing and Evapotranspiration Mapping: Implications for the Upper Orange River Basin, South Africa – Part 3. ***The 170th International Conference on Environmental Science and Development (ICESD)*** on May 4th - 5th, 2017. Putrajaya, Malaysia.

Water Demand Management in the Upper Orange River Catchment, South Africa. ***The 2nd Africa Water Symposium in Conjunction with the 6th Orange River Basin Symposium*** held on the 7th - 8th October 2015. University of the Free State, Bloemfontein Campus.

Water Demand Management in the Upper Orange River Catchment, South Africa. 5th Annual Geography Doctoral Students and Post-doctoral Seminar. ***Geography in a Changing World.*** 08th September 2015. University of South Africa. Florida Campus.

Water Demand Management in the Orange - Senqu River Catchment of the Afro-montane Drakensberg, South Africa. WRC Khuluma Sizwe Series - ***Hydropedology in support of Hydrology and Eco-hydrology*** hosted by the Department of Water Affairs (DWA) and Water Research Commission (WRC) Monday, 17th November 2014, Venue: The Farm Inn Country Hotel and Wildlife Sanctuary, Pretoria.

Water Demand Management in the Orange - Senqu River Catchment of the Afro-montane Drakensberg, South Africa. ***Sustainable Rural Learning Ecologies Colloquium (SuRLEc) – 2014***, 29th - 31st October 2014, University of the Free State, Phuthaditjhaba.

Catchment Management and Water Resources of the Drakensberg Afro-montane, South Africa. ***Sustainable Rural Learning Ecologies Colloquium (SuRLEc) – 2014***, 29th - 31st October 2014, University of the Free State, Phuthaditjhaba.

Water Demand Management in the Orange River Catchment, South Africa. ***Science for Impact: Impact of Environmental and Health Sciences. Faculty FAST Day – 2014***, 17th October 2014, North West University (Mafikeng Campus), Mmabatho.

Water Demand Management in the Orange - Senqu River Catchment of the Afro-montane Drakensberg, South Africa. ***Society of South African Geographers' 10th Conference – 2014***, 22nd - 27th June 2014, University of Fort Hare, East London.