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ASSESSING THE IMPACT OF HUMAN BEHAVIOUR ON RESERVOIR SYSTEM PERFORMANCE USING DYNAMIC CO-EVOLUTION

Nura Jafar Shanono

A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Johannesburg, 2019

DECLARATION

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



……..
(Signature of Candidate)

14th ……day of **October, 2019**

ABSTRACT

Water resource systems management entails the coordination of hydrologic, infrastructural and human activities to plan, develop and supply water efficiently and sustainably. Hydrologic and human behaviour involve high levels of uncertainty and therefore pose unique challenges to water management. In reservoir yield and operation analysis, hydrologic uncertainties are usually incorporated in risk analysis using stochastically generated data but the impacts of human behaviour, although significant, are typically not incorporated. This study was therefore inspired by the need to quantitatively incorporate the impact of human behaviour into reservoir system performance thereby adding value to reservoir operational decision making. Unauthorised water abstraction is a significant human behaviour-related activity and was therefore selected for this study. A socio-hydrological model that simulates, couples and dynamically co-evolves reservoir operation and human behaviour to assess the impact of unauthorised water abstractions on reservoir yield and operation was developed. The model quantitatively and stochastically relates four-state drivers; hydrological state, users' compliance, management competence and reservoir performance. Users' compliance and management competence were modelled statistically by a 3-parameter skew-normal distribution and the propensity to unauthorised water abstraction (risk perception) was modelled as a function of users' compliance, management competence and the hydrological state. The occurrence of unauthorised water abstraction was modelled stochastically by relating a sigmoidal function of risk perception to management competence. To assess the impact of human behaviour, nine scenarios derived from the different combinations of 3 categories of users' compliance and management competence were developed and tested. The model was applied at a monthly time step to 2 hypothetical but realistic reservoir systems that were based on 90 years of hydrology and configuration of the Elands and the Olifants River reservoir systems in South Africa. Reservoir operation for maximizing yield was optimized by applying a simulation-optimization approach that used 3 reservoir operating rule curves defined

using trigonometric and simple linear functions. Shuffled complex evolution (SCE-UA) was used for optimisation.

The SCE-UA was effective for the optimisation of the two reservoir systems when simple linear operating rules were applied. When trigonometric rule curves were applied, the SCE-UA optimized the Elands system effectively but repeatedly terminated at a local optimum with 35% less yield for the larger Olifants system. It was therefore decided to mainly use the results from the linear rule curves to assess the effect of human behaviour on the performance of the two systems. Realistic time series of unauthorised water abstractions whose severity increased as users' compliance and management competence declined were obtained. The losses in average yield for varying combinations of users' compliance and management competence ranged from 2.3 to 9.2% and 5.3 to 11.5% for the Elands and Olifants systems respectively. The overall average loss in yield for all the nine scenarios were 5.8% and 8.9% for the Elands and Olifants River systems respectively. The losses in yield in individual years, however, varied considerably and during the drought years of the 90 year simulation period, they were much higher than the average losses. In one year, a 55% reduction in yield resulted from the scenario with the most adverse human behaviour. Optimised reservoir operating rule curves became more restrictive and lower reservoir storage trajectories were obtained as human behaviour declined. The modelling, therefore, revealed that yield reduced as human behaviour deteriorated and the losses obtained were reasonably close to the reported annual water loss due to unlawful uses of 6.4% in South Africa. The sensitive nature of the subject of study makes model verification on real-life systems challenging. However, the research shows that practical reservoir system modelling that quantitatively incorporate the impact of human behaviour is a future possibility.

DEDICATION

To my late uncle,

Alhaji Malam Muhammad Namama Muhammad Abdullahi Shanono

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LIST OF ABBREVIATIONS

CCE	Competitive Complex Evolution
CHANS	Coupled Human and Natural Systems
CMS	Catchment Management Strategies
COMEST	World Commission on the Ethics of Scientific Knowledge and Technology
CV	Coefficient of Variation
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EA	Evolutionary Algorithm
EFR	Environmental Flow Requirement
ELWU	Existing Lawful Water Use
EWR	Ecological Water Requirement
GA	Genetic Algorithms
HDI	Human Development Index
HS	Hydrological State
IAHS	International Association of Hydrological Sciences
IAM	Integrated Assessment Models
ICMA	Inkomati Catchment Management Agency
ISP	Internal Strategic Perspective
IWRM	Integrated Water Resources Management
IWRP	Integrated Water Resources Planning
KNP	Kruger National Park
LHWP	Lesotho Highlands Water Project
MC	Management Competence
NDP	National Development Plan
NRF	National Research Foundation
NWA	National Water Act
NWRS	National Water Resource Strategy
OECD	Organisation for Economic Co-operation and Development
ORWMA	Olifants River Water Management Area
RDM	Resource Directed Measures

RP	Risk Perception
RQO	Resource Quality Objectives
SAM	Strategic adaptive management
SCE-UA	Shuffled Complex Evolution
SDC	Source Directed Controls
SDGs	Sustainable Development Goals
SESs	Social-Ecological Systems
SHSs	Socio-Hydrological Systems
S-O	Simulation-Optimisation
SPI	Social Progress Index
SYR	Storage–Yield–Reliability
UC	Users' Compliance
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
V-STEEP	Values, Social, Technology, Economy, Environment and Policy
WAMI	Water Allocation Monitoring Index
WAR	Water Allocation Reform
WCWDM	Water Conservation and Water Demand Management
WMA	Water Management Area
WMR	Water Management Region
WPI	Water Poverty Index
WR2012	South Africa Water Resource Study - 2012
WRC	Water Research Commission
WRS	Water Resource Systems
WRSA	Water Resources Systems Analysis
WUAs	Water User Associations
WUE	Water Use Efficiency
WWAP	World Water Assessment Programme

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

The pursuit of sustainable natural resources utilisation is an integrated part of the ongoing 2030 agenda for sustainable development goals (SDGs). It is one of the 169 agreed targets being aimed at for monitoring and assessing the level of sustainability with which resources, such as water, are being managed (Osborn *et al*., 2015; Bartram *et al*., 2018). With the aim to change the current water governance regime for achieving the SDGs' goals, an international decade for action was recently launched (2018–2028), themed '*water for sustainable development*' (UN-Water, 2018). This is in response to concern about how to sustainably utilise the limited water resources in the face of rapid socio-economic development, and climate change. However, a problem that has been affecting the water sector, and attracted little attention, while also remaining elusive, is the impact of unlawful human activities (Groenfeldt, 2013) on this critical resource. Some of the reported activities adversely affecting the water sector include unlawful water abstractions, improper water usage (wastage); poor acceptance of water re-use measures, and excessive operational losses. Others comprise contamination of water bodies by discharging untreated or improperly treated wastewater, over-application of chemicals in agricultural activities, and fraudulent system operation. Although adherence to water ethics in addressing these undesirable human activities thereby achieving water management goals has been stressed (Falkenmark & Folke, 2002; UNESCO, 2011), to date, these issues have not been explicitly addressed.

Ethics are codes of conduct governing human behaviour with which human actions are judged as either ethical or unethical (Ssonko, 2010; Cameron *et al*., 2004). Globally, ethics-centred approaches such as water conservation campaigns and participation, monitoring compliance, and enforcement, policy dialogues, legal actions, and other demand management measures have been reported to improve water management (Liu *et al*., 2009; WGF, 2000, 2016). Conversely, unlawful human

activities are reportedly linked to the deterioration of the water sector (Plummer & Cross, 2006; Hermann-friede *et al*., 2014; SABPP, 2013; WWAP, 2017).

In South Africa, reservoirs are a major feature of the water resource systems, and reservoir operation is, therefore, an essential aspect of the country's water management. Reservoir operation is a challenging water management task, and when behaviour-driven problems arise, it may turn out to be even more complicated. The South African Department of Water and Sanitation (DWS) identifies unlawful water use as one of the major problems affecting the water sector. However, many stakeholders consider the low implementation level of water laws as the main cause of these problems (DWA, 2012). According to Mckenzie *et al*., (2012) the total water loss in South Africa amounts to 31.8 % of which 6.4 % is considered as commercial losses due to unlawful use and meter inaccuracies. The annual total water loss and water loss due to unlawful use are estimated to be 1,366 and 275 million m^3 respectively. Illegal abstraction locations exist, and several of them were identified in the farming areas of the Western Cape Province in 2017 (Philanda, 2017).

Another case in point, which has reportedly been linked to the role of human behaviour, is the Cape Town water scarcity crisis (Muller, 2017). Water conservation and water demand management (WC/WDM) measures were implemented, and a considerable reduction in consumption was recorded from 2011 to 2014. It was then presumed that no water resource development was needed until 2024, if water users in the city maintained this behaviour. However, in 2015, the city's water consumption significantly increased, due to a change in users' behaviour with regard to the WC/WDM measures. The situation is also suspected to have been exacerbated by the failure to impose restrictions on time, and by over-allocation to agricultural users, in addition to the prolonged drought condition (Muller, 2017). This reveals that the inter-play between human behaviour and hydrological conditions is highly uncertain, but essential to be incorporated into water resources management. Hence, it is crucial to initiate, and develop practical methods for explicitly incorporating human behaviour in reservoir planning, operation, and yield analysis.

Although freshwater is plentiful in some parts of the world, it is scarce in some regions such as Southern Africa (Basson e*t al*., 1994). To address the potentially conflicting water demands in such regions, water managers need to account for all losses, thereby improving the performance of existing reservoirs *(*Yu *et al*., 2013; Kuria & Vogel, 2014). Such non-structural risk reduction measures have been identified as an imperative option, due to limited sites for constructing new reservoirs (Basson & Van Rooyen, 2001; Ndiritu, 2005; WWAP, 2018). South Africa is a water-stressed country, due to several factors including droughts, socio-economic growth, unlawful water use, and excessive operational losses. It has been predicted by the Department of Water Affairs and Forestry (DWAF) that unless consumption patterns change, by 2025 the country may not be able to sustain its water demand (DWAF, 1997a). Recently, studies revealed that the country's demand-supply deficit could reach 17% by 2030, if the demand continue to grow at the current rate (DWS, 2018; Colvin & Muruven, 2017). This agrees with the assertion that water demands are expected to escalate in countries with emerging economic development, such as South Africa (WWAP, 2018).

Moreover, South Africa faces the most severe surface water scarcity in Sub-Saharan Africa (see Figure 1.1) (Burek *et al*., 2016). As of January 2018, the DWS categorised the flow in 243 (43%) of South Africa's 565 rivers as low or very low, which means the country's overall water crisis is not limited to the Western Cape (Donnenfeld, 2018). Several studies have highlighted the risk of water scarcity in Southern Africa (McMahon *et al*., 2007; Pietersen *et al*., 2008; Wada *et al*., 2016).

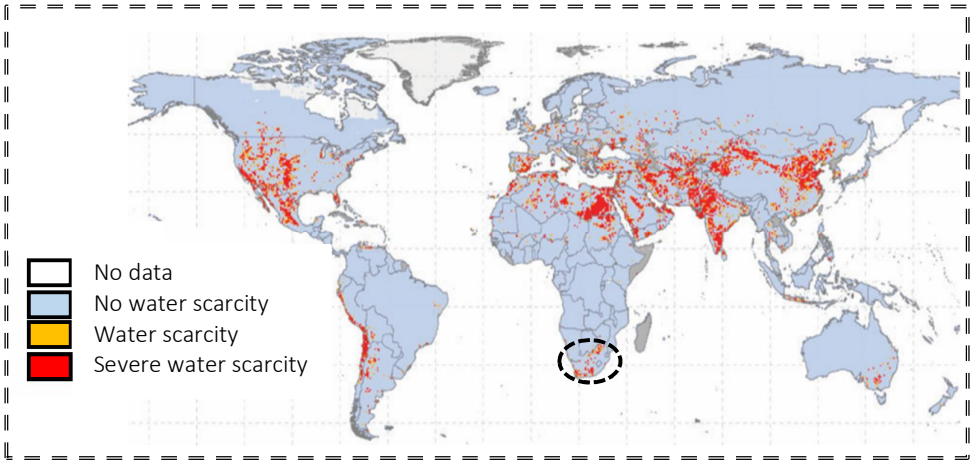


Figure 1.1: World map showing the severity of water scarcity (Burek et al., 2016)

In its effort to act against such prolonged severe water scarcity, the DWS proposed alternative ways to reduce water demand, and increase its availability, as highlighted in the second National Water Resource Strategy - NWRS2 (DWS, 2013c). These alternatives include WC/WDM measures, desalination, wastewater re-use, improving rainwater harvesting techniques, and the increased utilisation of groundwater. However, none of these alternative measures consider the dynamics of the causes, and the effects of the probability of changing water users' behaviour over time.

Several studies have revealed how human activities impact on water systems, or how water systems influence stakeholders' decisions (UNESCO, 2011; Groenfeldt, 2013; Firoz *et al*., 2017). However, these studies were typically conducted in the form of a one-way analysis. It is only recently that research on the interactions, feedbacks, and co-evolutionary dynamics of the linked human-water systems, termed socio-hydrology, has been formalised (Sivapalan *et al*., 2012). Socio-hydrology is a recent inter-disciplinary field of study, which encompasses many disciplines, such as hydrology, sociology, ecology, philosophy, anthropology, and economics, among others. Socio-hydrology aims to study the interplay, and the co-evolutionary dynamics that are due to the complex interactions, and feedbacks between humans and water systems (Montanari *et al*., 2013; Savenije, 2015). This aims to effectively bridge the existing human-water gaps by integrating the social, cultural, economic, and environmental aspects of water, through coupling the social and hydrological drivers that act as the missing links (McMillan *et al*., 2016). Socio-hydrological models are usually developed, and applied to analyse the impacts of changing societal norms and values (behaviour) on water systems, and vice versa (Sivapalan *et al*., 2014). Figure 1.2 shows a conceptualised socio-hydrologic interplay in the context of water resource systems (WRS) management.

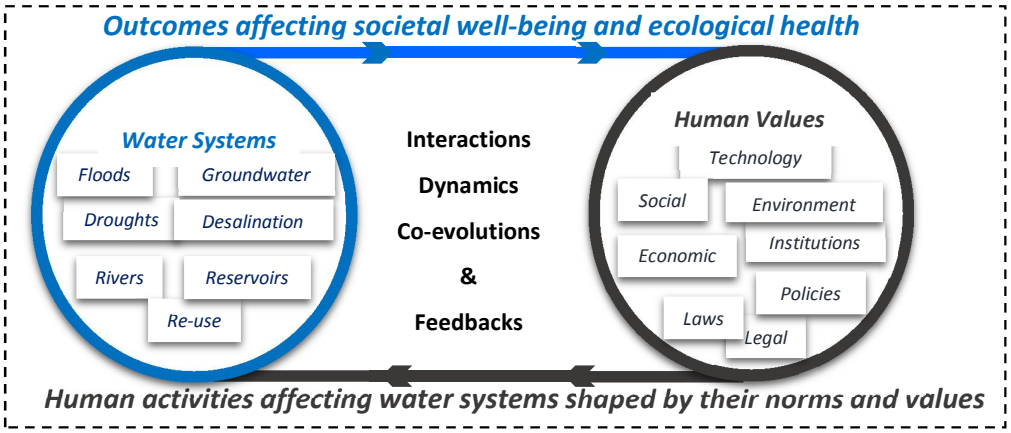


Figure 1.2: Interplay between human and water in the context of WRS

For example, reservoir analysis has been used to determine yield potential under various physical and hydrological constraints (Basson *et al*., 1994), but this does not incorporate the impact of human behaviour. Figure 1.3 schematically compares the conventional, and the socio-hydrological approach to reservoir yield analysis.

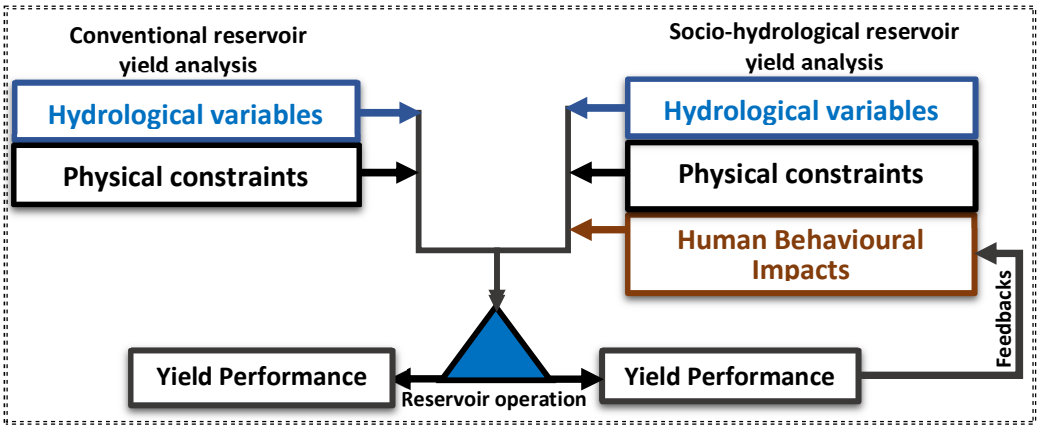


Figure 1.3: Conventional and socio-hydrological approach to reservoir yield analysis

1.2 Statement of the Problem

Water management entails the coordination of hydrologic infrastructures and human activities to efficiently, and sustainably supply water to meet various demands. However, the current issue of concern is the global increase in water demand, which amounts to about 1% annually (WWAP, 2018), and is reportedly linked to socio-

economic growth, climate change, and unlawful human activities. Demand dynamics as well as hydrologic and human behaviours involve high levels of uncertainty, and, therefore, pose unique challenges to the management of water resources. In reservoir yield analysis, demand dynamics, and hydrological uncertainties are typically incorporated, using risk analysis that usually includes the use of stochastically generated data. However, the impacts of unlawful human activities on yield, though significant, are typically not explicitly incorporated into reservoir planning, and yield analysis, and ideal human behaviour is often assumed.

Several unlawful activities have been reported to affect the water sector, but this study is restricted to unlawful water abstraction, which has been found to significantly affect WRS performance (van Oel *et al*., 2008; Baleta & Pengram, 2014). Although South Africa is a water-scarce country the problem of illegal water abstraction is persistent (DWS, 2016; Philanda, 2017), as a significant 6.4% of the country's resource is considered as commercial loss which involves unauthorised consumption and meter inaccuracies (Mckenzie *et al.*, 2012).

Despite advances in reservoir analysis incorporating human activities to assess their impact on reservoir yield quantitatively, solutions remain elusive. Water planners and managers often employ structural risk reduction measures to meet the ever-increasing water demand, with little consideration of non-structural measures. In South Africa, substantial capital investments have been made to construct new water infrastructures to meet water demands, rather than minimising losses, such as unlawful use (Chikwanda, 2011). Moreover, this has led to limited sites for constructing new reservoirs (Basson & Van Rooyen, 2001; Ndiritu, 2005). In addition, water user associations (WUAs) have been found to lack enthusiasim for minimising unlawful abstractions (DWA, 2012).

Although some non-structural risk reduction measures like WC/WDM are in place in some catchments, there is a need to dynamically consider the impacts of unlawful activities relating to water abstractions. To achieve this, the causes and effects of such unlawful human activities need to be explored, well-understood, and realistically incorporated into analysis for decision support. The primary cause of this problem is

considered to be a resource shortfall (drought), which is linked to the escalation of water consumption due to users' perceived threat to their quality of life (van Oel *et al*., 2008; Elshafei *et al*., 2014; Firoz *et al*., 2017). Also, ineffectiveness in enforcing water laws and other situational factors related to water users has contributed immensely to this problem. Hence, a need to develop a reservoir operation model that integrates these aspects holistically.

Below are some specific problems which this study aims to investigate:

- Inexplicit incorporation of the effects of human activities in reservoir planning, and yield analysis results in a poor understanding of the quantitative impacts of human behaviour on reservoir system performance.
- No methodological framework that quantitatively relates human behaviour to reservoir system performance, and couples the two systems in such a way that they co-evolve, and vary dynamically with the reservoir hydrological state, has been found in the literature.
- Considerable studies of human impact on various water systems have been conducted, but human behaviour has not been explicitly modelled to quantitatively account for its effect on reservoir system performance.
- Although much attention has been given to studying the human-water inter-play in the field of socio-hydrology, very few studies relating reservoir system operation to stakeholders' behaviour have been found in the literature.
- A large proportion of socio-hydrological studies have focused on rivers, floodplains, and irrigation catchments as the hydrological sub-system. This study intends to apply socio-hydrological modelling to reservoir systems, since reservoir operation is an essential aspect of South Africa's water resource management, and human impacts on water management are significant.

1.3 Research Objectives

This section describes the general objective (aim) and specific objectives of the study.

1.3.1 Aims of the research

The objective of this research is to develop a reservoir operation-human behaviour socio-hydrological simulation-optimization model for assessing the impact of human behaviour on reservoir performance. Thus, the main aim is to incorporate the impact of human behaviour into reservoir operation holistically, in a manner that quantifies its impact.

1.3.2 Specific objectives of the research

The specific objectives are:

Objective 1

To investigate and identify critical behaviour-driven human activities that affect the performance of WRS, drawn from local and international experience, and to develop a socio-hydrological model for quantifying the impacts of human behaviour that enables the incorporation of feedback mechanisms between human behaviour, and the hydrological state of a reservoir system.

Objective 2

To develop a reservoir operation-human behaviour socio-hydrological model that simulates, couples and dynamically co-evolves human behaviour, and reservoir operation, and use it to quantify the impact of incorporating human behaviour on reservoir system performance.

Objective 3

To test and assess the practical applicability of the developed model in reservoir system operation, through the development of a simulation-optimisation modelling tool that optimises the yield performance and reservoir operating rules under varying levels of human influence.

1.4 Scope of the Study

Unlawful human activities relating to water abstraction have been reported to affect reservoir system performance adversely. This study is focused on the impact of unlawful water abstractions by irrigation users along the streamflows and other waterways, on reservoir performance as issues of illegal water use affect water sector substantially in South Africa. This requires the development of a model for quantifying the behaviour of the stakeholders of the reservoir system (irrigation users, and managers of the system). The developed behaviour quantification model is then incorporated into the reservoir operations simulation model in a manner that enables the dynamic co-evolution of the hydrological state, and human behaviour. The coupled reservoir operation socio-hydrological model is then used to quantitatively assess the impact of unlawful water use on reservoir system performance.

1.5 Overview of the Thesis

The thesis is comprised of seven chapters, which are summarised in Figure 1.4. The first chapter is the introduction. It provides the background of the study, problem

statements, and objectives. This chapter also highlights the research scope, and provides a general overview of the thesis. In the second chapter, an extensive literature review is provided, with the aim to position the present study in the theory of the inter-disciplinary subject of socio-hydrology, and the impact of human behaviour on WRS performance. The review chapter is categorised into three main parts:

i) Water management and hydrological studies (hydrological);
ii) Ethics of water use and management (social); and
iii) Interdisciplinary study of people and water (socio-hydrology).

In the third chapter, the conceptual and mathematical development of the stakeholders' behaviour socio-hydrological model is presented. This chapter also contains a description of the formulation of human behaviour scenarios, while chapter four provides a detailed description of the case study areas, and simulation-optimisation modelling set-ups.

The results obtained from one case study (The Elands River Reservoir System), and another case study (The Olifants River Reservoir System) are respectively presented, analysed, and discussed in chapters five and six. Chapter seven provides the summary, conclusions, limitations, contributions to knowledge, and recommendations as deduced from the study. Lastly, a list of references, and appendices are provided at the end of the thesis.

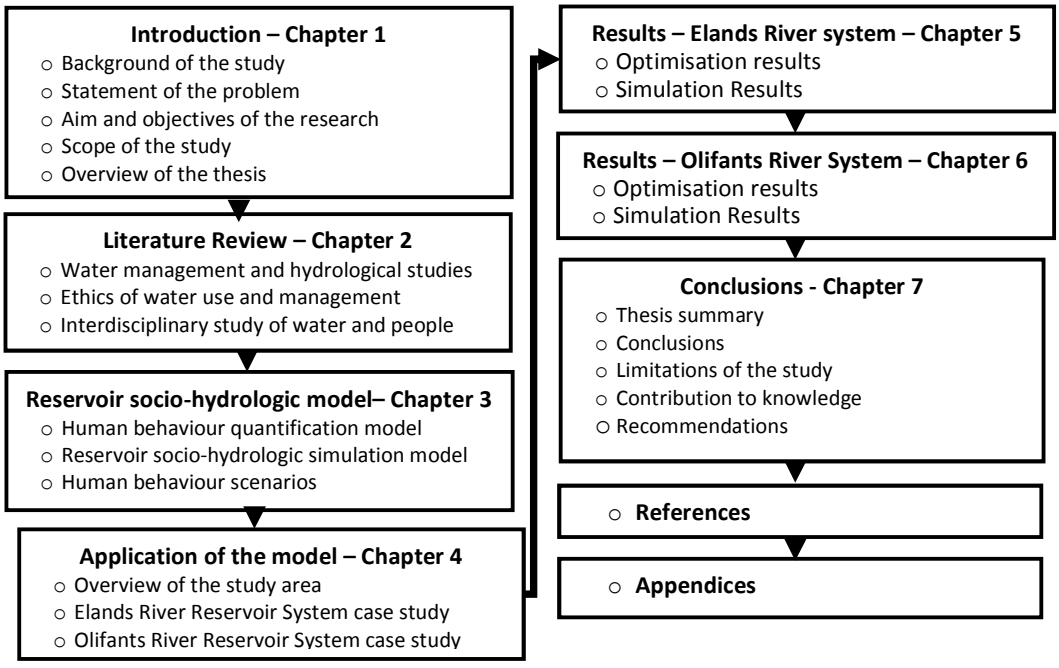


Figure 1.4: Summary of the thesis chapters

CHAPTER TWO

2.0 SOCIO-HYDROLOGICAL PARADIGMS IN WATER RESOURCE SYSTEMS PLANNING AND MANAGEMENT: A REVIEW

The aim of this chapter is to gain insight from past water related inter-disciplinary studies through an extensive literature review. This is done in order to position the present research in the literature, and theory of the inter-disciplinary subject of socio-hydrology. Also, to determine how stakeholders' propensity for compliant or unlawful activities relating to water abstractions change in the face of a changing hydrological state, and, also, how behavioural change impact on water resource systems' (WRS) performance. To achieve these, the review is broadly categorised into three parts:

1) Water management, and hydrological studies (*hydrological aspects*);
2) Ethics of water use and management (*social aspects*);
3) Inter-disciplinary studies on water and people (*socio-hydrological studies*).

2.1 Water Management and Hydrological Systems Studies

This section is the first of three categories of the review chapter which begins with a brief discussion on the role of water, both in human prosperity, and environmental health. The challenges encountered by water managers due to the inter-disciplinary nature of water management are also highlighted. The review pays more attention to the management, and operation of reservoir systems.

2.1.1 Interdisciplinary water management

Water is an essential element for life, economic growth, social well-being, and ecosystem health (OECD, 2011). Thus, water affects all aspects of human endeavours (Cilliers *et al*., 2013; Pollard *et al*., 2014), and in protecting the natural environment (Jackson, 2013; Odume & de Wet, 2016) and sustainable water management, and, therefore, entails meeting a balance between human and environmental needs (Wheater, 2014). These human and environmental water values pose unique challenges that call for inter-disciplinary frameworks for water management that holistically integrate these values (GWP, 2000; Max-neef, 2005).

The well-known and widely used inter-disciplinary framework for water management is Integrated Water Resources Management (IWRM), which aims to promote a sustainable water, land and other resources management system (GWP, 2000, 2005;

Hooper, 2006). IWRM requires cooperation between the public sector, civic society, and various disciplines (Falkenmark *et al*., 2004; Mostert *et al*., 2008). The framework has been in use in many countries for more than four decades, and serves as an essential benchmark for sustainable water management (Cardwell *et al*., 2006). It is, however, found to ignore the resulting impact and feedbacks due to the co-evolving dynamics, and complex interactions between various human and water components (Montanari *et al*., 2013). For example, the causes and effects of the stakeholders' propensity for compliant or unlawful activities relating to water use, water pollution and inefficient uses (*the ethics of water use*) have not been explicitly incorporated into IWRS (Groenfeldt, 2010; 2013).

2.1.2 The impact of human behaviour on water management

Water management entails planning, developing, and supplying water to various demands efficiently, and sustainably. The uncertainties associated with water sources, demand dynamics, and human activities make water management challenging. Water management is typically regarded as effective if it guarantees a reliable, and cost-effective water supply (Mogaka *et al*., 2006; Nkwonta *et al*., 2017). However, sustainable water management needs to incorporate the dynamics of the impact of societal responses (Carey *et al*., 2014; Walker *et al*., 2015), as these responses largely determine the success or failure of managerial goals (Rittel & Webber, 1973). Hence, the need arises to explicitly incorporate the realities of societal norms, and values (ethics) in both water policies and practices (Groenfeldt, 2010). It is, therefore, imprudent to make water management decisions without comprehending, and incorporating the impacts of human behaviour (Muller, 2017).

Effective water policies are usually developed using the outcomes of the possible future scenarios of the simulated WRS (Krueger *et al*., 2001; Murray-Rust *et al*., 2013). According to Walker *et al*., (2001), plausible future scenarios that incorporate societal responses dynamically lead to the development of robust policies. Therefore, incorporating the effects of human behaviour in WRS analysis could inform water decision and policy makers on the impact of societal responses (Haasnoot & Middelkoop, 2012).

2.1.3 Water resource status and management in South Africa

This section highlights the contextual issues in the South African water management sector that relate to the objectives of this study. It also informs about the key values operating in the country's water management strategies that relate to the objective of the study.

2.1.3.1 Hydro-climatic conditions of South Africa

South Africa is a water-scarce country with a relatively low mean annual precipitation of 497 mm, which is lower than the world average 860 mm, and is unevenly distributed in both time and space. It is characterised by a high annual evaporation of 1500 mm, low runoff, and high hydrologic variability (Basson & van Rooyen, 2001). According to a study of global stream flows (McMahon *et al*., 2007), the southern Africa region has the highest coefficient of variation of annual flows of 0.82, which is higher by far than the value of 0.22 in the South Pacific, which has the least variable flows in the world. It has been predicted that South Africa and other African countries (Morocco, Algeria, Tunisia, Libya, Egypt, Ethiopia, Somalia, Kenya and Malawi) will experience severe water scarcity by the year 2025 (Pietersen *et al*., 2008) . This prediction is in agreement with that of South African Department of Water Affairs and Forestry (DWAF), that the country may not be able to sustain water demand by 2025 unless water consumption patterns change (DWAF, 1997a). It appears that these predictions are valid, as recently highlighted in the 2018 water and sanitation master plan, and in the report on the scenarios for the future of water in South Africa. These reports indicated that the demand-supply deficit could reach 17% by 2030 (DWS, 2018; Colvin & Muruven, 2017). These hydrological issues pose unique challenges to the country's water planners, and managers.

With the aim to counter these challenges, and to attain a reliable water supply, many large, medium and small-scale dams have been constructed. Moreover, most of the large dams are operated in an integrated manner that includes substantial inter-basin transfers. Integrated implementation, and operation of systems also helps to spread the risk of failure (Basson & van Rooyen, 2001; Mckenzie & van Rooyen, 2002). These integrated methods of reservoir system operation across basins make South Africa's water management strategy one of the most sophisticated in the world (Groenfeldt,

2010). Other non-structural measures for reducing water demand, and increasing its availability, have also been proposed in the second National Water Resource Strategy (DWS, 2013c). These measures include water conservation and water demand management (WCWDM), desalination, further utilisation of groundwater, wastewater re-use, and rainwater harvesting (DWS, 2013c).

2.1.3.2 Fundamental values operating in South Africa's water sector

South Africa has long been transforming its water management sector, and the current strategy is based on three fundamental values, that underpin the water management plan adopted from the concept of IWRM (DWAF, 1997b). These values include equity, efficiency, and sustainability in allocating water to various demands (NWA, 1998). The aim of meeting the IWRM mandates led to the creation of two interdependent directorates. i) The Resource Directed Measures (RDM), to ensure water is being used efficiently and sustainably, and to prescribed Resource Quality Objectives (RQOs). ii) Source-Directed Controls (SDC), responsible for authorisations, registrations, licenses, permits, and imposing restrictions (DWA, 2010, 2013). The success of IWRM, however, also depends on the societal responses to the activities of these directorates, and the following questions, therefore, arise:

a) Do the stakeholders fully comply with these directorates?
b) What drives the stakeholders'level of compliance?
c) Moreover, how do stakeholders'level of compliance affect the performance of the water resource systems?

These questions need to be explored in order to understand the causes, and effects of social responses relating to water use on water management performance.

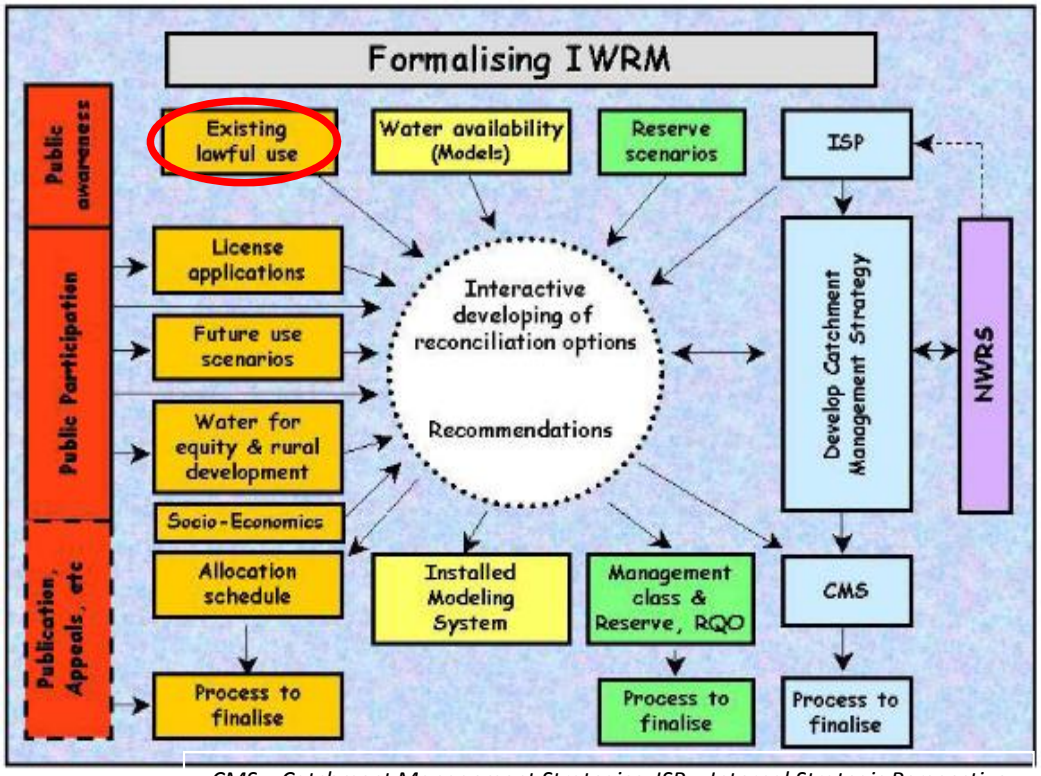
The Department of Water and Sanitation (DWS) is the custodian of South Africa's water resources with a mandate to achieve three key values using the set strategic plan. The first National Water Resources Strategy (NWRS-1) focused on the three values (equity, efficiency, and sustainability). NWRS-1 also emphasised applying the water research output, which has been facilitated by the Water Research Commission (WRC) (DWA, 2004). The second National Water Resources Strategy (NWRS-2) currently in use aligned its visions with that of South Africa's National Development Plan (NDP) '*vision 2030*' (DWS, 2013a; NDP, 2011). The main objectives of NWRS-2

include: i) to support social development and to eliminate poverty, and inequality, ii) to improve the economy, and job creation, iii) to sustainably plan, develop, and supply water (DWS, 2013c). However, the probable impacts of changing societal norms, and values on the objectives are not explicitly reflected in either of the two strategies. According to van Zyl (2001), the trend of increasing water demands in South Africa can only be met if measures for changing the way people use water are in place. Thus, to achieve NDP's 2030 vision, as envisioned in the NWRS-2, issues affecting stakeholders' propensity for compliance or unlawful water use are essential for strategic water management plans. The major water user sectors in South Africa comprised agriculture, industries and domestic. There several behaviour-related activites by water users that can adversely affect the performance of water management sector. For example, issues related to over-application of chemical and unlawful water abstractions by agricultural users, discharhing untreated or poorly treated wastewater by industrial users and poor acceptance of water conservation measures by householders (Plummer & Cross, 2006; Hermann-friede *et al*., 2014).

Figure 2.1 shows the summary of South Africa's strategic water management approach for achieving the IWRM mandate. Lawfulness of water use have been included in this strategic approach, and attempts to explicitly incorporate them into WRS planning, and operational analysis have persisted. Several efforts for tackling unlawful use, in the form of proposals, have been made in many water reconciliation strategy studies conducted across the South African water management areas. In the Olifants River, for example, seven strategies for reducing water demand, and increasing its availability, were proposed with different targeted dates (Beumer *et al*., 2011; DWA, 2011). These strategies include treatment of acid mine drainage water, removing alien plants, developing groundwater resource, and the re-use of return flows. The remaining three strategies listed below are behaviour-related:

i) Eliminating unlawful water use, with 2018 as the target date, after which compliance monitoring, and enforcement will remain an on-going activity;
ii) Implementing water conservation, and water demand management (WC/WDM) is expected to be achieved within five years in the irrigation and urban water use sectors, and within ten years in the mining sector, from the implementation date;

iii) Implementing water use efficiency (WUE) measures, especially in agricultural sectors, which will be traded back into the market by ensuring users are responsible for selling their water savings.



CMS = Catchment Management Strategies, ISP = Internal Strategic Perspective

Figure 2.1: South Africa's strategic plan for achieving IWRM mandate (DWAF, 2004a).

2.1.4 Managing WRS in the face of human behavioural impacts

A water resource system consists of inter-connected hydrologic, infrastructure, and human activities that involves water (Brown *et al*., 2015). The modern WRS constitutes a very complex system for supplying water, reducing flood risk, and meeting environmental needs. The quest for choosing the right combination of system variables that maximise benefits, and minimise costs for given constraints, are the main reasons for WRS analysis. Constraints can be economic, social, technical, or hydrological. One of the social problems of water management which has attracted little attention, and remains elusive, is unlawful practices relating to water use (Rammel *et al*., 2007; Groenfeldt, 2013). It is, therefore, crucial to note that managing WRS requires information from both physical, and social sciences (Cardwell *et al*., 2009; Loucks *et al*., 2005; Ceola *et al*., 2016). Hence, information related to causes of

such undesirable societal responses as unlawful water use, and their impacts need to be incorporated in the WRS planning, and operational analysis realistically.

Water managers around the world have for long been struggling to manage the limited resource in the face of demand dynamics, infrastructural development, and climate variability (Brown *et al*., 2015). The task involves predicting future challenges due to hydrological and demand uncertainties, and proposing alternative solutions (Loucks *et al*., 2005; Dolnicar & Hurlimann, 2010), and this has been the norm without incorporating human impact. For example, reservoir yield analysis typically incorporates hydrologic and reservoir characteristics without incorporating the impact of human behaviour, although it can affect system performance significantly. Thus, reservoir yield analysis requires the inclusion of the impact of human behaviour (Wang *et al*., 2013; Hunter *et al*., 2015; Muller, 2017; Zhang *et al*., 2017). This could be achieved if the causes and effects of unlawful activities relating to water abstractions are explored, well-understood, and realistically incorporated into the analysis (Ceola *et al*., 2016). It is expected that this would add value to reservoir planning, and operational decision making processes.

2.1.4.1 Incorporating human behavioural impact in WRS analysis

WRS planning involves organising, developing, and managing water (Beekman, 2002). The main aim of WRS management is to attain a balance between the availability, and the demand of the water (Nkwonta *et al*., 2017). WRS planning, and operational analysis have been conducted using the Integrated Water Resources Planning (IWRP). The Water Resources Systems Analysis tools (WRSA) is a tool for conducting IWRP (AWWA, 2001; Cohon & Marks, .1975; Rosenberg & Asce, 2014).The primary aim of IWRP is to strategise the system operation for an extended period (Palmer & Lundberg, 2003). Whereas WRSA evolves from pursuing optimal system performance to seeking insights into the complex interactions between humans and water (Cohon & Marks, 1975; *Weiskel et al*., 2007; Sivapalan *et al*., 2012). Therefore, the Water Resources Systems Analysis is an impact prediction tool for modelling the WRS processes to obtain insight into the future, in order to inform decision making.

Models are typically developed, and used to aid in quantitative impact predictions. The structure of models includes input data, objectives, and other plausible assumptions on how the real system behave under various scenarios. The quantitative predicted future events are the useful variables that are typically used in WRS operational decisions (Loucks & van Beek, 2017). The variables of the WRS analysis are usually hydro-climatic data, and physical characteristics only, though, unlawful activities which can affect WRS performance typically are not incorporated (Loucks *et al*., 2005). Several studies have reported inference about human activities that adversely affected water availability, and these can be grouped into three categories; i) unlawful water abstractions (Lanini *et al*., 2004; Ndiritu *et al*., 2017; DWS, 2016). ii) Water wastage behaviour (Dolnicar & Hurlimann, 2010; World Bank, 2015; Muller, 2017; DeOreo *et al*., 2011; Escriva-Bou *et al*., 2015; Blokker *et al*., 2010; Cahill *et al*., 2013). iii) Fraudulent system operation at the top management (IPCA, 2010; Transparency International, 2008). Although it has been acknowledged that these issues negatively impact on the WRS performance (Groenfeldt, 2013; Wanders & Wada, 2015), incorporating them into WRS analysis remains elusive (Brown *et al*., 2015) as human behaviour was acknowledged cannot easily be quantified and modelled.

Hence, there is a need to develop a modelling tool that can explicitly and holistically integrate hydrological, and social aspects of WRS, as explained in the concept of socio-hydrology (Sivapalan *et al*., 2012). By applying such models, the impacts of human behaviour could be incorporated into decision support systems for WRS management.

2.1.4.2 Application of WRS analysis tools in policy formulation

Water policies are the result of quantitative impact assessment studies under plausible scenarios, and are found to be robust when developed from an inter-disciplinary perspective (Hanak *et al*., 2011). Managing WRS is replete with value-related conflicts as it involves many stakeholders with varying contextual issues. WRS management is typically capital and interest-intensive, which requires authorisation from a long hierarchy of stakeholders, including political leaders, public and private agencies, civil societies, international organisations, and users (Loucks *et al*., 2005). Usually, WRS analysts handle such conflicts through assessing alternatives by

incorporating various anticipated stakeholders' issues using scenario analysis (Brown *et al*., 2015). Such scenarios are constructed, and fed into the WRS analysis models, and the changes observed from the outcomes due to these alternatives, are the policy decision variables. These outcomes are typically analysed, and compared with all sources of interest (economic, social, technical, financial, political, and environmental) to arrive at a desirable solution (Beekman, 2002; Palmer & Lundberg, 2003; WWAP, 2012).

2.1.4.3 Simulation and optimisation models for WRS analysis

2.1.4.3.1 Simulation modelling

Simulation modelling is the process of developing a prototype model of a real physical system, to analyse its behaviour (Maria, 1997). Reservoir hydrologic and physical variables are typically simulated to analyse system behaviour (Klipsch & Hurst, 2007), and simulation modelling has been extensively used in reservoir system analysis (Palmer & Lundberg, 2003; Joshi & Gupta, 2009b; Yu *et al*., 2013a; Kuria & Vogel, 2014). Some of these models are solely for yield analysis (Joshi & Gupta, 2009b; Tobergte & Curtis, 2013; Zarriello, 2002; Yu et *al*., 2013a) whereas, others are for integrated storage-yield-reliability analysis (Vogel & Bolognese, 1995; Vogel & Stedinger, 1987; Kuria & Vogel, 2015; McMahon *et al*., 2007a, 2007b; Ndiritu *et al*., 2017). Simulation modelling is also applied for rainwater harvesting analysis (Ndiritu *et al*., 2014; Su *et al*., 2009; Ndiritu *et al*., 2011). However, studies that explicitly incorporate the impact of stakeholders' behaviour, while simulating reservoir operation quantitatively to assess the impact of human behaviour on yield performance, have not been found in the literature.

2.1.4.3.2 Optimisation modelling

Optimisation modelling is an approach normally used to come up with an optimum solution (Rao, 2009). Decision variables are quantified with as aim to achieve a set of performance objectives. Objective functions are set to be maximised or minimised with respect to: i) variables that drive the system, ii) the dynamic nature of the variables and iii) constraints (Rao, 2009; Grames *et al*., 2015). When a crucial decision is required, a single performance objective is set, such as minimising the net costs or

maximising the benefits (Hanak *et al*., 2011). In WRS management, this single objective can be related to the cost of water allocation, construction of levee, hydroelectric production, or supply yield (Labadie, 2004; Ndiritu, 2005). According to Labadie (2004), operational efficiency of existing reservoirs can be improved, if the operational variables are systematically coordinated using optimisation modelling to arrive at an optimal solution. For example, optimisation modelling has been used to arrive at an optimum cost and the heights of levee systems that can ensure safety (Eijgenraam *et al*., 2014; Grames *et al*., 2015). Optimisation models have also been used to optimise reservoir system operating rules for optimum yield (Wei & Hsu, 2009; Zhou *et al*., 2016; Ndiritu *et al*., 2017b).

The conventional methods of optimisation includes linear and non-linear, geometric, discrete and differential dynamics, network flow, and stochastic programming (Labadie, 2004). More recently, heuristic methods of optimisation including genetic algorithms, fuzzy systems, and neural network-based optimisation have been developed (Rao, 2009). Among the traditional methods, the most preferred, and commonly used in reservoir analysis is linear programming, owing to its simplicity, efficiency, and effectiveness. The advantages of linear programming include: ability to solve large-scale problems efficiently, and ease of problem setup and solution (Labadie, 2004). Conversely, heuristic methods are based on rules-of-thumb, and various analogies that can be applied to both qualitative and quantitative data. Although heuristic programs have no termination assurance, even at local optimal solutions, they are capable of achieving global optimal solutions to problems where traditional algorithmic methods would fail (Labadie, 2004).

Genetic algorithms (GA) is a widely used heuristic method, which operates on the principle of survival of the fittest as hypothesised in Darwin's theory of evolution (Ndiritu, 2005; Rao, 2009; Nicklow *et al*., 2010). GA optimisation comprises of three heuristic processes of selection, crossover, and mutation, that are applied to probabilistically produce new populations repeatedly (Raju & Kumar, 2004). Each of these three steps contributes to the optimisation processes. Selection helps to weed out low performing members, thereby preserving the higher performing ones. Crossover searches for better combinations of the selected high performing

members, whereas mutation helps uphold diversity, and guide the search to new regions of the search space (Ndiritu, 2005). New populations of solutions whose offspring demonstrate high levels of fitness, are continuously generated and produced. The newly produced population is further evaluated, and tested until the termination criterion is reached, as shown in Figure 2.2 (Nicklow *et al.*, 2010).

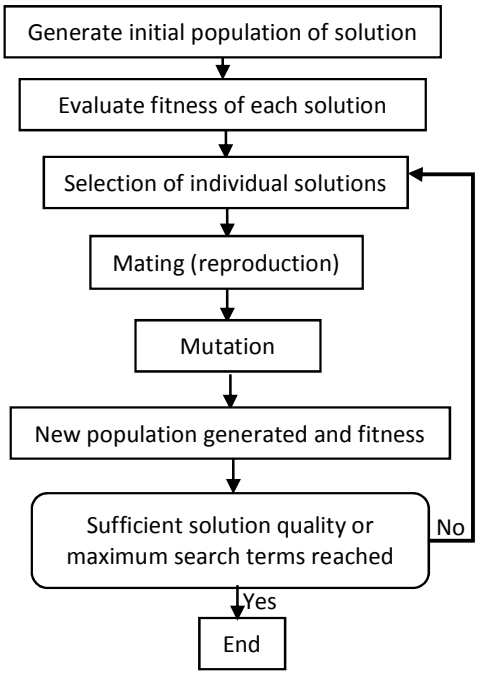


Figure 2.2: Operational framework of genetic algorithm (Nicklow et al., 2010).

The major disadvantage of GA, is the difficulty in accounting for constraints, and in maintaining feasible solutions. Constraints are indirectly taking into consideration through the use of penalty relations incorporated into the objective function (Raju & Kumar, 2004). The major advantage of GA is that it can easily be linked with other simulation models. Also, system performance measures can be incorporated into GA-simulation model linkage (Labadie, 2004). The GA-simulation method has been applied to a three-reservoir system to optimise the operating rule curves, and was found to perform better than Dynamic Programming and Regression, in both computational speed and objective value (Momtahen & Darian, 2006). The GA has been applied to irrigation water allocation problems under different weather conditions, and found to be effective (Sadati *et al.*, 2014). Ndiritu, (2003) used multi-population GA to optimise a reservoir system that supply to a monthly varying water

demands, and obtained optimal monthly operating rules. Several WRS analysis studies applied GA, and found it to be promising (Dibike & Velickov, 2001; Hinçal, Altan-Sakarya, & Ger, 2011; Sonaliya & Suryanarayana, 2014; Tang & Mays, 1998).

The Schuffled Complex Evolution (SCE-UA) (Duan *et al*., 1992, 1994) is another population-based evolutionary, and heuristic global optimisation method that combines deterministic, and stochastic search approaches. The SCE-UA algorithm was developed for parameter estimation in calibrating conceptual rainfall-runoff models (Duan *et al*., 1992), and is based on four principles: i) combination of probabilistic and deterministic approaches; ii) systematic evolution of a "complex" of points spanning the parameter space in the direction of global improvement; iii) competitive evolution; iv) complex shuffling (Duan *et al*., 1994). Initially, a random set of points (population) is sampled and is then partitioned into a number of complexes. Each of these complexes is then allowed to evolve using the competitive evolution techniques that are primarily based on the simplex method (Nelder & Mead, 1965). At periodic stages in the evolution, the entire set of points are shuffled, and reallocated to new complexes to enable information sharing. As the search progresses, the entire population is expected to move toward the vicinity of the global optimum, especially if the initial population size is adequately large.

The combination of competitive evolution, and complex shuffling guarantees that the information on the parameter space gained by each of the individual complexes is shared with the entire population. This leads to a more robust optimisation algorithm that searches the parameter space effectively (Duan *et al*., 1992). The SCE-UA is found to be almost twice as robust than traditional algorithm optimisation methods, due to its ability to use multiple complexes and shuffling (Thyer *et al*., 1999; Muttil & Jayawardena, 2008). Although SCE-UA has been widely applied to catchment model calibration (rainfall-runoff) (Duan et al.1994; Seong et al., 2015), it has also been employed in reservoir operation problems (*Lin et al*., 2008; Ngo, 2006; Ndiritu & Sinha, 2009; Ndiritu *et al*., 2017). Ndiritu & Sinha, (2009) used the SCE-UA method to parsimoniously optimise reservoir operating rule curves that maximise yield using a simple trigonometric function via simulation-optimisation modelling, and found it to be effective.

A comparative study between the GA and the SCE-UA methods has been conducted using the simulation-optimisation method to attain an optimum reservoir size, and operating rules. SCE-UA yielded the best objective, while GA was found to perform better in computationally demanding problems (Cui & Kuczera, 2003). Recently, Ndiritu *et al.*, (2017) applied the SCE-UA algorithm to develop probabilistic operating rules for Hluhluwe Dam, South Africa and found it to be effective.

The SCE-UA method contains different competitive complex evolution (CCE) algorithmic parameters on which the efficiency of the method relies, and the choice of these parameters must, therefore, be made carefully. Duan *et al*., (1994) analysed these CCE algorithmic parameters using different case studies, and a recommended a range of values (Table 2.1) which could guide users of the method. If these guidelines are applied, the number of complexes (*p*) is the only variable to be specified by the user.

Table 2.1: The CCE algorithmic parameters for SCE-UA method (Duan et al., 1994).

Parameter	Description	Range	Recommended value
p	Number of complexes	$p \geq 1$	-
m	Number of points in each complex	$m \geq 2$	$2n + 1$
q	Number of points in a sub-complex	$2 \leq q \leq m$	$n + 1$
β	Number of evolution steps taken by each complex before shuffling	$\beta \geq 2$	$2n + 1$
p_{min}	Minimum number of complexes required in the population	$1 \leq p_{min} \leq p$	p

n = number of decision variables

Table 2.2 presents the steps of the SCE-UA algorithm, whereas Figure 2.3 shows the flowchart of the SCE-UA algorithm (Duan *et al*., 1994; Duan *et al*., 1992).

Table 2.2: Steps of the SCE-UA algorithm (Duan et al., 1994)

Steps	Actions	Descriptions
1	Generate sample	A sample of points, i.e. parameter sets or sets of decision variables, are randomly generated from the feasible parameter space. For each parameter set, the objective function value is calculated. The initial sample has the size $s = p * r$. where p = number of complexes and r is the number of points in each complex
2	Rank points	Sort the s points in order of increasing objective function value so that the first point represents the point with the smallest objective function value (best point) and the last point represents the point with the largest objective function value
3	Partition into complexes	Partition the s points into p complexes, such that the first complex contains every $p(k-1)+1$ ranked point, the second complex contains every $p(k-1)+2$ ranked point, and so on, where $k = 1,2, \ldots\ldots, r$
4	Evolution	A sub-complex of size q is formed from the complex by randomly choosing q points. A triangular probability distribution is used for assigning the probability of a point to be included in the sub-complex (larger probability for points with smaller objective function value). The sub-complex is evolved according to the simplex algorithm (Nelder & Mead, 1965). Each complex is evolved β times.
5	Complex shuffling	Combine the points in the evolved complexes into a single sample of s points and return to step 2.

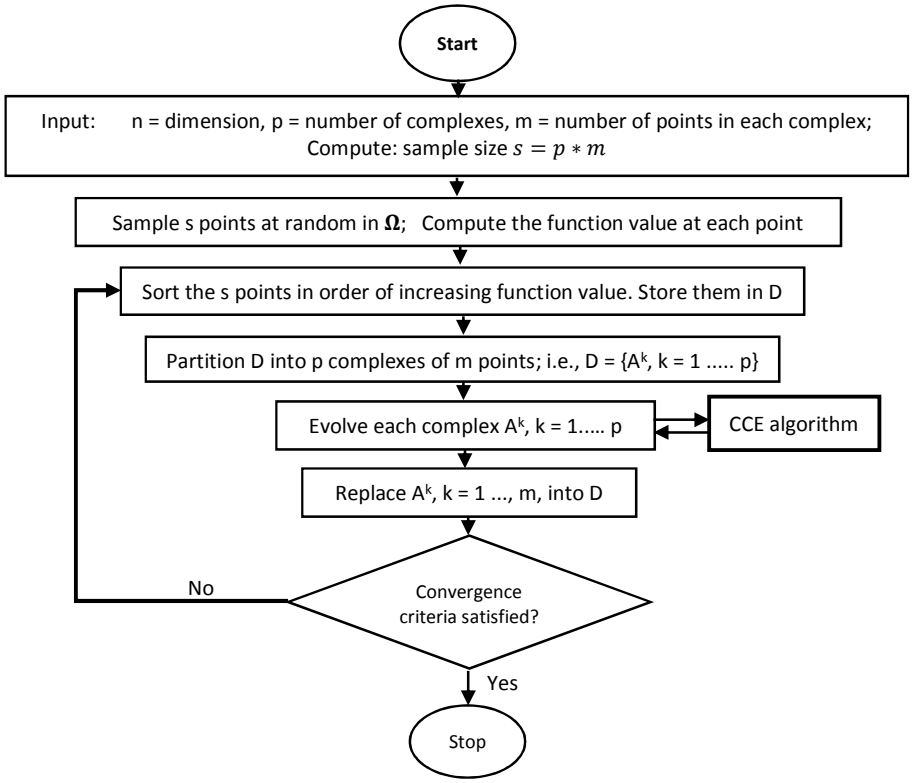


Figure 2.3: Flowchart of the SCE-UA algorithm (Duan et al., 1992)

2.1.4.3.3 Simulation-optimisation modelling

Population-based optimisation methods are often linked with the simulation models to perform an optimisation task (Ranjithan, 2005), in what is termed simulation-optimisation (S-O) modelling or mixed simulation, and optimisation modelling. S-O modelling involves generating the control strategies from different parameter sets, and for each parameter set, a simulation model is used to evaluate the objective function. An optimisation algorithm is then employed to modify the parameter sets for a better objective function, and therefore the optimum. This process is repeated until one of the termination criteria is satisfied. The S-O approach has gained acceptability, not only due to its ability to comprehensively incorporate the required system performance, but also its capability in handling computationally intensive problems (Ndiritu & Sinha, 2009). The S-O modelling has been used to link the reservoir analysis model with the genetic algorithm to maximise water yield under various reliability constraints (Ndiritu, 2005). Reservoir operation rule curves have also been optimised by linking simulation, and SCE-UA algorithms (Ngo, 2006; Ngo *et al*., 2007; Ndiritu *et al*., 2017). Other studies that have used S-O modelling in WRS management include Sechi & Sulis, (2009), Alemu *et a*l., (2011), Ahmed *et al*., (2013) and Fang *et al*., (2014). Figure 2.4 shows the framework of the S-O modelling for reservoir analysis (Ngo, 2006).

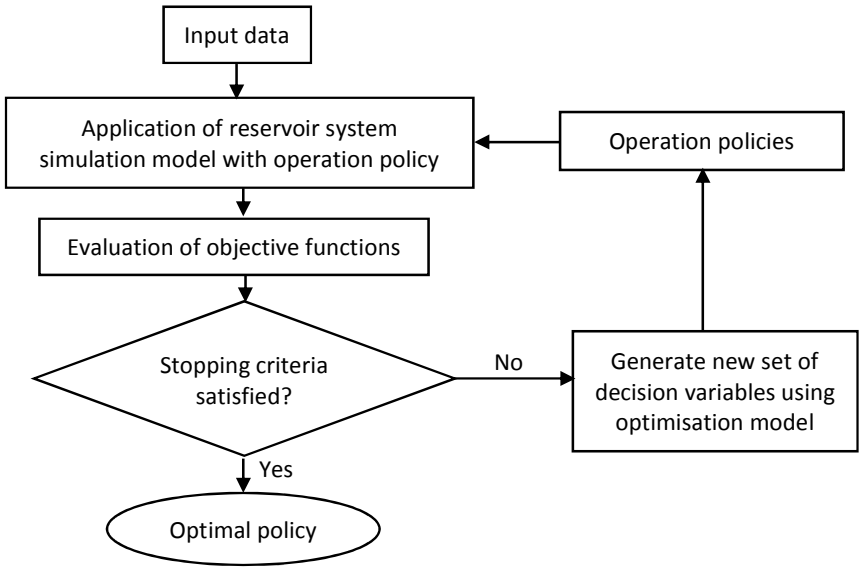


Figure 2.4: The S-O modelling framework for reservoir operation (Ngo, 2006)

Moreover, an approach that can reduce the number of decision variables without compromising the optimisation result, has been recommended by Ngo, (2006). In this regard, Ndiritu & Sinha, (2009) developed a parsimonious approach for defining optimum reservoir operating rule curves using a simple trigonometric function, which reduced the number of decision variables considerably. The function is defined such that it allows the rule curves to have a vast range of shapes to enable a vigorous search. Unlike in the free specification methods for defining reservoir operating rules curves, which requires about 36 parameters for a single reservoir, the trigonometric function uses only four (4) parameters for each reservoir. The function was linked with SCE-UA, and applied to a system with two reservoirs, and found to be effective. However, the optimum solution revealed no need for employing such a function in a system of two reservoirs with a similar objective function (Ndiritu & Sinha, 2009). The study informed that the simple trigonometric functions could, however, be applicable to more complex reservoir operation problems.

2.1.4.4 Scenarios and sensitivity analysis of the coupled models

This section presents the review on the application of the scenario analysis, and sensitivity analysis in the coupled models.

2.1.4.4.1 Scenario analysis

Scenario analysis has been used as a suitable method to explore the future in the presence of considerable uncertainties. Scenario analysis has been employed in the risk management-related researches aimed at developing robust and reliable strategic plans in the face of an uncertain future (*Krueger et al.*, 2001). It entails the description of a possible future situation, arranged in paths of development, which may lead to that future situation. Scenarios analysis are mostly applied in risk management, building consensus for change, monitoring progress, and changes and in predicting ,and gaining insights into the future (Kosow & GaBner, 2008). Scenarios are not meant to predict how the exact future situation could be, but to explore a range of future possibilities by considering alternatives. Scenario-based methods help to avoid various computational and conceptual problems, and it normally starts with the construction of storylines (Murray-Rust *et al.*, 2013). In the field of water

management, exploring the future with several alternatives could help water planners and managers to deal with uncertainties, and to make sustainable and prudent decisions (Haasnoot & Middelkoop, 2012; Kuzdas & Wiek, 2014).

2.1.4.4.2 Sensitivity analysis

Sensitivity analysis is the process for determining the approximate contributions of individual model parameters to the overall model output (Xu & Gertner, 2008). Such an analysis of a model's response (output) to its inputs (parameters), is required in order to determine which of the model parameters require calibration, so as to achieve an acceptable model performance. While calibration is used to obtain parameter values that maximise model performance, sensitivity analysis seeks to establish parameters that can positively and significantly impact on model performance. There are two major classifications of techniques used for sensitivity analysis, namely local and global sensitivity analysis methods. The local techniques examine the local response of the models' output(s) through varying input parameters by holding other parameters, which are referred to as manual method. This method is normally used when the outputs are linear (Helton, 1993). This method, therefore, fails to produce meaningful results when the model is non-linear (Da Veiga *et al*., 2009). Global sensitivity methods examine the global response (averaged over the variation of all the parameters) of the model output(s) by exploring a finite or infinite region (Helton *et al*., 2005).

There are automatic approaches to sensitivity analysis (optimisation), which are based on the sampling of parameter values from a given range of parameter values. This approach involves sampling of a set of initial model parameter values, which are then varied using such an automatic calibration method. Population-based optimisation methods, such as the GA or the SCE-UA, are suited to this approach of sensitivity analysis.

2.1.5 Socio-hydrology: a paradigm shift in hydrological studies

Traditionally, hydrological studies seek to assist water management decision making without considering the effects of human behaviour. It has been acknowledged that pure physical hydrologic science has limitations in diagnosing the resulting water

usage, and management problems, and in informing societal responses (Carey *et al*., 2014; Vogel *et al*., 2015; Srinivasan *et al*., 2017). With the aim to enhance the traditional methods of hydrological studies, human influences are now incorporated to assess the human impact on water systems, using the concept of socio-hydrology (Sivapalan *et al*., 2012). Socio-hydrological modelling seeks to understand the co-evolutionary dynamics of diverse coupled human–water systems, and thereby help in tackling human-induced water problems (van Emmerik *et al*., 2014). Therefore, socio-hydrology recognises human activities as an inherent part of the water systems (Vogel *et al*., 2015; Troy *et a*l., 2015). The organisational framework for socio-hydrological studies aims at evaluating how human values and norms (behaviour) impact on the structure, and dynamics of various water systems at different spatio-temporal scales. It also aims to find out how water systems, in turn, impact on the social well-being, and decision-making processes, as depicted in Figure 2.5 (Sivapalan *et al*., 2014).

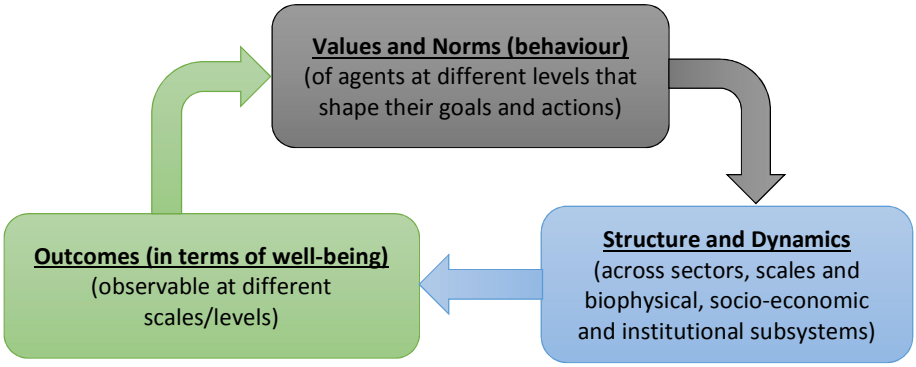


Figure 2.5: Framework for socio-hydrological system studies (Sivapalan et al., 2014)

The International Association of Hydrological Sciences (IAHS) launched the socio-hydrological research decade 2013–2022 with as theme "*Panta Rhei (everything flows): Change in Hydrology and Society*" (McMillan *et al*., 2016). *Panta Rhei* seeks to attain a better understanding of the inter-connections between water systems, and human activities (Blair and Buytaert, 2016; Kreibich *et al*., 2017).

There are three (3) primary goals that socio-hydrology aims to achieve (Sivapalan *et al*., 2014):

1) To study the dynamics, and feedbacks due to complex interaction between water and human systems on various scales, to understand the underlying features.
2) To provide inference, and elucidate the responses due to socio-hydrological system interactions, to gain insight into possible future system shift (forecast).
3) To further understand water systems from various perspectives (cultural, social, economic, and political) alongside its biophysical attributes.

The three proposed targets of socio-hydrological research activities are (McMillan *et al*., 2016; Montanari *et al*., 2013):

1) ***System understanding:*** To holistically understand the coupled human-water systems. In addition to quantitative data, qualitative information is also required to comprehend the history of the coupled system through qualitative studies.
2) ***Forecasting and prediction:*** The developed coupled model can be used to predict what might probably happen in future. Such a model could be of great value as it can aid in developing foresight for possible adaptive actions.
3) ***Policy and decision-making:*** The developed socio-hydrological model can be used to frame policy, policy alteration, or any management strategies.

The six science questions related to the three targets are (McMillan *et al*., 2016; Montanari *et al*., 2013):

Science Question 1: What are the key gaps in our understanding of hydrological change?

Science Question 2: How do changes in hydrological systems interact with, and feed back to, natural and social systems driven by hydrological processes?

Science Question 3: What are the boundaries of coupled hydrological and societal systems?

Science Question 4: How can we use the improved knowledge of coupled hydrological and social systems to improve model predictions, including estimation of predictive uncertainty, and assessment of predictability?

Science Question 5: How can we advance our monitoring and data analysis capabilities to predict, and manage hydrological change?

Science Question 6: How can we support societies to adapt to changing conditions by considering the uncertainties, and feedbacks between natural and human-induced hydrological changes?

2.1.5.1 Theoretical and conceptual basis of socio-hydrology

Although human beings are the primary agents for altering the state of the ecosystem, classical hydrology does not incorporate human impacts explicitly. However, prudent water management policies need to be developed with consideration of the complex interactions, and feedbacks between humans and water systems (Sivapalan *et al*., 2012). This hypothesis is based on the notion that the relationships between humans and water are changing, such that decisions that impact water also affects humans (Blair & Buytaert, 2016). The main aim of socio-hydrology is, therefore, to develop modelling tools that jointly treat social, and hydrological aspects of water management (Wescoat, 2013; Ceola *et al*., 2015; Wesselink *et al*., 2017). IWRM includes the inter-connectedness between human and water, but it treats the two systems in isolation (without two-way feedbacks), and gives little consideration to the complex interactions, co-evolutions, and feedbacks between humans and water systems (Montanari *et al*., 2013; Elshafei *et al*., 2014). Socio-hydrology, therefore, seeks to analyse the impact of changing societal norms, and values on water systems using dynamic co-evolution (Sivapalan *et al*., 2014).

Before the emergence of socio-hydrology, several inter-disciplinary approaches have been used to study the relationship between humans and water. These include socio-eco-hydrology, hydro-cosmology, hydro-sociology, hydro-solidarity, eco-hydrology, and eco-hydro-solidarity (Falkenmark & Folke, 2002; Gerlak *et al*., 2011; Boelens, 2014; Falkenmark, 1979; Falkenmark *et al*., 2009; Sivakumar, 2012; Lin *et al*., 2013; Linton & Budds, 2014; Zalewski, 2015). In these studies, the inherent complexities, and co-evolutionary dynamics of human-water interactions were not explicitly integrated. However, socio-hydrology seeks to achieve that through a holistic understanding of human-water inter-play, prediction of the future, and to put the predicted results into practice (Sivapalan *et al*., 2012; Montanari *et al*., 2013). Thus, socio-hydrological models could serve as a suitable tool for exploring co-evolving dynamics, complex interactions, and feedbacks between humans, and water (Vogel *et al*., 2015). Recently, Wesselink *et al*. (2017) provided a review on the key differences between socio-hydrology and hydro-social research, as summarised in Table 2.3.

Table 2.3: Comparison of socio-hydrological and hydro-social researches (Wesselink *et al*., 2017)

	Socio-hydrological Research	Hydro-social Research
Paradigms	Positivist; post-positivist	Constructivist; critical theory
Ontology	Objectivist; holistic; parts can be separated; interaction gives emergent properties	Holistic; parts constitute each other, and cannot be separated
Epistemology	Objective	Subjective
Methodology	Quantitative modelling	Historical materialist analysis
Starting point	Natural system	Society and technology
Keyword	Interaction	Power

Blair & Buytaert (2016) provide an extensive review of how socio-hydrological system models need to be conceptualised, and developed. The review highlights some fundamental similarities between socio-hydrology and other water-related inter-disciplinary subjects, and the unique aspects of socio-hydrology (Table 2.4). To deal with the complexities associated with developing socio-hydrological models, Kelly *et al*., (2013) proposed three alternative methods with which socio-hydrological models could be simplified to obtain the desired results: i) the Monte Carlo simulations technique, ii) scenario analysis and iii) optimisation methods.

Table 2.4: Similarities and uniqueness of socio-hydrology and other water studies (Blair & Buytaert, 2016).

Similarities	Uniqueness
Uncertainties: In both coupled systems there are uncertainties due to implicit interactions and feedbacks between the human and all natural systems.	Nature of water: Water obeys physical rules and can be modelled in many ways but, it has cultural and religious significance beyond other resources.
Complexities and co-evolution: Both coupled systems have had complexities and co-evolutionary dynamics: –*Non-linearity* (regime shift, time lags and tipping points) –*Feedbacks* (two-way interactions between human and nature).	The role of changing norms: Socio-hydrological models aim at assessing the impact of changing social norms and values. Water-related norms & values changes on long time scales and are highly unpredictable
Inter-scale analysis: Both coupled systems involve processes which occurs on various spatio-temporal scales.	Uncertainties: the level of the unknown in socio-hydrological systems is far beyond in other interdisciplinary subjects hence the uncertainties will be higher.
Interdisciplinary processes: Both coupled system involves coupling social subsystems with various ecological, hydrological and other natural subsystems as the case may be.	Scale: the spatio-temporal scales of socio-hydrological syatems modelling are expected to present a unique problem due to the broad nature of spatial and temporal scales.

2.1.6 Socio-hydrology of reservoir operation

The co-evolutionary dynamics, interactions and feedbacks between reservoir operation, and human behaviour are still not well-understood. Reservoir yield analysis entails assessing the system's yield potential under specified constraints. These constraints can be hydrological (rainfall, inflows, evaporation), physical (storage capacity and volume, conveyance capacity) and policy (reliability, operating rules) (Basson *et al.*, 1994). Such traditional methods of yield analysis can fail to assess the actual dynamics of the system, as the impacts of changing human behaviour are not explicitly incorporated, which might lead to imprudent decisions.

Several studies have been conducted on the impact of human activities on water resource systems, or how people respond to changing the hydrological state (Dolnicar & Hurlimann, 2010; World Bank, 2015). However, it is only now that the impacts resulting from the reciprocal relationships between humans and water have been studied using the concept of socio-hydrology (Sivapalan *et al.*, 2012). Furthermore, detailed socio-hydrological studies of reservoir operation have not been found in the literature, although human activities are known to substantially impact on reservoir operation. For example, whenever drought conditions are experienced water managers respond through implementing various adaptive strategies, such as restrictions, pressure reduction, intermittent supply, awareness campaigns, law enforcement, and other conservation measures (Yu *et al.*, 2013; Kuria & Vogel, 2014). Some water users can adjust to such conditions, whereas others could decide to unlawfully abstract water (Dolnicar & Hurlimann, 2010; Philanda, 2017).

Di Baldassarre *et al.*, (2017) developed a stylised model that simulates the co-evolution of hydrological extremes (floods and droughts), and water management in the context of reservoir operation. The model was conceptualised based on the view that decision makers usually capitalised on probable events without substantial evidence, which commonly leads to systematic biases (Tversky & Kahneman, 1973). The model traces how the storage state changes due to human activities characterised by massive water withdrawals amid resource shortfall, as illustrated in Figure 2.6 (blue shaded area).

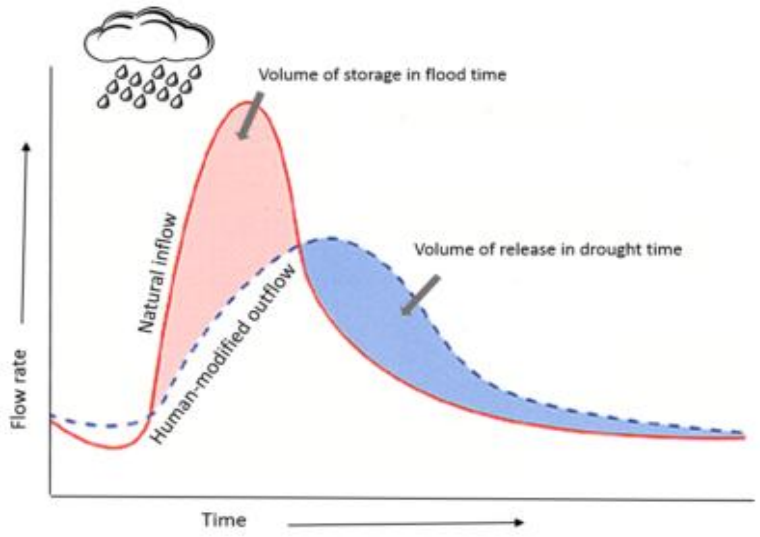


Figure 2.6: Human impact on reservoir during hydrological extremes: i) low releases (blue dash line) during high-inflow (red line); ii) high outflow during low-inflow (shaded blue) (Di Baldassarre et al., 2017)

Studies have also revealed that increased severity of droughts increases the rate at which water is abstracted, due to the perceived threat to users' quality of life (Elshafei *et al*., 2014; Firoz *et al*., 2017). According to Elshafei *et al*., (2014) whenever the available amount of water decreases, and users become well aware of the situation, the users' perceived risk increase. Hence, hydrological conditions can affect users' perceived threat, which can generate more concern, and subsequently change their compliance behaviour. There were several studies relating water to society that have been conducted in the Southern Africa (Gallego-ayala & Juízo, 2011; Kapangaziwiri et al., 2018; Mogomotsi et al., 2018; Sokile & Koppen, 2004; Tempelhoff, 2009). But in these studies the dynamics of the causes and effects (feedbacks) of changing human behaviour due to a change in hydrological state on water management performance in the context of reservoir operation, have not been found in the literature. Hence, developing a reservoir operation socio-hydrological model that incorporates the effects of human behaviour, and the feedbacks between this behaviour and the hydrological state is crucial. This would contribute to science question 2 of *Panta Rhei* (McMillan *et al*., 2016; Montanari *et al*., 2013): "*How do changes in hydrological systems interact with, and feedback to both natural, and social sub-systems driven by hydrological processes*?"

2.1.6.1 The need to incorporate human impact in reservoir yield analysis

Reservoir planning, and yield analysis is a technique for assessing systems' yield potential under the anticipated range of varying conditions (McMahon *et al*., 2006). Yield is the amount of water abstracted over a specified period, and a system is said to perform well if its yield is equal to the target draft. Target draft is the total volume of water required from the system to fully satisfy demand over a specified period, and this may not be fully supplied when the storage is low (Basson *et al*., 1994). In conventional yield analysis, it is assumed that yield falls below target draft only in times of drought, but this is not always the case as human activities, such as unlawful abstractions, can also affect yield significantly.

Reliability analysis is one of the methods that has been used to assess the yield potential of a reservoir system. A regional study on the reliability metric performance of reservoirs has been conducted using the global streamflows (McMahon *et al*., 2007). The highest reliability was found in the South Pacific, and Europe, whereas the lowest was observed in Southern Africa. Stream flows in the Southern Africa region exhibit the highest annual coefficient of variation of 0.82 which is 3.7 times more variable than the variation in the South Pacific (McMahon *et al*., 2007). Based on this, prudent planning and management of reservoir systems in Southern African requires the incorporation of human impacts, including probable losses due to unauthorised water abstractions.

2.2 The Ethics of Water Use and Management

This part of the chapter reviews the social aspects of water management that relate to the objective of the research. The section begins with the definition of ethics, and its relevance to water management. Ethical theories, and their applications in water policies, are briefly discussed. Situational factors affecting water users' propensity for compliance or unlawful behaviour, and the reported favourable and adverse human activities affecting the water sector, are presented. The value of management intervention as a response to unlawful activities is also reviewed.

2.2.1 Ethics and its relevance to water management

Ethics is a branch of philosophy that involves methodising, and recommending the concept of right and wrong conduct. From a moral standpoint, ethics are codes of conduct governing human behaviour, as reflected in actions and practices (Ssonko, 2010). It is a systematic way of limiting human activities through advocating virtuousness (Van Zyl, 2001; Crebert *et al*., 2011). Applying ethics can take care of ethical questions from technical, cultural, legal, environmental, social, and economic dimensions, thereby creating credibility, and uniting people through sound leadership (Groenfeldt & Schmidt, 2013). When a society attains these values, the ethical climate is said to have prevailed, and positive responses are always expected from that society. The ethical climate of a given organisation or society is the overall view of the moral atmosphere within that organisation or society (Treviño *et al*., 2006). Thus, it is desirable that such a moral atmosphere is created in all management activities, including water management, as it typically involves diverse stakeholders with different values.

The World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), warned that ethics in the 21st century are presented with many challenges due to the power of technology in modifying the world, and increasing peoples' propensity for unlawful activities (UNESCO, 2013). Hence, there is a need to explicitly incorporate the realities of human behaviour with water governance, as stressed by Falkenmark & Folke, (2002). Additionally, this needs to be based on generally agreed basic ethical principles that justify the moral prescriptions, and evaluations of human activities (APA, 2017).

2.2.1.1 Ethical theories and their classifications

Broadly, philosophers classify ethical theories into four subject areas: the meta-ethics, normative ethics, applied ethics, and descriptive ethics. *Meta-ethics* examines where ethical principles come from, and what they stand for. *Normative ethics* involve practical tasks to arrive at moral standards that regulate right and wrong conduct. It articulates the good habits that people should acquire, the functions that they should perform, or the consequences of their actions. *Applied ethics* entail examining what a

person is obligated or permitted to do, such as animal rights, preserving ecological integrity etc. *Descriptive ethics* describe how people behave, and the moral standards they claim to follow (IEP, 2016; Bonde & Firenze, 2016).

Normative ethical theories are used to judge individuals' behaviour as either morally right or wrong using the three normative ethics theories of virtue, duty and consequentiality (STS, 2017). *Virtue theories* emphasise the importance of developing good character, such as generosity, kindness, honesty, integrity, conscience etc. *Duty theories* stress the obligations people have as human beings, such as to care for their children, not to commit murder etc. The virtue and duty theories are sometimes called deontological, or non-consequentialist (duties that are obligatory irrespective of the consequences that might follow). *Consequentialist theories* determine moral responsibility by weighing the consequences of actions. An action is morally right if the outcomes are more favourable than unfavourable. The three types of consequentialism are: Egoism, Altruism and Utilitarianism, respectively defined as morally right if the outcomes are more favourable than unfavourable to the agent acting only, everyone except the agent, and everyone (Miller, 2009).

2.2.1.2 Application of ethical theories to water management policies

Human beings are known as the major agents for altering the state of the natural ecosystem, and the effort to limit adverse human effect in water management, therefore, needs to incorporate the realities of the impact of human behaviour (Carey *et al*., 2014). Wescoat-Jr., (2013) suggested that effects of human behaviour can be taken into account with the aid of historical socio-hydrology. Historical socio-hydrology is one of the three main areas of socio-hydrological research (historical, comparative, and process) with which the impacts of changing societal norms, and values about water and the environment can be studied (Sivapalan *et al*., 2012; Sivapalan & Blöschl, 2015).

The quest for water utilisation without undermining future generations and environmental quality, necessitates a distinctive ethical explanation (Jennings *et al*., 2009). In the 19th and 20th century, issues related to water rights led to some ethical debates on the moral philosophy of water management, drawn from ethics theories

such as utilitarianism, and deontology (Wescoat-Jr, 2013). Deontology is the philosophy of duty based on virtuousness, without regard to the outcomes (Kordig, 1974), whereas utilitarianism evaluates actions based on the benefits on which most water management policies were developed (Miller, 2007). As envisioned in the fields of water ethics and environmental ethics, socio-hydrology also seeks to attain sustainable water management by ensuring the need of both humans and the environment (Wescoat-Jr, 1992; Groenfeldt, 2010; 2013; Odume & De Wet, 2016). Thus, the utilitarian approach seems to have no application in the realities of socio-hydrology, where water and water users are reciprocally related (Wescoat, 2013). It is, therefore, preferable to manage water from a deontological standpoint (Brown and Schmidt, 2010).

With the aim to arrive at robust water management policies, humans and water systems need to be analysed in tandem by coupling and assessing human impact on water, as expounded in the concept of socio-hydrology (Montanari *et al*., 2013). Water availability studies predict an increase in variability and uncertainty, which can generate concern and risk perceptions of the users' (McMahon *et al*., 2007; Rochdane *et al*., 2012). The drivers and dynamics that shape water utilisation patterns due to users' perceived level of risk can be studied using the historic water use, and hydrological data as a means for assessing societal response to water availability (Carey *et al*., 2014). Recently, historical data has been analysed to track the drivers, and dynamics that moulded the development of hydrological understanding for the last century. The study revealed that the progress in hydrological understanding is due to changing societal needs (values), and technological advances (Sivapalan & Bloschl, 2017). Therefore, the practice of tracing historical events can serve as a reliable source of data for socio-hydrologic studies (Zlinszky & Timár, 2013).

2.2.1.3 Relating water stakeholders' behaviour to ethical theories

Water users have been blamed for aggressive habits toward maximising usage, which commonly leads to resource failure (Ostrom *et a*l., 2002). Agricultural, mining and industrial users are known to operate for maximising production (profit), and can be viewed through the lens of egoism, ethical theory, and rational choice theory/*homo*

economicus (Monroe, 2001). Egoism is one of three consequentialist ethical theories which emphasises that actions are morally right if the consequences of that actions are more favourable than unfavourable only to the agent acting (Miller, 2009). *Homo economicus*, or rational choice, is one of the economic theories that describe people as agents that consistently work for their self-interest in attempting to maximise utility, hence economic profit (Persky, 1995). Therefore, any decision by agricultural, mining, and industrial users in using the water is primarily based on self-interest to maximise utility, and benefit. These users are known to operate with explicit knowledge (unrestricted cognitive capacity) of the impact of their actions on the system (Schlüter *et al*., 2017). In reservoir operation, whenever there is poor a storage state due to droughts, restrictions are usually imposed (Basson *et al*., 1994). In restriction periods, some users are expected to comply, whereas others could decide to unlawfully abstract water they are not allocated. Such relationships between resource shortfalls, and human activities can significantly impact on water management performance. Awareness campaigns, law enforcement, and legal actions by the management, in addition to whistleblowing and lodging complaints with the relevant authority by co-water users, can help tackle this problem.

The major problem with domestic and other municipal users are lack of active participation in water demand management measures (Dolnicar & Hurlimann, 2010; World Bank, 2015; Muller, 2017). Domestic water consumers usually use water based on influences from observing the behaviour of others (family members, and societal culture and religion). This can be viewed through the lens of descriptive social norms theory. Human beings occasionally observe, and imitate the way others do things, and this creates imitation dynamics, which subconsciously commonly lead to the evolution of new social norms (Levin *et al*., 2013). *Descriptive social norm* theory is similar to *social learning theory*, namely that behaviour is learned through observing and imitating others' actions (McLeod, 2016). Such observation, and copying take place involuntarily, such as with the littering habit (Cialdini *et al*., 2003). The appropriate approaches for solving such problems are social norms interventions, which include policy dialogues, participation, and awareness campaigns. Social norms interventions have been successful in reducing social vices, and in addressing

violence, and social justice issues (Lewis & Neighbors, 2006). Water pricing was also found to play a vital role in addressing these problems (Hornberger *et al*., 2015).

2.2.2 Factors affecting water users' propensity to compliant or unlawful activities

This section reviews the situational factors that have been found to affect water consumption patterns, and behaviour, and are categorised in three major factors.

a) Hydro-climatic situational factors (reservoir hydrological state)
b) Water user situational factors (users' compliance)
c) Water management situational factors (management competence)

2.2.2.1 Reservoir hydrological state

Reservoir hydrological state factors are hydro-climatic variables known to affect the reservoir storage state. The hydro-climatic variables include inflows, rainfall, and the evaporation rate. A decrease in the reservoir hydrological state is expected to generate concern that can change the state of water users' level of risk perception. It has been observed that the severity of a drought has a direct relationship with the rate at which farmers abstract water, due to a perceived threat to their quality of life (Elshafei *et al*., 2014; Firoz *et al*., 2017). According to Elshafei *et al*. (2014), whenever the available amount of water decreases, and water users become well aware of the situation, the users' perceived level of risk increases. In years of drought, when the available monthly supply is below the demand due to supply restrictions, the risk perception is expected to intensify. An increase in risk perception can drive users to disobey the allocation rules, by abstracting water unlawfully. Therefore, the reservoir hydrological state can influence users' perceived threat, and, hence, can affect their propensity for lawful or unlawful activities.

Hydro-climatic conditions are natural phenomena that can affect the water consumption pattern. For example, the drier a year is, the higher the evapotranspiration, and crop water requirement (Abbas & Chowdhury, 2016), thus, the more aggressive users could become due to the perceived threat to their quality of life. Depending on the nature of the problem at hand, the aridity or dryness index could be employed as an indicator of WRS hydrological state. An aridity index is an indicator representing the degree of dryness of the climate, and is used to delineate

regions that suffer from a deficit of water availability (Sahin, 2012). The aridity index is the ratio of the average annual precipitation to the sum of annual potential evapotranspiration (UNEP, 1992). Moreover, the aridity index has been found to reasonably estimate water utilisation patterns (Tabari & Aghajanloo, 2013), and, hence, can be used as a surrogate to the hydrological state. The annual values of hydro-climatic variables (rainfall, temperature, evaporation) could also be used as indicators of the hydrological state of the system for a given year.

2.2.2.2 Water users' compliance

Many situational factors have been found to affect the level of users' compliance with water allocation rules. Therefore, these factors directly represent the level of users' moral awareness, understanding, and cooperation, especially in drought periods. Moral or ethical awareness is the ability of an individual to identify his deliberate action, and figure out what consequences that action could cause to others, and understand his instinctive feelings (De Cremer *et al*., 2010). Humans' decisive actions, which can have positive or negative impacts, can be categorised as either ethical or unethical respectively (Cameron *et al*., 2004). Ethical decision-making and action is the people's will to adhere to commonly accepted rules, as in allocating valuable resources such as water. Thus, for an individual to make a decision that is ethical or not, depends on whether that individual is morally aware of the consequences (Tenbrunsel & Smith-Crowe, 2008). Such decision can lead to either ethical or unethical practices, and depends on individual's motives (self-interest or fairness), shaped by some inherent factors (Tenbrunsel & Smith-Crowe, 2008; De Cremer *et al*., 2010). These factors comprise culture, awareness or knowledge, religious, social well-being, and other societal value-related attributes known to shape individuals' moral thinking, and actions (Treviño *et al*., 2006). These socio-cultural values are known to influence how new, and innovative policies are received, and adopted by indigenous societies (Akiwumi, 1998). These factors also affect personality characteristics such as trust or distrust, as in accepting and complying with newly introduced natural resources conservation policies (Rim-Rukeh *et al*., 2013).

Socio-cultural and economic values that encourage individuals to behave ethically asre comprised of equity, recognition ,and commitment (participation, engagement, and sharing of responsibilities). Others include public trust, integrity and credibility, respect for indigenous traditions, religious and cultural beliefs. Other factors include social well-being, such as access to good health care, education, electricity, water, sanitation, and transportation systems (Van Zyl, 2001; Akiwumi, 2010; Rogers & Luton, 2011). A well-being index for a given society is used to represent the level of development with regarding to the standard of living based on basic human needs (Friedman, 2013). Composite indicators such as the Human Development Index - HDI (UNDP, 1990, 2015), or the Social Progress Index - SPI (Porter *et al*., 2016) can be used as a proxy for this factor. Studies revealed positive relationships between society's well-being and ethical practices, as in accepting new resources management policies (Tiliouine & Cummins, 2006; Bravo, 2014; Bergheim, 2006). Additionally, a positive relationship exists between individuals' well-being, and behaviour with regard to environmental sensitivity (Bergheim, 2006; Ferrer-i-carbonell & Gowdy, 2007). Therefore, the less prosperous society is, the more the concerned and reactive that society could respond to perceived threats to their quality of life. Conversely, the more prosperous a society is, the lower the impact is of perceived threats to its behaviour.

2.2.2.3 Water managers' competence

The water managers' competence factor is comprised of the factors that can affect the overall water management performance in discharging their duties. These factors include the system's infrastructural development, such as flow measuring equipment, and surveillance systems. Others include water managers' expertise, and monitoring compliance, and enforcement to tackle unlawful activities. These factors can shape water users' perception of the level of system effectiveness, and water managers' expertise (skills, knowledge, and experience) in discharging their responsibilities. It involves the overall competence of the compliance monitoring and enforcement unit for enforcing water laws (DWA, 2009; Arle *et al*., 2016; Pang *et al*., 2014). Management compliance can also be affected by issues such as political agenda, political affiliation, and employees' job satisfaction (promotion, incentives, and other

benefits). When users perceive that the water management skills, supply facilities, and surveillance systems are satisfactory, they are expected to have peace of mind, and, hence, their risk perception would be low. Conversely, when users perceive management and facilities as poor, this would generate concern, and their risk perceptions are expected to be high, and more likely to lead to unlawful activities (Omar *et al*., 2017). Depending on the available information, some quantifiable parameters related to water allocation efficiency can be used to serve as surrogates for these factors.

2.2.3 Behaviour-driven human activities affecting water sectors

This section reviews studies in which human activities have been found to affect water management performance. There have been positive impacts resulting from participation and the sharing of responsibilities, dialogues, compliance with restrictions, demand management measures, and reporting unlawful activities (whistleblowing). Other positive activities include enhanced monitoring, law enforcement, and conservation awareness campaigns (Liu *et al*., 2009; Groenfeldt & Schmidt, 2013; WGF, 2000, 2016). Conversely, unlawful activities such as illegal water abstractions, water wastage, discharging untreated or poorly treated wastewater, over-application of chemicals, and fraudulent system operation have negatively affected water availability, and quality (Plummer & Cross, 2006; UNDP, 2011; Hermann-friede *et al*., 2014; SABPP, 2013; WWAP, 2017).

2.2.3.1 Unlawful activities affecting water management

Individuals' activities that are not following the set ethical standards can negatively impact the managerial goals (Cameron *et al*., 2004; Askew *et al*., 2015). Understanding the causes and effects of changing societal norms, and values can, therefore, be essential in formulating solutions to water management problems (Lopez-gunn *et al*., 2012). Although unlawful activities occur in all parts of the water sector, those that are often documented are related to drinking water and sanitation (UNDP, 2011). For example, the Information Portal on Corruption in Africa IPCA (2010), reported that a water management official was found guilty of taking bribes from multi-nationals to obtain tenders in the Lesotho Highlands Water Project (LHWP). Also, a water

employee was found guilty of conspiring with an estate owner to extort money from households in New Jersey, USA (Transparency International, 2008). Several water-related irregularities have also been reported from Australia, Mexico, Kenya, India, and many countries in Africa, and South Asia (Hermann-friede *et al*., 2014). A simulation model for water sharing in the Herault River Basin (HRB) in France, revealed how massive amounts of water amounting to about three times that which was allocated, was diverted from the Herault River (Lanini *et al*., 2004).

There are several occurrences of unlawful water abstractions that have been reported in South Africa, including unlawful abstractions for irrigation purposes along the Axle and Liebenbergsvlei water transfer scheme (Ginster *et al*., 2010). Reservoir simulation revealed that massive water releases were made in 2006 from the Hluhluwe Dam in KwaZulu Natal Province, while the storage was low (Ndiritu *et al*., 2017). Since the storage state was low at the beginning of the decision month, these massive water releases were inferred to be unlawful. Blue Scorpions, the regulatory body within the DWS created to enforce South Africa's water laws, and regulations, revealed unauthorised abstractions by farmers from the Vaal River, Umvoti, and Illovo rivers (Ginster *et al*., 2010). Unlawful irrigation use was found to exist in the Olifants River water management area in the Western Cape province, and out of the 8 082 identified irrigation users, only 5 435 were legally registered (DWA, 2011b). A dam constructed without authorisation, was found in Breede Valley (DWS, 2016b).

Several illegal connections and dams have been discovered in the farming areas of Western Cape, and are reportedly linked to the recent Cape Town water crises (Philanda, 2017). Based on this, the Green Scorpions, a regulatory body that investigate environmental crimes in South Africa, has been reportedly intensifying law enforcement in that area. A report was received from residents who had witnessed how water was being abstracted unlawfully, and most of these unlawful abstractions were committed by irrigation users (Philanda, 2017). According to the report on South Africa's water status, the annual commercial losses and meter inaccuracies amount to more than 20% of the total country's water loss, which is about 6.4% of the total country's water resources (Mckenzie *et al*., 2012).

With as aim to counteract such unlawful activities in South Africa, the DWS tasked its regional offices to liaise with police, and arrest those stealing water (Philanda, 2017). Moreover, untreated or poorly treated wastewater sometimes are discharged into rivers. About 71% of the wastewater treatment facilities in South Africa have been reported to discharge wastewater that does not meet the set standards (OUTA, 2017). More than 3 734 million litres of partially treated or untreated raw sewage is discharged annually, causing severe pollution of the water resources of South Africa (OUTA, 2017). Table 2.5 summarised these, and other occurrences of unlawful activities by users or management in the water sector that have been reported locally, and internationally.

2.2.3.2 Lawful activities affecting water management

Several approaches have been reported to affect water management positively. Some of these approaches include participatory, and decentralising water governance, collective actions by management, and enhanced monitoring and compliance with water demand management measures by users, and civil society. Demand management measures comprise of water use efficiency, conservation awareness campaigns, law enforcement and legal proceedings, and whistleblowing. For example, a reduction of about 32% in domestic water consumption has been achieved in Australia after the launch of technological, and water conservation campaigns (Dolnicar & Hurlimann, 2010). Water consumption was also found to significantly reduce when conservation measures were implemented in the city of Cape Town (Muller, 2017). The DWS has reportedly become resolute to take legal actions against Western cape irrigation users found to abstract water unlawfully (Philanda, 2017). Table 2.6 summarises these and other occurrences of activities that have enhanced water management across the world.

Table 2.5: Sample of unlawful activities in the water management sector

Sectors	Adverse cases	Locations	References
Water Users			
Irrigation *(agricultural)*	1) Unlawful abstractions	Vaal dam, Western Cape, Umvoti and Illovo rivers Axle and Liebenbergsvlei water transfer scheme	(Ginster et al., 2010), (DWS, 2016b), (Philanda, 2017)
	2) Unauthorised dam construction	Breede Valley,	(DWS, 2016b)
	3) Over-irrigation ignorantly	Western Cape: South Africa, Afghanistan, South Asia	(Philanda, 2017) (Qureshi, 2002) (Hasanain et al., 2012)
Domestic *(municipal)*	1) Bribery to: avoid water fees, tamper with the water meter 2) Wastage habit	USA, South Africa, Kenya, China, India	(Hermann-friede et al., 2014), (Davis, 2004), (González de Asís et al., 2009) (Ménard et al., 2018)
Commercial *(Industrial)*	1) Bribery to discharge untreated wastewater	South Africa, China, India	(OUTA, 2017), (UNDP, 2011)
Water Managers			
Public agencies	1) Bribery in water dev. Projects contracts (contract bids)	Lesotho; South Africa; Western Europe; North America; India; Japan	(IPCA, 2010), (Davis, 2004)
	2) Suspected unlawful releases	Herault River Basin, France; Hluhluwe dam, South Africa	(Lanini et al., 2004), (Ndiritu et al., 2017)
	3) Collecting bribe to favour promotions and transfers	India	(Davis, 2004)
	4) Bribery to discharge untreated wastewater.	South Africa; China; India	(OUTA, 2017), (UNDP, 2011)
	5) Poor complaint mechanism and inadequate monitoring equipment and strategies	Sidney; Australia; Kenya	(ICAC, 2011), (Achermann et al., 2014),
Private agencies	1) Bribery to: avoid water fees, tamper with the water meter, postpone disconnections, extorting money from householders, in fixing leaks or sewer blockages	USA; Peru; Kenya; India; Pakistan; Sierra Leone; Australia; South Asia's Water and Sanitation Sector	Transparency International, (2008), (Hermann-friede et al., 2014), (Davis, 2004)

Table 2.6: Sample of lawful activities in the water management sector

Sectors	Case	Locations	References
Water users perspectives			
Irrigation ***(agricultural)***	1) Participatory management	USA, China, Bolivia, Philippines, Mexico, Peru, Uganda, Indonesia, Sri Lanka, Ethiopia, Chile etc.	(UNDP, 2011), (Groenfeldt & Schmidt, 2013)
	2) Whistleblowing	Western Cape, South Africa	(Philanda, 2017)
Domestic ***(municipal)***	1) Compliance with conservation campaigns	Rand water, South Africa; Bolivia; China etc.	(RandWater, 2017), (World Bank, 2015), (Liu et al., 2009), (Muller, 2017)
Water managers perspectives			
Public agencies	Active anti-corruption agencies and strong auditing exercise	South Africa, Lesotho, Kenya, Zambia, Uganda, Peru, Columbia, Ecuador, Denmark	(IPCA, 2010), (UNDP, 2011), Hermann-friede et al., 2014)
Private agencies	Enhanced monitoring by government, users and civil societies	South Africa, Lesotho, India, Peru, Uganda, China, Zambia, Kenya, Mexico	(IPCA, 2010), (UNDP, 2011)

2.2.4 Water demand management as a response to unlawful activities

Several interventions can be used by management to serve as a response to unlawful activities, especially in drought periods. Such measures can be employed whenever management becomes aware of occurrences of unlawful activities. Broadly, this review categorises these measures into four groups: i) Education and awareness campaigns (DWAF, 2004b; Dolnicar & Hurlimann, 2010; World Bank, 2015), ii) Law enforcement and legal actions (DWS, 2016; Philanda, 2017), iii) Participation and sharing of responsibilities (Choles *et al*., 2014) and iv) Engagement and policy dialogues (Rogers & Luton, 2011).

2.2.4.1 Educational and awareness-raising campaigns

Awareness campaigns are social norms interventions for educating people to become aware of the dangers associated with water misuse habits (Lewis & Neighbors, 2006). Ethics education, and training is found to promote a positive state of mind, characterised by vigour and dedication, leading to participation, and work engagement (Bakker & Demerouti, 2008; Bew, 2014). These measures can subsequently increase stakeholders' propensity for lawful activities. There are many

reports which highlighted the importance of awareness campaigns in the water management sector. Behavioural sensitisation has been used to promote water conservation in the city of Bogota, Colombia through educating householders on effective water use (World Bank, 2015; Dolnicar & Hurlimann, 2010). Stickers were put up in strategic places describing the danger of water wastage, house to house visits to inform people, and publicising the reports of the water consumption in the country's major newspapers, were undertaken. These sensitisation campaigns reduced the total city water demand by about 13.8% within eight weeks (World Bank, 2015). A reduction of about 32% in domestic water consumption has also been achieved in Australia after launching water conservation campaigns (Dolnicar & Hurlimann, 2010). A similar campaign was launched in the city of Cape Town in 2011, and a considerable reduction in water consumption was achieved (Muller, 2017). Hence, such interventions can improve the performance of the water management sector.

2.2.4.2 Law enforcement and legal actions

This involves enforcing the law through instituting legal proceedings against those who transgress the rules. There were several cases which led to such legal actions, including the Lesotho Highlands Water Project (LHWP) corruption case with regard to obtaining tenders (IPCA, 2010), and the case of colluding with an estate owner to extort money from householders in New Jersey, USA (Transparency International, 2008). The case of construction of a dam without authorisation in the Breede Valley, South Africa led to the transgressors (DWS, 2016b) being fined. As a result of rampant unlawful abstractions in the agricultural area of the Western Cape, the DWS has tasked its regional offices to liaise with the police to arrest transgressors (Philanda, 2017). Several water-related irregularities that led to legal actions were reported in Australia, Kenya, Mexico, and many countries in Africa, and South Asia (Hermann-friede *et al.*, 2014) and these actions led to system performance improvement.

2.2.4.3 Participation and sharing of responsibilities

Stakeholder engagement refers to the manner in which representatives of water users come to the decision to actively participate in tackling the challenges associated

with water in their respective locality (Choles *et al*., 2014). The focus of water management is increasingly shifting from command and control, to decentralised and user-oriented approaches. Water governance literature reveals that stakeholder engagement is an integral part of sound water governance (Akhmouch & Clavreul, 2016). Stakeholders' engagement, and active participation have since been recognised as an important component of sustainable water management, ranging from planning, and operations to consumption (GWP, 2000; Megdal *et al*., 2017; Bartula *et al*., 2017). Such user-oriented approaches are designed to place more emphasis on stakeholder participation through local organisations (Dube & Swatuk, 2001). Involving traditional leaders, and community-based associations also offer a significant facet for dealing with unlawful human activities (Summerill *et al*., 2010). These approaches enable water stakeholders to feel, and see themselves as agents of change, which can improve the performance of the water management sector.

2.2.4.4 Engagement and policy dialogues

This is the act of involving all stakeholders in the procedural, and decision-making processes (Chikozho, 2001). This improves management through active participation, transparency, accountability, and public-private collaboration, and partnership (Rogers & Luton, 2011; Wheater, 2014). According to Wheater (2014), engaging stakeholders in both water planning and management dialogues is not an option, but a necessity. To check whether all the stakeholders are involved in policy development, there is a need to answer some ethical questions. The questions include: who participates in the decision-making process? Are participants active? Are their views considered in formulating policies? Is there respect for socio-cultural, traditional, and religious beliefs? (Jennings *et al*., 2009; Barbara van Koppen, 2018). Answering these ethical questions can help in developing robust policies, such as dynamic adaptive policies - DAP (Walker *et al*., 2001), social learning - SL (Mostert *et al*., 2008), strategic adaptive management - SAM (Rsogers & Luton, 2011), among others.

2.2.5 Studying and modelling of human behaviour

The study of human behaviour has a long history, although the progress as such has been markedly slow due to the complex nature of the human mind (Kean, 2011). In

the middle of the 20th century, the evolvement of cognitive science resulted in several studies on human behavioural science, leading to several frameworks for understanding the human mind with regard to inputs, processes, and outputs (Farina, 2011). Cognitive science researches seek to understand human cognition concerning rational, emotional, intuitive, and erroneous factors, which are found to have guided human behaviour modellers (Kahneman, 2003). Studying and modelling human behaviour, either as individuals or groups, is a difficult task as in understanding humans themselves, sourcing data, validation and verification. Modelling and incorporating human behaviour into other existing models to assess the impact of human behaviour on the modelled systems is also challenging (Kennedy, 2012). In the quest to model human behaviour, the first question is at what level the behaviour should be modelled (individual, household, or society). Statistical methods are normally used to model human behaviour at society level, without dealing with individuals (Kennedy, 2012). Modelling human behaviour requires some degree of problem-solving capabilities in dealing with complexities, non-linearity, and the dynamics of social behaviours, such as in '*theory of mind*' (Wilson, 1978; Ondobaka *et al*., 2017). There are five basic principles of human social behaviour, as highlighted by Kennedy, (2012):

i) ***Information processor:*** Human beings are capable of processing sensory information about their status, environment, and of remembering historical events before making decisions and taking action.
ii) ***Rational:*** Humans behave, and act sensibly, as explained in the '*rational choice theory*' (Monroe, 2001). Humans typically operate with the presumption of maximising benefits or minimising costs systematically ,and logically.
iii) ***Motivational:*** Human motivations are based on the '*hierarchy of needs*' (Maslow, 1943). The first human need is to meet basic physiological requirements, followed by safety and security, and, lastly, the social needs.
iv) ***Emotional:*** In addition to being rational, human behaviour, and decision-making processes can be affected by emotion and intuition, or the unconscious. Emotions (interest, joy, happiness, sadness, anger, disgust, and fear or risk perception) can lead to longer term moods, and result in changing behaviour. Studies reveal that emotions could alter rational decisions by distorting the individual's perceptions of himself, and the external environment (Izard, 2007).

v) ***Social:*** Humans are social beings, and input from others can shape their behaviour in two ways: i) imagining what the others' goals, thoughts and feelings are, and ii) being influenced by the actions of others – imitation dynamics (Latane, 1981).

There are many ways through which human behaviour can be modelled, and they are broadly categorised into mathematical, conceptual frameworks, and cognitive architecture (Pirolli, 1999; Ajzen, 1991; Kelly *et al*., 2013).

a) ***Mathematical approaches:*** These are methods that represent human behaviour, using mathematical simplifications, and notations: i) Using random number generators in selecting between predefined possible choices of actions. ii) Using direct coding of threshold-based rules, such as, if a parameter or a variable is equal to, greater or less than a given threshold, specific human action will result. iii) Using multi-dimensional functions of parameters, rather than comparing a single parameter or variable to a threshold. iv) Using dynamic modelling by representing human actions as 'stocks and flows', and differential equations to describe relationships between the parameters, and variables of the model (Barlas, 1996; Majid & Herawan, 2013; Kelly *et al*., 2013).
b) ***Conceptual framework:*** This approach to modelling human behaviour is more abstract than mathematical methods. The commonly used conceptual framework includes the beliefs, desires and intentions (BDI), the physical, emotional, cognitive and social status (PECS), and fast and frugal decision hierarchies. i) The BDI approach is a theoretical framework based on the idea that human behaviour can be modelled by representing an individual's beliefs (individual's knowledge about the world - perceptions), desires (individual's motivation - goals), and intentions (deliberative states) (Ajzen, 1991). The BDI framework is very general, and it provides little more than a conceptual framework for thinking about how to model the human cognition behind the behaviour. ii) The PECS model represents the human mind in terms of perception and behaviours (Schmidt, 2002). The model also represents physiology, emotion, cognition, and social status mathematically. The PECS framework also represents simple stimulus-response reactions, and more complex behaviours that involve the determination of drivers, needs, and desires, and their transformation into motives and actions. iii) The fast and frugal framework has been used in analysing data on human decisions (Dhami & Harries, 2001).
c) ***Cognitive architectures:*** This approach converts research into abstract or theoretical cognition, as well as understanding human perception. Cognitive models of specific tasks are usually implemented within the cognitive architectures, and usually used to drive human behaviour (Pirolli, 1999).

2.3 Modelling and Coupling of Human and Water Systems

This section of the chapter reviews the modelling and coupling of human and water systems. Through this, insights are gained for the development, and application of the reservoir operation-human behaviour socio-hydrological model in this study. The section begins with the uses, abilities, and limitations of coupled modelling, after which inter-disciplinary studies for managing natural resources are broadly reviewed. A detailed review of socio-hydrological research is then carried out.

2.3.1 Uses, abilities and limitations of coupled modelling

Coupling is the process of connecting or linking two or more entities together and getting them to work as an integrated entity. The functions of coupled modelling in socio-hydrology are similar to that of Integrated Assessment Modelling (IAM) that is applied to inform policy-making (Sharma & Norton, 2005). Coupling enables impact assessment by including cause-effect dynamic interactions and feedbacks from diverse disciplines and is considered to enhance understand and prediction for decision-making (Sivapalan *et al*., 2012; Montanari *et al*., 2013). Therefore, a system is said to be a linked system if two or more separate systems are modelled, and linked together based on their constitutive relationship (Polhill *et al*., 2016). There are many reasons that encouraged the development of coupled modelling in water management, including the following:

i) The complexities of interactions between water availability and societal norms, and values (behaviour);
ii) The need for more insights into how hydrological systems influence societal settings;
iii) The need to predict the resulting impact due to the co-evolutionary dynamics of the human-water systems;
iv) The need to explicitly relate science and policy (Carey *et al*., 2014; McMillan *et al*., 2016; Montanari *et al*., et al., 2013).

Basically, there are two types of coupling approaches; loose and tight coupling. Loose coupling links two or more existing models on an input-output basis only, which hinders the actual dynamics of the systems due to problems of an irresolvable mix-up of the models and processes (Magombeyi & Taigbenu, 2014). It also has a limitation in capturing the non-linear interactions, and feedbacks as its only links, but does not

integrate the subsystems (Rotmans & Asselt, 2001). Conversely, tight coupling involves developing and coupling simplified inter-disciplinary models based on how the two or more systems inter-relate and operate (Garcia *et al*., 2016). It captures the inherent co-evolving dynamics, and feedbacks due to complex interactions between the sub-systems in a simplified manner, and this is essential for socio-hydrological modelling (Blair & Buytaert, 2016).

Below are some limitations of coupled socio-hydrological modelling as highlighted by Mount *et al*., (2016) and Blair & Buytaert, (2016):

i) Realistic estimation and quantification of the appropriate complexities, inter-dependencies and trade-offs between the variables can be challenging;
ii) Conducting precise calibration, and validation of the developed socio-hydrological systems models may be difficult;
iii) Sourcing data from different sources, including social science, can be tasking, and its availability is also another issue;
iv) The issue of the unpredictability of human responses, emergence behaviour and stochastic nature of the coupled system can also be challenging;
v) Devising means of practical application of the findings in real world problems as in policy decisions.

Based on these limitations, coupled socio-hydrological modelling needs to be conducted in a simplified way to avoid the challenges mentioned above, without compromising some vital issues that need to be captured (Blair & Buytaert, 2016).

2.3.2 Interdisciplinary studies for managing natural resources

Effective management of natural resources requires rigorous, and dynamic decision-making processes (Walker *et al*., 2001; Elsawah *et al*., 2015). Therefore, the task of formulating, and implementing effective natural resources management policies needs to be informed based on the holistic understanding of the system processes. This includes understanding of the interactions, and feedbacks between policy choices and complex social, economic, technical and environmental processes, and how the system could respond to various changes (Akegbejo-samsons, 2011; Kelly *et al.*, 2013). Such an approach can help understand how water stakeholders could respond to supply decisions, especially in drought periods (Carey *et al*., 2014) and

requires more information, and experts from both natural, and social science disciplines.

The quest for more information on how people's culture, politics, economics, and other social values impact on nature and resources management, studies have been undertaken using the concept of coupled natural and social systems (Levins & Culver, 1971). These inter-disciplinary studies have been conducted under the two major subjects: coupled human, and natural systems (CHANS), and social-ecological systems (SES) (Monticino *et al*., 2007; Liu *et al*., 2007; Werner & McNamara, 2007; Schlüter *et al*., 2009; Ostrom, 2009). According to Blair & Buytaert, (2016) these two inter-disciplinary research subjects (CHANS and SES) are areas from which socio-hydrological modelling can learn.

2.3.2.1 Social and ecological systems (SESs)

SES is an ecology-based inter-disciplinary area of study for the management of natural resources that links and treats people, and the natural ecosystem as a single entity. It is a complex approach with essential dynamic features, such as interactions, non-linearity, feedbacks, heterogeneity, and co-evolution (Levins & Culver, 1971; Schlüter *et al*., 2009). SES models take into consideration how systems' properties emerge on large scale due to interactions from small scales, which then feedback and influence the overall behaviour of the system (Ostrom, 2009; Levin *et al*., 2013; Kevin *et al.*, 2013). Four critical issues underpinning the SES studies, from which socio-hydrological modellers can learn, as proposed by Schlüter et al. (2012), are:

i) Complexities in the management of ecological resources;
ii) Uncertainties associated with social and ecological dynamics;
iii) Co-evolutionary dynamics of the coupled social and ecological systems;
iv) Understanding the drivers of human behaviour at both micro and macro scales.

2.3.2.2 Coupled human and natural systems (CHANS)

The concept of modelling and coupling human and natural systems (CHANS) has also developed fundamentally within the theory and literature of ecological studies (Liu *et al.*, 2007). The concept of CHANS has been evolving, particularly in the modelling and coupling of human systems with natural systems (O'Connell & O'Donnell, 2014). The

aim is similar to that of SES, understanding the complexity of human–nature interactions for human well-being, environmental integrity, and global sustainability (BESA, 2011; An, 2012; Liu *et al*., 2007). A typical example on human-nature interctions in the Southern Africa is the issue on human-wildlife conflicts in Southern Africa with a specific case in Mozambique and in Zimbabwe (Bel et al., 2011).

2.3.3 The emergence of socio-hydrology

Human beings have for long been considered as the primary causes of global changes in both biological and physical processes, including hydrological systems (Falkenmark, 1979). This has led to the evolution of inter-disciplinary studies on the inter-play between human activities and water systems to gain insight into the complex interactions between the two systems (Falkenmark & Folke, 2002; Gerlak *et al*., 2011; Boelens, 2014; Falkenmark, 1979; Falkenmark *et al*., 2009; Sivakumar, 2012; Lin *et al*., 2013; Zalewski, 2015). The common goal of most of the previous attempts for humans-water studies was to obtain reliable information, due to such complex interactions for possible future adaptation strategies (Falkenmark & Folke, 2002). Recently, socio-hydrology has also emerged as a new science of people and water (Sivapalan *et a*l., 2012), and has been used for studying the reciprocal relationships between human activities (due to changing societal norms and values), and various water systems. As in the other transdisciplinary analyses where human activities, and diverse natural resource systems are coupled to assess the impact of human on nature and *vice versa* (feedback effects), socio-hydrology entails coupling the societal responses (human activities) with water systems for the same purpose.

2.3.4 Conceptual basis of socio-hydrology

This section presents a review of the conceptual basis of socio-hydrology. Research in socio-hydrology progressed rapidly during the last five years (2013-2018), and a variety of socio-hydrological modelling with different conceptual bases have been developed (Di Baldassarre, *et al*., 2013, 2017; Viglione *et al*., 2014; Elshafei *et al*., 2014; Liu *et al*., 2015; Grames *et al*., 2016). The human characteristics that have been used in socio-hydrology include societal response, economic development, social well-being, cultural affiliation, risk coping strategies, technological influences,

behavioural changes, interventions, political agenda, policy formulation, and alteration. The water systems (hydrological) aspects have included water sources (river, rainfall harvesting, lakes, dams and groundwater), land resources, vegetation, aquatic life, and hydrological extremes (droughts and floods). Socio-hydrological models are often conceptualised, and developed based on general assumptions about how the two systems (human and water) interact with one another on both spatial and temporal scales (Garcia *et al*., 2016). The reviewed socio-hydrological literature indicates that most studies have dealt with human-water interactions on floodplains, and in agricultural catchments.

2.3.4.1 Human-water interactions in floodplains

Rivers enhance the life of its neighbourhood dwellers, which enable water supplies for agriculture, industries, domestic consumption, transportation, cultural and spiritual values, as well as trade (Di Baldassarre *et al*., 2010). This has led people to settle close to the rivers to gain such socio-economic benefits from it, regardless of the probable consequences of flooding. Many studies have been conducted on how human beings affected flooding events under certain conditions, including settlement patterns, land use, and other economic activities (Schultz & Elliott, 2012). Classic studies on human-floods interactions do not include coupling, and focus on either the impact of human interventions, such as the construction of levees, and land use changes on the frequency, and magnitude of flooding events, or the other way round (Heine & Pinter, 2012). According to Di Baldassarre *et al*., (2015), most of the developed frameworks for analysing the risk associated with flooding events failed to capture such dynamics from two-way feedbacks between floods, and human activities. Recently, some studies were conducted that account for the bi-directional effects between humans and water sub-systems on floodplains. These studies have focused on how people influence flooding in both magnitude and frequency, and how flooding, in turn, affects people's well-being and decisions (Di Baldassarre, *et al*., 2013; Viglione *et al*., 2014).

Simulation modelling on the interplay between the socio-economic development of settlements close to the river, and the natural disaster of flooding has been

conducted. Some of these studies include the inter-play between societal socio-economic development, the tradition of raising levee and individual behaviour as the social aspects, and flooding events as the hydrological aspect (Di Baldassarre, *et al*., 2013, 2015; Viglione *et al*., 2014; Li *et al*., 2015; Merz *et al*., 2014). Generally, these studies have focused on the propensity of people to settle close to rivers for social and economic advantages, and how flood occurrence alters this propensity, and preparedness for future flooding. The conceptual basis for modelling of the inter-play between socio-economic development, and flooding events developed by Viglione *et al*. (2014), and Di Baldassarre, *et al*. (2013), is summarised in five steps below:

a) How a flooding event makes humans become aware of the situation in the form of perceived risk (mental sensitivity);
b) How perception of risk leads to more awareness of flooding consequences, which necessitates the building of protection (levees;
c) How such protection structures make humans to quickly forget the dangers associated with flooding events, thus, they begin to move towards the rivers to reap more economic advantages;
d) How these levees lead to rare but catastrophic flooding events; and
e) How floods hit society's economy even harder when the water levels rise higher than the constructed levees.

Optimisation models have also developed to arrive at optimum levee height, as well as the optimum economic investment in raising the levee (Chahim *et al*., 2013; Grames *et al*., 2015, 2016). Grames et al. (2015) considered human-floods trade-offs from the economic point of view, and developed an optimisation model based on the existing descriptive human-flood model developed by Viglione *et al*. (2014). The stochastic property of the model was transformed into a deterministic one, by substituting the stochastic function of rainfall with a periodic deterministic function (Grames *et al*., 2015) by using the optimal control theory (Sritharan, 1992; Chahim *et al*., 2013). The main aim was to change the water function (rainfall) from stochastic to deterministic (although this is unrealistic), to analyse the behaviour of the coupled variables. The variables investigated include the memory of flooding events, the size of the settlement, the distance between the settlement and the river, and the height of the levees. A stylised model of human–flood interactions has been developed to analyse, and compare the inter-play between a society that employs non-structural

flood risk measures (the green system), and structural/levees measures (the technological system) (Ciullo *et al*., 2017). The result shows that the technological system provides better protection, but may result in catastrophic events, as observed by Di Baldassarre, *et al*., (2013) and Viglione *et al*., (2014).

2.3.4.2 Human-water interactions in an agricultural catchment

Several studies on the inter-play between socio-economic development, and water and land resources in irrigated catchments, have been developed. The interactions are mainly centered around the degradation of the environment (water and land resources) due to human activity, and how this in turn affects human well-being, and decisions for the enviro-centric utilisation of the resources (Kandasamy *et al*., 2014; Elshafei *et al*., 2014; Monticino *et al*., 2007).

The driving variables commonly used in irrigation catchment based socio-hydrology, include social (population dynamics), economic (irrigation), and other sources of income), as well as environmental/ecological (vegetation cover, aquatic life etc.), and political (policy formulation and alteration) aspects. Others include hydrological (reservoirs, rivers, groundwater etc.), technological influences (efficiency of irrigation), and human characteristics, including risk perception, and environmental awareness (Akiyama *et a*l., 2012; Fernald *et al*., 2012; Elshafei *et al*., 2014; Carey *et al*., 2014; van Emmerik *et al*., 2014; *Zhou et al*., 2015; Liu *et al*., 2015). Elshafei *et al*. (2014), and Van Emmerik *et al*. (2014) conceptualised how irrigated areas (land resources) changes depending on the level of water availability. Some internal (endogenous) and external (exogenous) factors known to effect the coupled system such as climate, political regimes, and societal well-being measures, also were incorporated into the analysis. Other models have been conceptualised, based on how irrigated area per capita changes due to technological advancement, water availability, and a community's environmental awareness (Kandasamy *et al*., 2014; van Emmerik *et al*., 2014). Table 2.7 provides a summary of the state drivers that have been involved in several socio-hydrological studies.

Table 2.7: State drivers of the interplays between human and water systems

Interplay	References	State Drivers for Coupling Human-Water Systems
Socio-economic development and flooding events	Di Baldassarre et al., (2013)	**Hydrological:** flooding, **Economic:** wealth, **Political:** distance and levees, **Social:** mental awareness and sensitivity
	Viglione et al., (2014)	**Hydrological, Economic and Political:** same as above, **Social:** collective memory, risk-taking attitude and trust in risk reduction measures)
	(Grames et al., 2016)	**Hydrological, Economic, Political and Social:** same as above, **Economic:** (rich and poor economy societies), **Hydrological:** (deterministic/periodic/intertemporal but not stochastic) and optimised to obtain optimal investment strategies
Socio-economic development & the state of natural resources (*land and water*)	Akiyama et al., 2012	**Hydrological:** Water storages, **Political:** water use guidelines, **Social:** culture and traditions, **Environmental:** environmental degradation, **Technological:** dams and channels
	Srinivasan et al., (2013)	**Hydrological:** water sources (storage), **Economic:** industrial develoment and land-use, **Social:** population dynamics, **Technological:** infrastructure
	Fernald et al., (2012, 2015)	**Hydrological**: water, **Economic:** irrigation, **Social:** society's culture, **Environmental:** Ecosystem health
	Elshafei et al., (2014)	**Hydrological:** all sources of water, **Economic:** irrigation, **Social:** community sensitivity and response, **Environmental:** ecosystem integrity, **Technological:** water use efficiency
	van Emmerik et al., (2014) Kandasamy et al., (2014)	**Hydrological:** water balance equations, **Economic:** irrigation, **Social:** population & enviro-awareness, **Environmental:** ecological integrity
	Carey et al., (2014)	**Hydrological:** glacier meltwater & precipitation, **Economic:** agricultural activities, **Social:** societal responses (value, knowledge & culture), **Technological:** technology and engineering
	Liu et al., (2015)	**Hydrological:** all sources of water, **Economic:** irrigation, **Social:** community sensitivity and response, **Environmental:** ecosystem, **Technological:** water use efficiency
	Zhou et al., (2015)	**Hydrological:** all sources of water, **Economic:** irrigation, industry, **Social:** population dynamics, **Environmental:** water quality

2.3.5 Development and application of socio-hydrological modelling

One of the pioneering socio-hydrological studies was the modelling that captured the interactions, and feedbacks between socio-economic activities, and flooding events (Di Baldassarre *et al*., (2013). The model conceptualised coupling that captured

societal decisions whenever it flooded, and how such decisions impacted on flood mitigation actions that altered the flooding frequency, and magnitude. The state drivers of the model (wealth, flooding, distance, awareness, and levees) are represented by a set of differential equations whose variables are upset from time to time by flooding events. These variables are lumped together as a single entity of flooding, societal mental shock, and the decision and coupled to co-evolve over time. Societal response (mental shock), and decisions (moving away from the river or raising levee) are dynamically coupled, and dependent on the magnitude of the flooding, and the cost attached to it.

Elshafei *et al*., (2014) coupled socio-economic development, and the state of land, and water resources in an irrigation catchment. The model is conceptualised based on the concept of "change occurs due to a corresponding change in certain influencing factors", and the paradigm of "exposure–sensitivity–response" as identified in the theory, and literature of resilience (Dale *et al*., 2010; Turner, 2010). Two human characteristics are coupled to serve as the social aspects of the model: i) Community sensitivity, and awareness (to capture the perceived level of danger to a community's quality of life), and ii) behavioural responses (to capture the state of land and water condition). A slight change in a community's awareness due to the change in social driving variables, will change the way in which people are using land, and water in an irrigation settlement, via the behavioural response. The model performs well in the Murrumbidgee and Lake Toolibin catchments in Australia.

Fernald *et al*., (2012) developed a model describing the interactions, and feedbacks between water, agriculture, society, and the economy, leading to a scenario-based analysis to forecast system sustainability. Environmental awareness has also been used to develop a mediating strategy model to resolve water competition between agriculture, and ecosystem health (van Emmerik *et al*., 2014). The model is applied and found to perform well in the Murrumbidgee River Basin, Australia. Carey *et al*. (2014) linked political agendas, governance, technology, land and resource use, and societal responses. The model has been operationalised, and found to perform well in the downstream use of glacier runoff in Santa River, Peru. Zhou *et al*. (2015)

developed a catchment water balance model for water sharing between human, and environmental needs. The model has been used to analyse the historical co-evolution of socio-hydrological regimes, and its effect on the environment in the Murray-Darling Basin, Australia for over 100 years. Liu *et al*. (2015) conceptualised a socio-hydrological model for the co-evolution of people, and water in the Tarim River Basin (TRB), China. The model captures the community's attitudinal change due to changing ecological health based on water management guidelines. Other socio-hydrological studies (Viglione *et al*., 2014; Grames *et al*., 2015, and Ciullo *et al*., 2017) have used the system dynamics approach, as summarised in Table 2.8.

A scenario-based socio-hydrological simulation model for IWRM for the Herault River Basin (HRB), France, traced how water amounting to about three times than that allocated was diverted from the Herault River (Lanini *et al*., 2004). Liu *et al*. (2015) coupled water balance (hydrological) with ecological (vegetation), economic (irrigation), and social (population) state drivers. The model has been used to analyse the impact of socio-economic development (irrigation and population) on nature (water and ecosystem) in the Tarim River Basin in western China. Akiyama *et al*., (2012) modified Ken Wilber's All Quadrants All Levels (AQAL) approach to developed scenario-based conceptual models, and analysed the inter-locking relationships among four perspectives (physical, personal, cultural, and social). The model has been applied to investigate the relationships between social systems (human activities), and the changes in the natural environment (water) in the Ili River Basin for the period 1900–2008. Historical evidence has been used to analyse the trend of agricultural development, and environmental degradation in the Murrumbidgee River Basin, Australia (Kandasamy *et al*., 2014). Others that have used historical events, and other plausible scenarios to analyse the coupled human-water systems, include Liu *et al*., (2014), Srinivasan, (2015), Sivapalan & Bloschl, (2017) and Wescoat-Jr., *et al*., (2018).

Table 2.8: Human characteristics and modelling approaches used in the previous socio-hydrological models.

Author(s) / Reference	Case studies	Human characteristics	Modelling approach
Akiyama et al., (2012)	Ili River, China /Almaty Oblast Kazakhstan	Aggressive Wealth Creation	Scenario Analysis
Carey et al., (2014)	Santa River, Peru	Societal Response	System Dynamics
Di Baldassarre et al., (2013,2015)	Hypothetical Floodplain	Societal Risk Awareness and Response	System Dynamics
Elshafei et al., (2014)	Murrumbidgee Catchment, Australia	Community Sensitivity & Behavioural Response	System Dynamics
Fernald et al., (2012)	New Mexico, USA	Societal Culture and Identity	System Dynamics
Fernald et al., (2015)	New Mexico, USA	Community Resilience and Cohesion	System Dynamics
Gober & Wheater, (2014)	Saskatchewan River Basin, Canada	Fragmented and Overlapping Governance	Scenario Analysis
Liu et al., (2015)	Tarim River Basin, China	Evolving Community Awareness	Scenario Analysis
Srinivasan, (2015)	Chennai city, India	Emergency Response	Scenario Analysis
van Emmerik et al., (2014)	Murrumbidgee River Basin, Australia	Environmental Awareness	System Dynamics
Viglione et al., (2014)	Hypothetical Catchment	Community Risk Coping Culture, collective memory and trust	System Dynamics

2.4 Summary of Literature Review

Although studying the human-water inter-play has recently attracted much attention, as discussed in Sections 2.3, studies relating reservoir operation to stakeholders' propensity to unlawful activities, have not been found in the literature. Morever, in South Africa, reservoir operation is an essential aspect of water management and the impact of human behaviour on water management is significant. Based on these, the knowledge gained from the review was then applied by developing a reservoir operation-human behaviour socio-hydrological simulation-optimisation model for assessing the impact of human behaviour on reservoir system performance. Such a novel approach of realistic incorporation of the causes and effects of human behaviour is in line with the quest for changing water governance towards the inclusion of new realities.

Therefore, a coupled reservoir operation and human behaviour socio-hydrological model should be developed based on the notion that reservoir hydrological state can affect water stakeholders' propensity to compliant or unlawful activities. The model was conceptualised using the concept of *'changes in human decisions and actions*

occur due to reaction (response) to certain influencing factors (stimuli)'. Such a concept has been identified in the literature and theory of resilience (Forbes et al., 2013) and recently used by Elshafei et al., (2014). The perceived influencing factors in this study are the reservoir hydro-climatic conditions or hydrological state (rainfall, streamflows and evaporation) have been found to affect stakeholders' risk perception and water utilisation patterns (Elshafei et al., 2014; Firoz et al., 2017). Therefore, the concept of stimuli-response of the resilience literature was used as the predictor for water stakeholders' propensity for lawful or unlawful activities relating to water abstractions. The conceptual basis and mathematical quantification of reservoir operation socio-hydrological model is extensively described, and presented in chapter three.

CHAPTER THREE

3.0 SOCIO-HYDROLOGICAL MODELLING FOR THE COUPLING OF RESERVOIR SYSTEM OPERATION AND HUMAN BEHAVIOUR

This chapter informs how the remaining objectives were achieved. Objective one has already been achieved in chapter three, whereas this chapter presents a detailed description of the conceptual basis and mathematical quantifications of the socio-hydrological model of reservoir operation (Section 3.1). This chapter also presents a reservoir operation simulation model that couples, and dynamically co-evolves hydrologic, and human behaviour (Section 3.2). The formulation of plausible scenarios of varied human behaviour and hydrologic states, to assess the impact of human behaviour on the reservoir system performance is then described (Section 3.2.2). The detailed simulation-optimisation modelling of the case study reservoir systems forms chapter five of this thesis.

3.1 Development of Human Behaviour Quantification Models

Unlawful water abstractions are behaviour-related activities, that can negatively affect reservoir system performance, especially in drought periods. The impact of such human activities on reservoir yield, though significant, are typically not explicitly incorporated into reservoir yield analysis. However, this study intends to develop reservoir yield analysis modelling, that will evaluate yield as not just the allocated supplies as typically assumed in conventional yield analyses, but more realistically by including the effects of human behaviour. Likewise, the inflows into the reservoirs were not just considered as the hydrologically estimated streamflows, but flows that also include human behaviour impacts. The aim was to account for the water abstractions along the waterways, and the reservoir upstream, that have been found to be significant (van Oel *et al.*, 2008). The vital part of this study is, therefore, not just the abstractions, but the human behaviour aspects relating to the abstraction. Thus, objective 2 aimed at developing a socio-hydrological model for quantifying water users' propensity for compliant, or unlawful behaviour relating to water use.

An attempt to incorporate the impact of lawful/unlawful water use in the reservoir yield analysis, can serve as a realistic assessment that minimises unnecessary

assumptions, as suggested by Ndiritu, (2005). Besides, the outcomes can add value to the reservoir operational decision making. The proposed modelling framework is built in a manner that allows the effect of human behaviour to vary dynamically with the hydrological state of a given reservoir system. The modelling assumes that unlawful abstractions can occur whenever water users' integrity is adversely impacted by rising perception of risk, due to the occurrence of a poor reservoir system hydrological state. In this study, unlawful water abstractions are considered to be all forms of water abstractions that exceed the authorised water allocation in time or space. Unauthorised water abstractions are known to occur widely, and many instances of this have been documented, including the following:

i) Unauthorised diversion or syphoning of water from waterways (Ginster *et al*., 2010; DWS, 2016; Philanda, 2017; Felbab-brown, 2017).
ii) Tampering with water meters to take more than the allocated amount (Hermann-friede *et al*., 2014; Davis, 2004; González de Asís *et a*l., 2009).
iii) Construction of mini farm dams upstream of the reservoirs without authorisation (DWS, 2016; Philanda, 2017).
iv) Collusion between users and operators to over-allocate water, or failure to impose restrictions (IPCA, 2010; Lanini *et al*., 2004; Ménard *et al*., 2018).
v) Over application of water by irrigation users ignorantly (Chikozho, 2001; Qureshi, 2002; Hasanain *et al*., 2012).
vi) Other forms of water usage that violate the rules (Hermann-friede *et al*., 2014; Davis, 2004; González de Asís *et al*., 2009).

At a particular time, unlawful water abstractions can occur at one or more of the following locations within a water resource system:.

i) Along inflows to the reservoirs which can be incremental runoff from the incremental catchment, regulated flows or spills from the upstream reservoir(s);
ii) At diversion/intake points to various water users (this may be through collusion with water operators or tampering with water meters);
iii) Along diversion channels before reaching the targeted user(s);
iv) Along the regulated flows from the upstream reservoir(s) before reaching the intended downstream reservoir(s);
v) Along inter-basin transfer schemes from one water management area (WMA) to the demand site(s) of another WMA;

vi) Along the international/interregional water transfer schemes from one country/region to the demand site(s) of another country/region respectively; and
vii) Along the flows that are intended for ecological use.

In South Africa, such unlawful water abstractions by irrigation users can have significant negative impacts on reservoir performance, as over 60% of the freshwater in South Africa is used by agricultural users (van Oel *et al*., 2008; Baleta & Pengram, 2014; IMPEL, 2017). With the aim to explore and gain insight into how and to what extent unlawful water abstractions can affect reservoir performance, the study is confined to investigating the impact of illegal water use by irrigation users as this found to significantly affect the performance of WRS in South Africa. Therefore, socio-hydrological modelling relating a reservoir system hydrological state to the behaviour of irrigation users, and managers of the reservoir system, is perceived, conceptualised, and developed in the next subsections.

3.1.1 Conceptual framework for coupling hydrological state with human behaviour

The reservoir operation-users' behaviour coupled socio-hydrological model is conceptualised based on the notion that the reservoir hydrological state can influence water stakeholders' behaviour. The coupled model is developed to gain insights into the following four questions.

a) How do changes in reservoir hydrology (rainfall, evaporation, and inflows) affect water users' propensity towards compliant, or indulge in unlawful activities?
b) How do water users' behaviour, and actions affect reservoir performance?
c) How can reservoir performance, in turn, influence stakeholders in terms of their well-being, and management decisions?
d) How do management decisions affect the reservoir hydrological status?

These questions are aligned with the Panta Rhei's science question number 2: "*how do changes in hydrological systems interact with, and feed back to, natural and social systems driven by hydrological processes"?* (Montanari *et al*., 2013). For example, in drought periods, reservoir storage drops and water managers usually respond by implementing demand management measures. Such measures comprise of supply restrictions (Kuria & Vogel, 2014), awareness-raising campaigns (World Bank, 2015),

legal actions (DWS, 2016), and participation and policy dialogues (Rogers & Luton, 2011). Some water users might adjust to such conditions, whereas others could decide to unlawfully abstract water not allocated to them (Philanda, 2017). Such unlawful activities upstream of a reservoir, and low runoff have been suspected to be the reason behind the drastic reduction in reservoir storage commonly experienced in drought periods (van Oel *et al*., 2008). Kinzig *et al*., (2013) suggested that the perceived level of risk by a given society can interrupt, and change that society's established norms and values (behaviour). For example, it has been observed that severity of drought has a direct relationship with the rate at which irrigation users abstract water, due to a rise in the perceived risk to their quality of life (Elshafei *et al*., 2014; Firoz *et al*., 2017). According to *Elshafei et al.* (2014), whenever the available amount of water decreases and water users become well aware of the situation, the users' perceived level of risk increases. Also, the drier and hotter a year is, the higher the evapotranspiration, and thus the higher the crop water requirement becomes (Abbas & Chowdhury, 2016). This will instigate irrigation users to demand more water, which could enhance concern over a perceived water shortage. Therefore, it can be ascertained that the hydrological state can change the level of irrigation users' perceived threat to their farming activities, and financial state. Such changes in the users' risk perceptions are also expected to subsequently change their level of compliance with the water allocation rules.

Apart from the hydrological state, the modelling also conceived and proposed two situational composite factors each for management and users, which can affect users' level of risk perception. The two factors are management competence, and users' compliance. These factors are specific to a given reservoir system, and are incorporated into the risk perception function, and are also used while developing human behaviour scenarios (Section 3.2.2). The change in users' risk perception, which could lead to being either compliant or engaging in unlawful activities, was then modelled, and related to the change in the following three variables:

i) Hydrological state
ii) Management competence
iii) Users' compliance

3.1.1.1 Modelling of hydrological state

The hydrological state is affected by hydro-climatic conditions, including rainfall, evaporation rate, and inflows. This then impacts the users' propensity for compliant, or unlawful activities, especially if supply restrictions or other demand management measures are anticipated in that cropping season. In years of drought, when the available monthly supply is below the normal supply due to imposed restrictions, it is expected that the risk perception will intensify. Hence, it can be deduced that the state of hydro-climatic conditions can have a direct influence on the irrigation users' behaviour (intentions and actions). In reservoir operation, the major hydro-climatic variables known to influence the storage state are inflow into the system, and the net evaporation from the system. Thus, hydro-climatic data could be used as an indicator of the system's hydrological state.

As stated in Section 3.1.1, the annual users' risk perception depends on the annual hydrologic state, which are natural phenomena, and highly variable. Also, users do not know what the storage state could be at the end of the rainy season. When the rainy season begins, the water stakeholders are known to monitor the pattern of the rainfall, and temperatures based on their experience, and weather reports. The concern due to risk perceptions will begin to heighten, or remain neutral, depending on whether the rainy season is considered as dry and hot, or wet and cool. When the available water at the beginning of the water year is insufficient, the users' risk perception will rise (Elshafei *et al.*, 2014), and the higher the propensity for unlawful activities will be. Because drought (dry and hot) years are associated with a high crop water requirement (Abbas & Chowdhury, 2016), irrigation users will demand more water. Hence, the more aggressive irrigation users can be due to a perceived threat to their quality of life, the converse is the case if the year is wet and cool. The annual users' risk perception is, therefore, directly related to the change in the annual hydrological state, which is shaped by the hydro-climatic conditions. Hence, the need to develop a robust water allocating rules (reservoir operating rules) that can account for this.

Thus, the overall view of the hydro-climatic conditions of a given reservoir system is that of unpredictable factors, that affect users' risk perception, and water utilisation pattern. Depending on the nature of the problem at hand, an aridity index, or dryness index, could be employed as the parameter with which to represent the factor of the hydrological state. An aridity index is an indicator representing the degree of dryness of the climate, and is used to delineate regions that suffer from a deficit of water availability (Sahin, 2012). Although there are many methods for computing an aridity index, the one popularly used was developed by the United Nations Environmental Programme (UNEP) as the ratio of the average annual precipitation to the annual potential evapotranspiration (UNEP, 1992). Moreover, an aridity index has been found to reasonably estimate water utilisation patterns (Tabari & Aghajanloo, 2013). In this study, the hydro-climatic data used to serve as the surrogate for the hydrological state are rainfall, temperature, and storage. Since rainfall, temperature, and storage are highly variable, and often described probabilistically, the hydrological state can also be treated probabilistically.

Hence, the dynamic coupling of the hydrological state, and irrigation users' behaviour, is developed based on the probabilistic relationship that links the hydrological state to the users' risk perception, and behaviour. In essence, a decrease in the hydrological state can increase the level of users' risk perception, and hence increase a propensity for unlawful activities such as tendencies to abstract water unlawfully.

With the aim of relating the hydro-climatic variables to the hydrological state on a yearly basis, normalised annual relative changes of hydro-climatic variables are computed. The annual hydrological state is based on the deviation from the long-term average of the rainfall, evaporation, and storage state. The annual normalised deviation of rainfall, and the maximum temperature, can be computed as the difference between the mean annual value, and the annual value (annual deviations from the average values) divided by the mean annual value, as shown in equation 3.1**,** and 3.2 respectively. The storage state at the annual decision time, which is mostly after the end of rainy season (April) in South Africa, is used in the quantification of the hydrological state. The mean is replaced with a given storage-state-threshold value

above which no restrictions are imposed, and, hence, no risk perceptions are anticipated, as shown in Equation 3.3.

$$\tilde{P}_i = \frac{(P_{mean} - P_i)}{P_{mean}} \quad 3.1$$

$$\tilde{T}_i = \frac{(T_{mean} - T_i)}{T_{mean}} \quad 3.2$$

$$\tilde{S}_i = \frac{(S_{th} - S_i)}{S_{th}} \quad 3.3$$

Where*:* $\tilde{P}_i$, $\tilde{T}_i$and $\tilde{S}_i$ are the normalised deviation in precipitation, maximum temperature and storage state for year i. P_i, T_i and S_i are the values of precipitation, maximum temperature, and storage state for year i, P_{mean} and T_{mean} are the mean annual values of precipitation, and maximum temperature. S_{th} is the storage threshold value above which no risk perceptions are expected.

The corresponding annual hydrological state can be estimated as the weighted average of the three normalised hydro-climatic variables, as expressed in Equation 3.4. A negative sign is, however, assigned to the normalised deviation in temperature, because a high temperature is associated with a high rate of evaporation, and, hence, an unfavourable hydrologic state. Depending on the climate of the reservoir location, the rainfall, temperature, and storage can have varied impact, and weights (w_P, w_S and w_T) were introduced to enable this variability to be effected, as shown in Equation 3.5.

$$HS_i = w_P\tilde{P}_i + w_S\tilde{S}_i - w_T\tilde{T}_i \quad 3.4$$

$$w_P + w_S + w_T = 1 \quad 3.5$$

Where: HS_i is the hydrological state of year i, $\tilde{P}_i$, $\tilde{T}_i$and $\tilde{S}_i$ are the normalised deviation in annual precipitation, temperature, and storage state for year i, w_P, w_T and w_S are weighing parameters for rainfall, temperature, and the storage state which can be optimized.

3.1.1.2 Modelling of management competence

Management competence is comprised of many factors that affect water managers' performance. It represents a reservoir system's infrastructural development, and a water managers' expertise, monitoring, and law enforcement measures for preventing unlawful water use (DWA, 2009; Arle *et al*., 2016; Pang *et al*., 2014). This factor can also be affected by issues such as political agendas, and employees' job

satisfaction (promotion, incentives, and other benefits). When water users perceived that water managers, supply facilities, and surveillance systems are satisfactory, they are expected to have peace of mind, and, hence, the risk perception will reduce. Conversely, if users perceived that the managers and facilities are not satisfactory, this will intensify their level of risk perceptions (Omar *et al*., 2017).

The modelling incorporates the fact that whenever there are unlawful activities, the management will respond by employing measures to eliminate or reduce such activities. In a situation where a reservoir system is operated under few cases of unlawful water use, and the negative impact of such actions are negligible, the management may carelessly ignore it, and decide not to take any action. Because of this lack of action, unlawful activity is likely to proliferate with time, since capitalistic human tendencies work towards maximising the utility for economic benefits, as explained in the consequentialist ethical theories of egoism (Persky, 1995; Monroe, 2001). Another reason is that human beings are known to imitate the way in which others do things, which commonly lead to the evolution of new social norms, as explained in the descriptive social norms theory (Levin *et al*., 2013; McLeod, 2016). Hence, the absence of action on unauthorised water use may gradually lead to a severe negative impact on the reservoir system performance. It is possible that the low storage states observed for Hluhluwe Dam in South Africa during non-drought years (2001 to 2010) (Ndiritu *et al*., 2017), could be attributed to this.

The modelling perceived and assumed a situation whereby a given reservoir may be operated under such adverse unlawful water use. Such a situation can be found when the level of management competency, and users' compliance are very low. When such a condition continues, it is expected to reach a point where the impact of unlawful use will become noticeable, and intolerable. Depending on the level of ethical practices in that reservoir system, such situations is expected to attract the attention of water stakeholders, leading to implementing some intervention measures. When the management takes appropriate action, the unlawful activities are expected to decrease, leading to reservoir performance improvement. The time it will take while unlawful water use keeps on impacting on the system, can be referred to as the

adverse human impact period. Conversely, the time it will take before unlawful water use returns due to the variability of the hydrologic state, users' compliance and management competence can be termed as *the favourable human impact period*.

Depending on the availability of data, some measurable parameters related to water allocation efficiency can be used to serve as a surrogate for this factor. For example, the Water Allocation Monitoring Index (WAMI) can be employed as the parameter to represent this factor. WAMI is a water management area-based (WMA) index developed in South Africa to monitor the proposed water allocation reform (WAR) targets. The WAMI indicator is a composite indicator, which integrates water use data with environmental, economic, and equity data to provide a holistic picture of WAR for a given WMA into a single score (Anderson *et al*., 2008). As the WAMI decreases, the users' risk perception is expected to rise due to the perceived threat to their quality of life. Therefore, the WAMI (where available) or any other water allocation performance indices, can be used as a proxy to this factor. But, in this study, the management competence was incorporated dynamically for 90-years on monthly basis. Such long period data that would be required to verify the modelling using WAMI (or another approach) were not available and not obtainable within the time constraints which this led to the modelling of management competence hypothetically using a probability density function (PDF).

Thus, management competence was modelled probabilistically, using a probability density function (PDF). The moment of this distribution is varied to obtain different levels of management competences. Hence, management competence was modelled as the hypothetical function of system infrastructures, managers' efficiency, and job satisfaction. Depending on these factors, the overall management competence can change over time, and these changes can be obtained by analysing the distribution of the measured management performance data for a long period.

Management performance studies are usually conducted in human resource management, and the normal distribution has been found to fit the observed data accurately (Sarkar *et al*., 2011; RO, 2018). Depending on the employees' work engagement, the distribution of the organisational performance can skew to either

right or left, indicating ineffective, or effective performance respectively. The management competence distribution can, therefore, be skew-normal with the degree of asymmetry characterised by a negative or positive skew parameter ($\boldsymbol{\lambda}$).

The term skew-normal is a parametric class of probability distributions that extend the normal distribution by an additional shape parameter ($\boldsymbol{\lambda}$), which regulates the skewness in addition to location ($\boldsymbol{\mu}$) and scale of ($\boldsymbol{\delta}$) parameters (Azzalini, 1985). The shape parameter allows the continuous variation of the distribution from normal to skew-normal (Ashour & Abdel-hameed, 2010). As time goes on, some factors can affect the normal probability distribution of the management competence to skew. The probability of getting below average competence in right-skewed, is higher than that of getting above average, and this is conversely true of the left-skewed.

The management competence will be a random variable, since it was randomly generated from the parameters that plausibly estimated the PDFs (normal, right, and left-skewed). The cumulative probability functions (CDF) of management competence, was then constructed by integrating the PDF. The management competence with a different probability can then be drawn randomly, as shown in Figure 3.1.

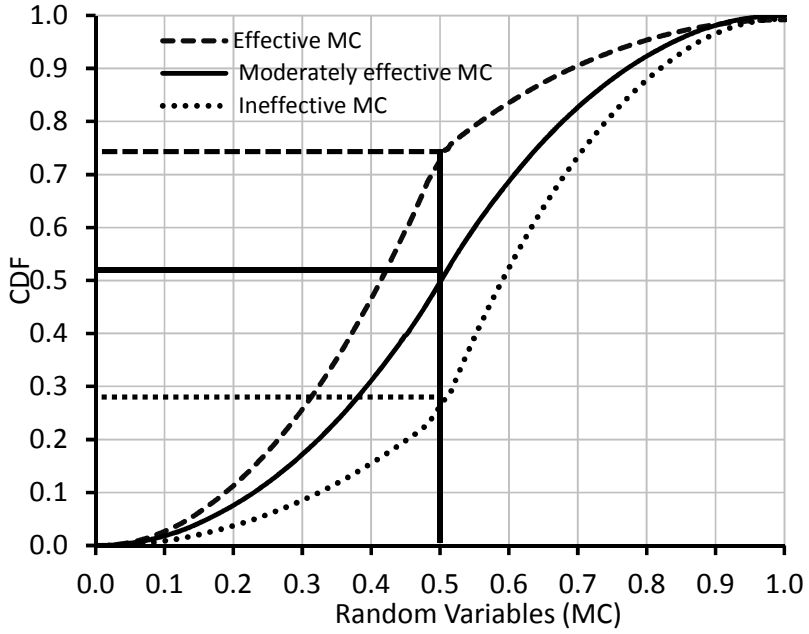


Figure 3.1: Cumulative probability functions for the three levels of management competence

3.1.1.3 Modelling of users' compliance

The water users' compliance factor is introduced to represent the level of users' awareness, understanding, cooperation, and propensity for compliance, especially in drought periods. This factor is proposed based on the imperical studies which revealed that an increase in risk perception has a direct influence on individuals' intentionin a manner thatcan shape their level of compliance to water allocation rules (Kinzig et al., 2013). Thus, users' level of risk perception can be influenced by their level of knowledge, culture, religious and spiritual beliefs, and awareness. Others include social well-being attributes, such as access to good healthcare, education, electricity, water, sanitation, and transportation systems (Van Zyl, 2001; Akiwumi, 2010; Rogers & Luton, 2011). A well-being index for a given society is normally used to estimate the level of development with regard to the standard of living, based on the basic human needs of that society (Friedman, 2013). Studies show that a positive relationship co-exists between society's well-being and ethical practices, as in accepting newly introduced resource management policies (Tiliouine & Cummins, 2006; Bravo, 2014; Bergheim, 2006). Therefore, the less prosperous a society is, the more concerned and hostile that society could be due to a perceived threat to their quality of life. A higher propensity for compliant activities is, however, expected in a flourishing society. Section 2.2.2.2 provides details on how users' compliance improved water management performance.

Indices that estimate human development, and social well-being can be used to serve as a proxy for this factor. Some of these social well-being indices include the Human Development Index - HDI (UNDP, 1990, 2015), and the Social Progress Index - SPI (Porter *et al*., 2016). But, in this study, users' level of compliance is also perceived to be changing with time in a probabilistic fashion, due to the unpredictable nature of human behaviour. Hence, the users' level of compliance was also modelled probabilistically, using PDF in the same way as management competence was modelled in Section 3.1.1.2.

Therefore, the annual irrigation users' risk perception as related to the hydrological state, management competence, and users' compliance, is as expressed in Equation

3.6. When the calculated annual users' risk perception at the beginning of water year is found to be less than or equal to zero, the higher the users' propensity for compliant behaviour. However, if the computed annual users' risk perception is greater than zero, the higher the users' propensity for unlawful actions, such as unlawful water use.

$$RP_{i,j} = (HS_i).\left(1 - UC_{i,j}\right).\left(1 - MC_{i,j}\right) \qquad 3.6$$

Where: $RP_{i,j}$ is the estimated level of users' risk perception in the month j of year i. HS_i is the hydrological state of year i. $MC_{i,j}$ and $UC_{i,j}$ are the levels of management competence and users' compliance in the month j of year i respectively.

Figure 3.2 shows the trajectory of the deviations of historical annual rainfall from the average value (600 mm) for the rainfall station 0551120W located in the quaternary B31C, which is situated in the Upper Middle Olifants River (Middleton & Bailey, 2008).

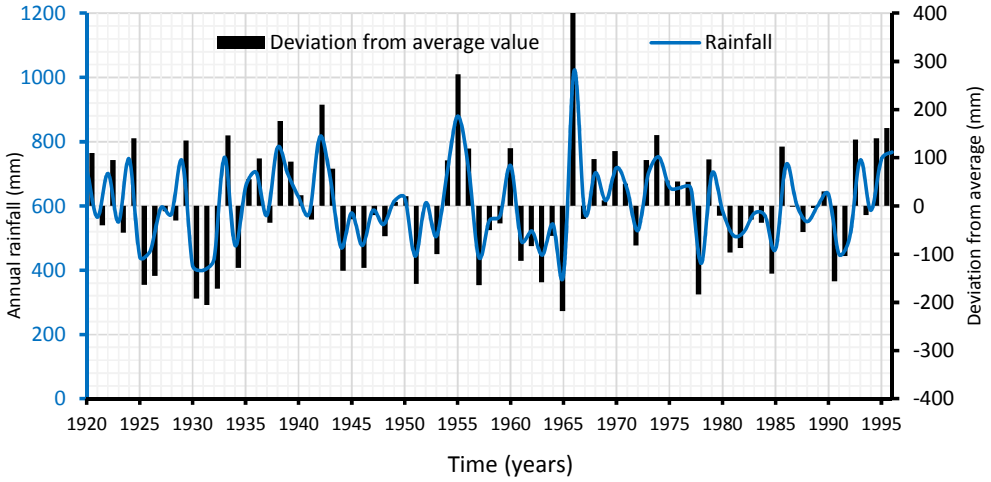


Figure 3.2: Deviations in annual rainfall values from the average annual value

Figure 3.3 shows the deviations of the annual storage levels from the storage threshold level (S_{th}) for the Rust de Winter Dam, situated in the Upper Middle Olifants River Water Management Area.

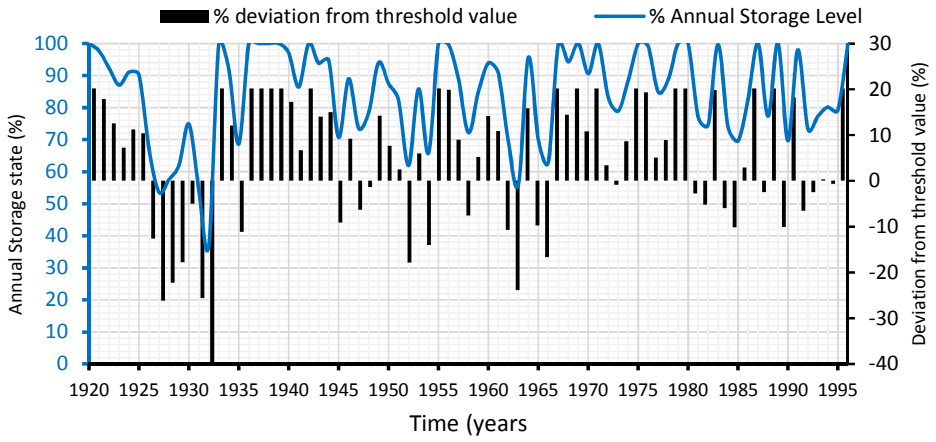


Figure 3.3: Deviations in annual storage levels from the storage threshold value (S_{th})

Figure 3.4 show the trajectory of the modelled users' risk perception as a function of the hydrological state, management competence, and users' compliance. The hydro-climatic data for the data station (0551120W), which is close to the reservoir system under consideration, were used. The users' risk perception was found to increase or decrease whenever the hydrological state, management competence, and users' compliance decrease, or increase respectively.

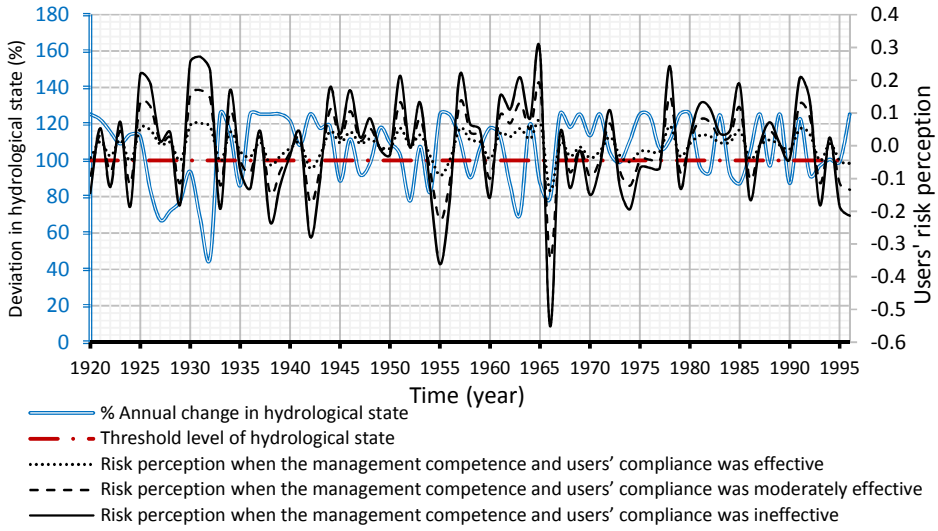


Figure 3.4: Trajectory of the annual users' risk perception as a function of the hydrological state, management competence and users' compliance.

3.1.1.4 Modelling of users' behavioural intention

The modelling further perceived, and conceptualised, how an increase in users' risk perception could lead to change in users' behavioural intention. Behavioural intention is defined as the individual's perceived likelihood (subjective behavioural control) to engage in a particular manner (Ajzen, 1991). Risk perception has been found to influence individuals' behavioural intentions and actions, thereby eroding the propensity for compliance (Gonzalez & Sawicka, 2003; Williams & Noyes, 2007). The inclination of users' behavioural intention towards compliance, or violation of rules due to change in their risk perception, was modelled as a stimuli-response system. Therefore, the users' level of risk perception, and the resultant probable behavioural intention, which can either be compliant or unlawful, are related to using the inverted sigmoidal function, as shown in Equation 3.7. Logistic regression functions are non-linear classification algorithms commonly used to classify, and discriminate between two or more probable events (Komarek & Moore, 2005). The logistic regression helps in predicting the possibilities for an event to occur, or not (Dreiseitl & Ohno-Machado, 2002). The behavioural intention (Equation 3.7) takes a value between 0 and 1, and is the probability estimate for predicting whether an action will occur based on the risk perception, which itself depends on the hydrological state, management competence, and users' compliance (Equation 3.6).

$$BI_{i,j} = \frac{1}{1 + e^{RP_{i,j}}} \qquad 3.7$$

Where: $BI_{i,j}$ and $RP_{i,j}$ are the users' behavioural intention and risk perception in the month j of year i respectively.

Users' perceived behavioural intention could lead to compliant or unlawful actions, and this depends on two possibilities.

i) The range in which the users' behavioural intention fall, on the scale ($0 \leq BI \leq 1$). A value of behavioural intention that exceed a given decision boundary parameter α ($BI \geq \alpha$), indicates a highly desirable intention that may lead to lawful activities, whereas a low value of behavioural intention, ($BI < \alpha$), indicates an intention that may likely lead to unlawful activities.

ii) The users' level of compliance due to uncertainties with ascertaining precisely when unlawful activities could occur. This situation is possible such as when users decide to comply with the rules, even when the behavioural intention is low, or management performs remarkably well in preventing unlawful water use. The users' level of compliance has already been modelled in Section 3.1.1.3

The inverted sigmoidal function will be incorporated into the reservoir operation simulation model, and set to predict results in a discrete output based on the decision boundary (α). The level of users' behavioural intention from the inverted sigmoidal function will, therefore, serve as the threshold that creates a decision boundary between the possibilities for compliant and unlawful activities at α. The occurrence or non-occurrence of unlawful water abstraction can thus be said to depend on the users' behavioural intention, and users' compliance. With the aim to incorporate a situation whereby users' can decide to abide by the rules, even at lower behavioural intention, a parameter β was introduced. This parameter describes the extent to which users' compliance can overcome the users' behavioural intention to engage in lawful activities, even if the intention is likely to lead to unlawful activities. Also, the parameter β can help in applying the model in other reservoir systems by calibrating or estimating it to match the study area Also, this was used to specify the time of month when the unlawful abstractions occurs. For example, in a drought year (i) in which the BI_i predicted that unlawful activities may occur, the users' level of compliance was used to randomly specify the time in the month (j) within that year when the unlawful water use could be invoked. Since it is unrealistic to assume that the unlawful abstractions will occur in every month of a year with low behavioural intention, the occurrence or non-occurrence of unlawful water abstraction is, therefore, determined as follows:

$$If \begin{cases} BI_{i,j} \geq \alpha; & Unlawful\ water\ abstraction\ does\ not\ occur \\ BI_{i,j} < \alpha \begin{cases} If\ UC_{i,j} > \beta * BI_{i,j}; & Unlawful\ water\ abstraction\ does\ not\ occur \\ If\ UC_{i,j} < \beta * BI_{i,j}; & Unlawful\ water\ abstraction\ occurs \end{cases} \end{cases}$$

Hence, when the parameters α and β increases, the higher the possibilities for the unlawful activities to occur. The α can take a value between 0.2 and 0.8, whereas β between 1 and 3. Figure 3.5 shows the stimuli-response relationship between the

users' risk perception, and behavioural intention using the inverted sigmoidal function (Equation 3.7), and the level of users' compliance. The users' risk perception-behavioural intention response shown in Figure 3.5 is for when $\alpha = 0.5$ and $\beta = 2$. Parameters α and β can be determine using reservoir operation and yield optimization modelling to define best values of α and β that can lead to better yield.

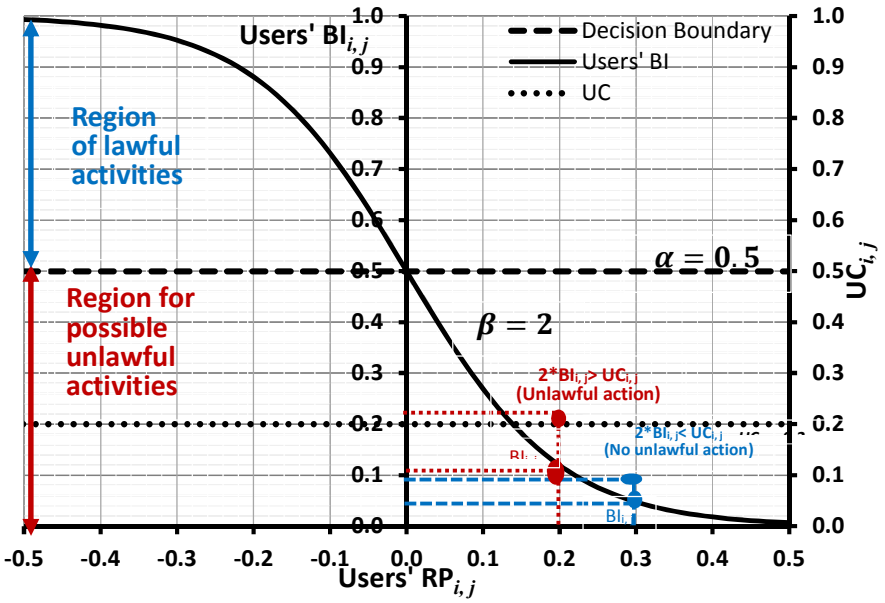


Figure 3.5: Risk perception-behavioural intention response from the sigmoidal function

Figure 3.5 gave an example with $\beta = 2$, when RP are 0.2 and 0.3 the corresponding BI were 0.12 and 0.05. Hence the $\beta * BI$ will be 0.24 and 0.1 respectively. Also, since UC = 0.2, therefore, unlawful abstraction may likely occur in the case with BI = 0.12 since $UC < \beta * BI$ (0.2 < 2.4).

3.1.1.5 Modelling and quantifying unlawful abstractions impact

This section presents the conceptual basis for the estimating the magnitude of the unlawful abstraction impact on the reservoir performance. The unlawful abstractions impact was modelled to vary with the level of users' perceived risk, as more water is expected to be abstracted illegally as risk perception increases (Firoz *et al*., 2017).

In Section 3.1.1.4, the users' behavioural intention was modelled to determine the frequency, and intensity of the occurrence of unlawful activities. However, the variable unlawful abstractions impact (UI) is introduced to quantify the impact of the

unlawful activities when they occur. In this study, the unlawful abstractions impact is considered as the proportion of water that is being abstracted unlawfully, mostly by irrigation users. Previously, the modelling related to the state drivers as follows:

i) Users' risk perception to the reservoir hydrological state, management competence, and users' compliance as presented in Section 3.1.1.1 through Section 3.1.1.3.
ii) Users' behavioural intention to users' risk perception, as described and modelled in Section 3.1.1.4.

However, the level of adverse effects due to unlawful activities is also perceived, and expected to vary with the level of users' risk perception, and the availability of the water at users' disposal. The modelling, therefore, relates unlawful abstraction impact as a response to users' risk perception, and water availability. Hence, response models can be used to model the users' response (unlawful water abstractions) to the level of perceived risk, and water availability.

Response models are used to model and predict the desired behaviour to act in a specific manner (Ham *et al.*, 2015). Response models have been used in different research disciplines such as marketing, healthcare and ecology (Hanssens *et al*., 2005; Hunsicker *et al*., 2011; Weng *et al.*, 2017). The popularly known and widely used response models in ecology are the functional response models, usually used to study the interplay between 'predator' and 'prey', and are generally classified into three types, Holling's types I, II, and III (Holling, 1959). Functional response models are used to model the intake rate of a consumer (predator) as a function of the food density (prey), the rate of the prey-predator encounter, and the time is taken before processing the food (Aljetlawi *et al*., 2004). The type I functional response model assumes a linear increase in intake rate with food density, without restrictions. Type II functional response is characterised by a slowing intake rate by the consumer due to limited capacity to process the prey (e.g., when the predator is about to be satisfied), and when there are less prey at predators' disposal. The type II model also allows ample time to process the food, whereas type III functional response is similar to type II, except that type III lacks theoretical basis (Skalski & Gilliam, 2001).

The modelling conceives that users abstract water unlawfully when the perceived threat to their quality of life intensifies as a result of a poor hydrological state, and other situational factors. Such risk perception-unlawful abstractions response can be related to when a hungry predator is looking for food (predator-prey). The rate at which the predator will hunt for prey, as identified in the ecology literature (Aljetlawi *et al*., 2004; Smout *et a*l., 2010), depends on:

i) prey-predator encounter rate
ii) availability of the prey at predators' disposal
iii) time to process the prey

Similarly, the magnitude of unlawful abstractions impact can be related to:

i) level of users' perceived risk,
ii) availability of the water at users' disposal
iii) time to use the illegally abstracted water (this time was simply considered as deterministic due to simulation time steps)

Based on the aforementioned predator-prey response relationship, it can be deduced that unlawful abstraction is a response to the users' risk perception, and water availability. Based on the identified variables, the Hollings type II functional response model was adopted to model the unlawful abstraction impact as a response to users' risk perception, availability of water at users' disposal, and the simulation time interval, as expressed in Equation 3.8. The water availability is the ratio of the allocated supply to the required demand. The time taken to use the illegally abstracted water, will be the ratio of the time-step used in the simulation (1/12 for monthly steps simulation).

$$UI_{i,j} = \frac{RP_{i,j}.\rho_{i,j}}{1 + UP_{i,j}.\rho_{i,j}.\tau} \qquad 3.8$$

Where: $UI_{i,j}$, $RP_{i,j}$ and $\rho_{i,j}$ are the adverse unlawful use impact, risk perception and proportion of allocated supply in the month j of year i. τ is the simulation time step.

Figure 3.6 shows the trajectories of the unlawful abstraction impact for different levels of users' level of risk perception, and the proportion of allocated supply.

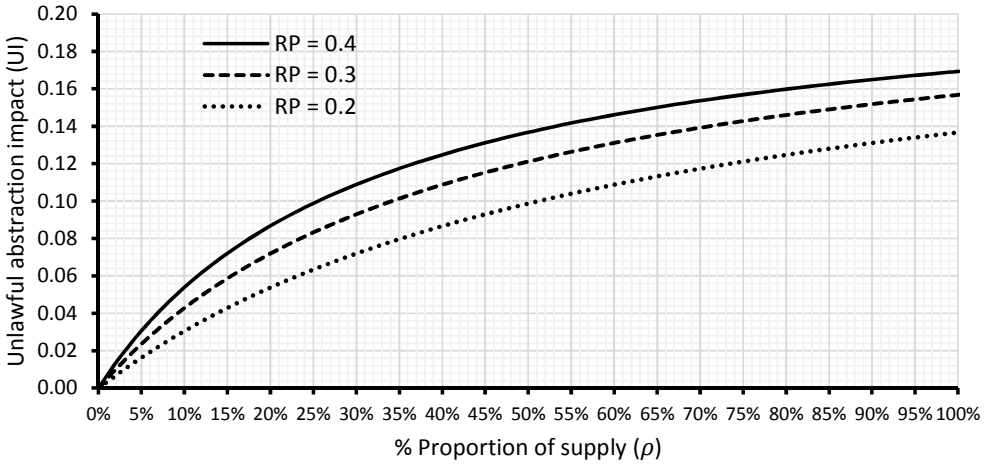


Figure 3.6: Hypothetical estimation of the unlawful abstraction impact for different levels of users' risk perception and proportions of allocated supply.

In a situation where such data are readily available, the model can be applied as follows:

- To set a boundary on the maximum amount of water that was reported to be abstracted unlawfully as modelled in Equation 3.8.
- The rate at which unlawful water abstractions occur can be incorporated into the model by calibrating the decision boundary parameter (α) to match the case study reservoir system such that the users' behavioural intention (BI) from the sigmoidal function (Equation 3.7) serves as the threshold that creates a decision boundary between the possibilities for compliant and unlawful water abstractions to occur at decision boundary, α.
- To incorporate the extent to which users' compliance can overcome the users' behavioural intention (BI) to engage in lawful activities, even if the intention is likely to lead to unlawful activities (compliance behaviour), the parameter β should be calibrated to match the reported instances where users abide by the water allocation rules amid water supply shortage.

3.1.2 Coupling unlawful abstractions impact with reservoir variables

This section describes how the unlawful abstractions impact was coupled with the reservoir mass balance variables. The aim was to create a link for assessing the impact of unlawful water use on reservoir system performance.

Unlike in the conventional yield analysis, where yield is typically measured without due consideration for the impact of human behaviour, in this study the impact of unlawful water use was incorporated. Such a paradigm of yield analysis that accounts for the impact of human behaviour, is expected to help minimise unnecessary assumptions in yield analysis. Reservoir storage influences the amount of water to be released, and releases are determined to satisfy demand. Basically, one of the two situations is usually encountered, either the system is capable of satisfying all the demands, or it can only satisfy a portion of the demands. In the latter case, restrictions and other demand management measures are normally implemented. Also, the extent of the restriction depends on the storage state, operating rules, and the set supply reliabilities.

Depending on the hydrological state, levels of management competence, and users' compliance, the delivered supply (R^d) to a particular demand site may be equal to, or less than the allocated supply (R^a). When the users' propensity for compliance is high, and management is effective, it is expected that the delivered supply will equal the allocated supply, and inflows into the reservoirs will be as expected (without illegal abstractions at reservoir upstream). Conversely, when users' propensity for unlawful activities is high, and management ineffective, the delivered supply can be less than the allocated supply, and inflows can become reduced due to unlawful abstractions along supply waterways, and upstream of reservoirs respectively. The delivered supply, and streamflows to the reservoirs can, therefore, be expressed as in Equation 3.9 and 3.10 respectively.

$$R_{i,j}^{d} = \begin{cases} R_{i,j}^{a} & ;If\ unlawful\ abstractions\ are\ negligible \\ \left(1 - UI_{i,j}\right)R_{i,j}^{a} & ;If\ unlawful\ abstractions\ are\ significant \end{cases} \quad 3.9$$

$$Q_{i,j}^{d} = \begin{cases} Q_{i,j} & ;If\ unlawful\ abstractions\ are\ negligible \\ (1 - UI_{i,j})Q_{i,j} & ;If\ unlawful\ abstractions\ are\ significant \end{cases} \quad 3.10$$

Where; $UI_{i,j}$ is the unlawful abstraction impact in the month j of year i,$R_{i,j}^{a}$ and $R_{i,j}^{d}$ are the allocated and delivered supplies in the month j of year i respectively, $Q_{i,j}$and $Q_{i,j}^{d}$ are the expected and actual inflows to reservoirs in the month j of year i.

3.1.3 Coupling management competence with unlawful abstractions impact

The level of management competence in rectifying users' unlawful activities as modelled in Section 3.1.1.2, was coupled with the unlawful abstractions impact to serve as a feedback (interventions). Whenever reservoir performance begins to deteriorate due to unlawful activities, the management usually responds by employing intervention measures to rectify the problem. Such interventions include awareness-raising campaigns, encouraging participation, incentivising whistle blowers, policy dialogues, penalties, and legal action. Suppose that the unlawful abstractions impact of a given reservoir system with a given level of management competence is UI_{MC}. The management competence was modelled and scaled in a closed interval ($0 \leq MC \leq 1$), with a value of 1, indicating the highest level of management competence. Let MC and 1 – MC be interpreted as the probability that the reservoir system is protected from, and vulnerable to the unlawful abstraction impact. For simplicity, a linear relationship was used to relate how MC reduces the negative effect of unlawful abstractions impact on reservoir system performance.

Management would aim to minimize the proportion of water that is being used unlawfully (UI) and the level of success would depend on the management competence (MC). This led to assuming a linear impact of management competence on unlawful water use. The users' unlawful abstraction impact ($0 \leq UI_{i,j} \leq 0.2$) for a given level of management competence ($0 \leq MC_{i,j} < 1$) are thus linearly related as the product of the unlawful abstraction impact ($UI_{i,j}$), and the probability that the system is vulnerable to unlawful abstractions impact ($1 - MC_{i,j}$) as shown in Equation 3.11.

$$UI_{i,j(MC)} = UI_{i,j}(1 - MC_{i,j}) \qquad 3.11$$

Where: $MC_{i,j}$ is the management competence in the month j of year i, $UI_{i,j(MC)}$ and $UI_{i,j}$ are the unlawful abstraction impacts when there is and when there is no MC in the month j of year i respectively.

The developed unlawful abstractions impact-management competence model will then be incorporated in the reservoir operation socio-hydrological model to assess the impact of unlawful abstractions on reservoir yield at different levels of management competence, via behaviour scenarios, as explained in Section 3.2.2.

3.1.4 Summary of the reservoir operation socio-hydrological model

This section provides a summary of the developed reservoir operation-human behaviour socio-hydrological model. As previously described, when users' perceived risk continues to increase, due to the decrease in the hydrological state, and management, as well as users' situational factors, the users' propensity for unlawful actions will increase. Conversely, when the hydrological state, and the situational factors improve, unlawful activities will be reduced, and eventually cease, leading to an improved reservoir hydrologic state, and, hence, yield performance. The improvement of the hydrologic state will reduce users' risk perception, and increase their propensity for lawful activities. Therefore, the reservoir hydrologic state (*hydrological*) has a direct influence on users' propensity for compliant, or unlawful activities (*social*). Also, users' activities have a direct impact on the reservoir hydrologic state, and, hence, performance. Moreover, reservoir performance can, in turn, influence water stakeholders' in terms of well-being, and decisions. Four-state drivers were thus identified to quantitatively and stochastically constitute the reservoir operation socio-hydrological model.

1) Hydrological state
2) Users' compliance
3) Management competence
4) System performance

Figure 3.7 shows the inter-relationship between the four-state drivers of the coupled reservoir operation socio-hydrological model.

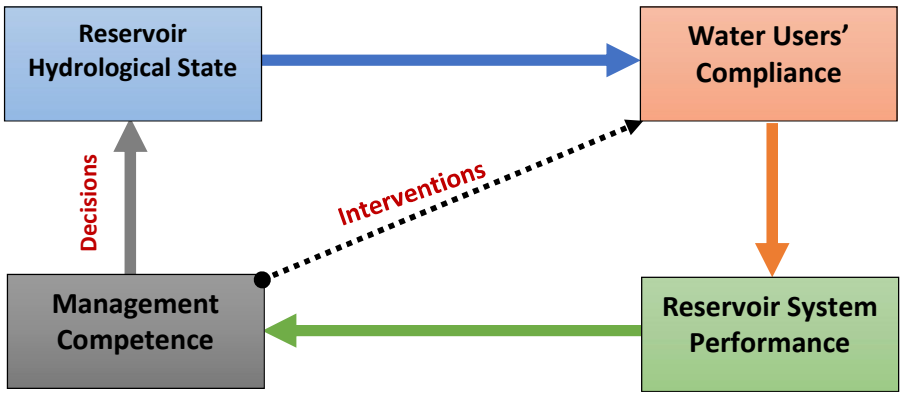


Figure 3.7: Interactions between the four-state drivers of the coupled model

Figure 3.8 shows the probable interactions and feedbacks between the variables of the reservoir, users, and management, which are expected to co-evolve dynamically.

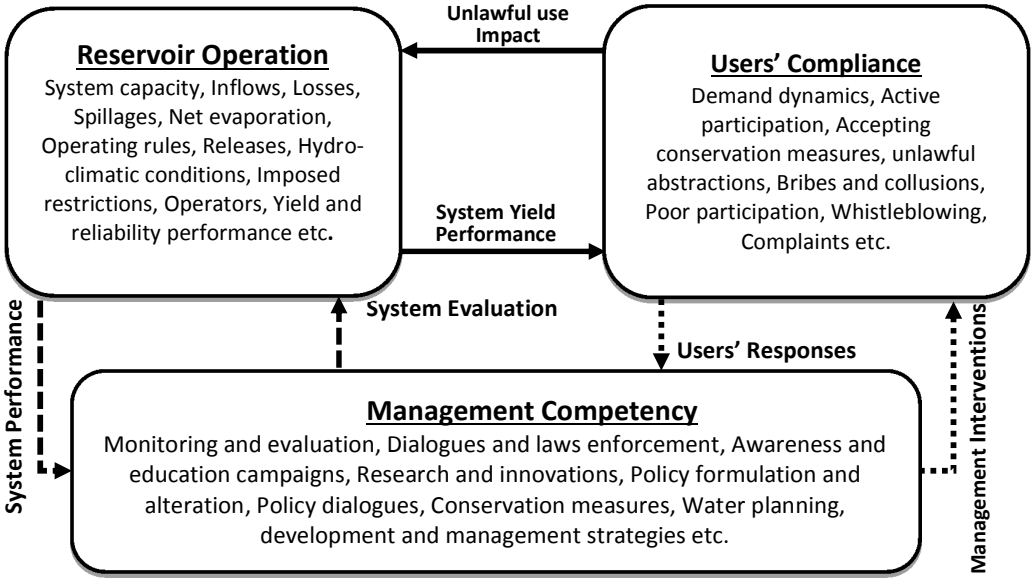


Figure 3.8: Interactions and feedbacks between reservoir, users and management

3.2 Reservoir System Socio-hydrological Simulation Model

Objective three aimed at developing a reservoir simulation model that incorporates the socio-hydrological model developed in Section 3.1. The simulation model was used to assess the impact of water users and managers on the reservoir performance, using plausible human behaviour scenarios. The model was formulated to assess the differences between the system yields when human behaviour was included, and when it was not. Reservoir yield was, therefore, computed based on the amount of water received by the targeted users, and not that allocated, as unauthorised abstractions may take some of the allocated water. The modelling assumed that conveyance losses were negligible since the study focus is on the human behaviour.

3.2.1 Data acquisition

This section describes how the hydrologic data, annual allocation, and monthly demand distribution were obtained. The study used 90-years (1920-2009) of monthly streamflows, rainfall, and Symon's pan evaporation data, provided by Water Resources of South Africa - 2012 Study (WR2012, 2018). The area–capacity

relationships of all the reservoirs under consideration were modelled using the second-order polynomials, as it has been found to fit better compared to the classic power-law model (Ndiritu, 2005). The Symon's pan evaporation was factored by 0.85 to obtain reservoir evaporation rates, and used to compute the net evaporation losses from each reservoir. In this study, the available historical hydrologic data are considered long enough (90-year) to study the impact of both annual, and decadal climate variability. The annual allocation is a function of the storage on the decision date, and this is the common practice in South Africa (Mckenzie & Allen, 1990). Therefore, the annual allocation was optimised to obtain a reservoir operating rule curve that can provide best yield under various behaviour scenarios. Monthly demand distribution was set to vary to reflect the seasonal variation of irrigation for the irrigation supply, and uniform for the municipal supply.

In South Africa, most reservoirs are operated in an integrated manner to combat water scarcity challenges, and to spread the risk of failure through regulated supply from upstream to downstream reservoirs, and inter-basin transfers (Mckenzie & Van Rooyen, 2002). Thus, the model was applied to two integrated reservoir systems, with two and five reservoirs, as explained in chapter five.

3.2.2 Formulation of scenarios

This section describes how the scenarios that was used to assess the effect of human behaviour on reservoir performance, were developed. The effect of human behaviour is assessed by comparing the yield indices obtained from the scenarios incorporating the effects of human behaviour, to the conventional reservoir yield, and operation analysis that ignores the effects of human behaviour. The human behaviour variables forming inputs into the socio-hydrological model are management competence, and users' compliance (see Sections 3.1.1.2 and 3.1.1.3), and three levels of these inputs were applied to create nine scenarios of the possible states of human behaviour that could occur. The level of management competence, and users' compliance are described in Table 3.1**,** and the resulting scenarios in Table 3.2.

Table 3.1: Descriptions and proposed range of values for the 3 levels of each factor

Factors	Levels	Descriptions	Mean values
Users' Compliance (UC)	UC_1	Users' behaviour is compliant and lawful although with some few but not significant unlawful abstraction cases.	$UC_1 = 0.75$
	UC_2	Users behaviour is moderately lawful but with worrisome unlawful abstraction cases.	$UC_2 = 0.50$
	UC_3	Rampant unlawful water abstraction cases.	$UC_3 = 0.25$
Management Competence (MC)	MC_1	Management performance is considered good with an excellent working environment.	$MC_1 = 0.75$
	MC_2	Management performance is considered fair with a moderately good working environment (equipment).	$MC_2 = 0.50$
	MC_3	Management performance is considered poor with fair working environment.	$MC_3 = 0.25$

Table 3.2: Nine scenarios from different combinations of 3 categories of users' compliance and management competence

Scenarios	1	2	3	4	5	6	7	8	9
Level of UC and MC	UC_1MC_1	UC_2MC_1	UC_3MC_1	UC_1MC_2	UC_2MC_2	UC_3MC_2	UC_1MC_3	UC_2MC_3	UC_3MC_3

Historic monthly hydrologic data (inflows, rainfall and evaporation) was used to reflect the natural variability of hydrological state. Figure 3.9 shows the overall flowchart of the reservoir operation socio-hydrological simulation model.

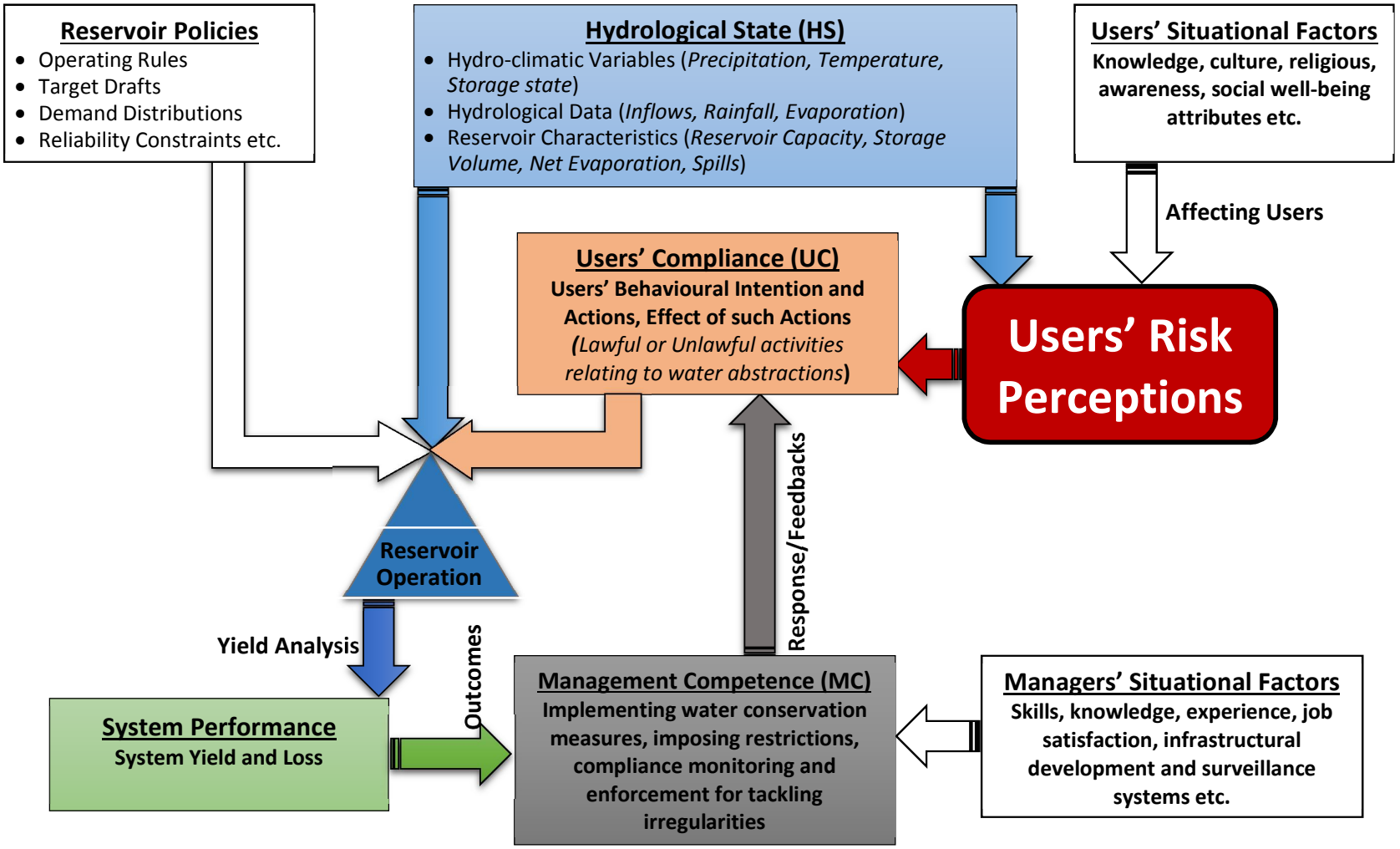


Figure 3.9: Overall flowchart of the reservoir operation-human behaviour socio-hydrological simulation model

CHAPTER FOUR

4.0 APPLICATION OF THE RESERVOIR OPERATION SOCIO-HYDROLOGICAL MODEL

This chapter provides an extensive description of the case study areas in which the reservoir system operation-human behaviour socio-hydrological model was applied. The chapter describes some essential characteristics of the selected areas (hydrological, geographical, climatic, social, economic, institutional, and physical). Detailed explanation of the simulation and optimisation modelling is presented. The scenarios are as described in chapter three, and presented here with small changes, where required. The yield performance indicator was assessed and used as an objective function that was optimised under different scenarios. Detailed description of the optimisation parameters, decision variables, and the method of optimisation are also presented.

4.1 Overview of the Study Area

The deveped reservoir operation socio-hydrological model was applied to two reservoir systems that are situated within the Olifants River Water Management Area (ORWMA) of South Africa. This section presents some basic characteristics of the Olifants River WMA.

4.1.1 Hydrological and geographical overview of the Olifants River WMA

The ORWMA is one of the 19 water management areas of South Africa, which is made up of six major rivers, including the Elands, Wilge, Steelpoort, Olifants, Klein Olifants, and Letaba (DWA, 2011). The Olifants River has a total length of 770km, which originates on the Highveld of Mpumalanga, east of Johannesburg. The river initially flows northwards before curving eastward through the Kruger National Park (KNP), where it joins the Letaba River before flowing into Mozambique, and ends at the confluence with the Limpopo River. The Olifants River catchment is the largest sub-catchment of the Limpopo River Basin, which is shared by South Africa, Botswana, Zimbabwe, and Mozambique, as shown in Figure 4.1 (Magagula *et al*., 2006). It is located between 21.5° and 26.5° S and 28.4° and 32.8° E, and shared by the three Provincial Governments of Gauteng, Mpumalanga, and Limpopo. The areas contributed by the Olifants, Shingwidzi and Letaba catchments to the ORWMA are

54,563 km^2, 5,310 km^2 and 13,669 km^2 respectively (Lange *et al*., 2003; DWAF, 2006; Middleton & Bailey, 2008; Ashton & Dabrowski, 2011). The ORWMA is situated in the semi-arid region with potential evaporation in excess of the rainfall, and an aridity index of 0.46 (Pollard & Retief, 2017).

The ORWMA has a seasonal rainfall occurring mainly in summer, which is characterised by considerable spatio-temporal variability that leads to seasonal dry spells, and water shortages. The mean annual precipitation (MAP) varies from 500 mm in the Lowveld region, increases to 1000 mm in the mountains, and decreases to 700 mm on the Mpumalanga Highveld. The ORWMA consists of five water management regions, the Upper Olifants River (B100 and B200), the Upper Middle Olifants River (B300), the Mountain Olifants River (B400), the Lower Middle Olifants River (B500) and the Lower Olifants River (600B and 700B) (Lange *et al*., 2003; BS, 2012). The gross annual resource is 1.074 Gm^3, which is below the annual demands, which led to the inter-basin transfer from the neighbouring WMA (DWAF, 2004). About 181.9 Mm^3 is transferred from the Vaal, Usutu and Komati Rivers for coal mining and power generation, and municipal use (DWAF, 2006; Magagula *et al*., 2006).

According to the reports on the water availability and allocation indicators, the ORWMA is water-stressed with a high inequality in water allocation *(Magagula et al*., 2006; DWA, 2011). The water allocation indicator of GINI-coefficient measures water use inequality with a value of 50, indicating equality, while the higher figure indicates inequality. The GINI-coefficient for the ORWMA is 85, as compared to the entire South African value of 58. For water availability, the Water Poverty Index (WPI) in the ORWMA was found to be 27.1 which is far below the national WPI of 52.2. The low value of WPI indicates that ORWMA is one of the highly water-stressed areas of South Africa (Magagula *et al*., 2006). The large hydrological constraints that exist in ORWMA, drew interest in this study, which relates hydrological status and water management performance to human behaviour. Figure 4.1 shows the location of the ORWMA in the Limpopo River Basin and South Africa, whereas Figure 4.2 shows the 19 WMA of South Africa, including the ORWMA.

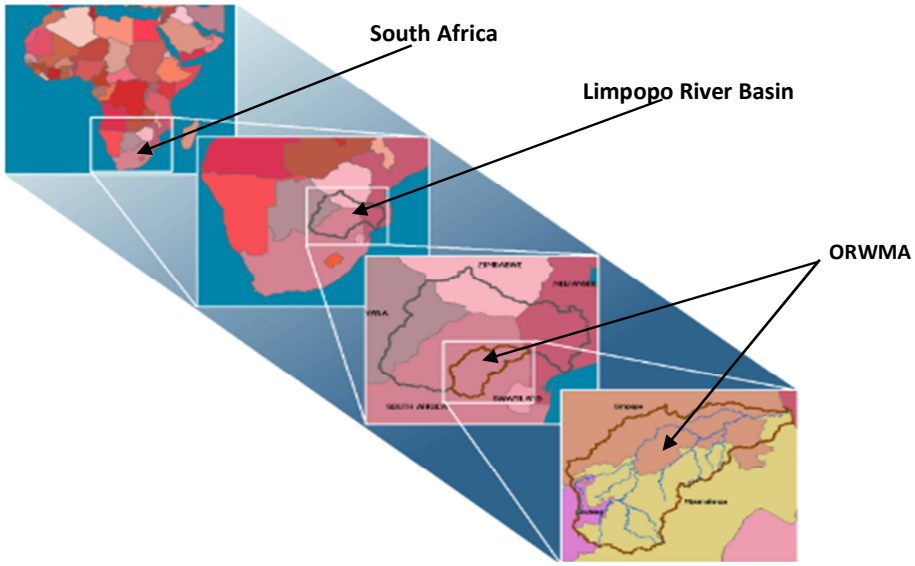


Figure 4.1: Location of Olifants River WMA in the Limpopo River Basin and South Africa (Magagula et al., 2006)

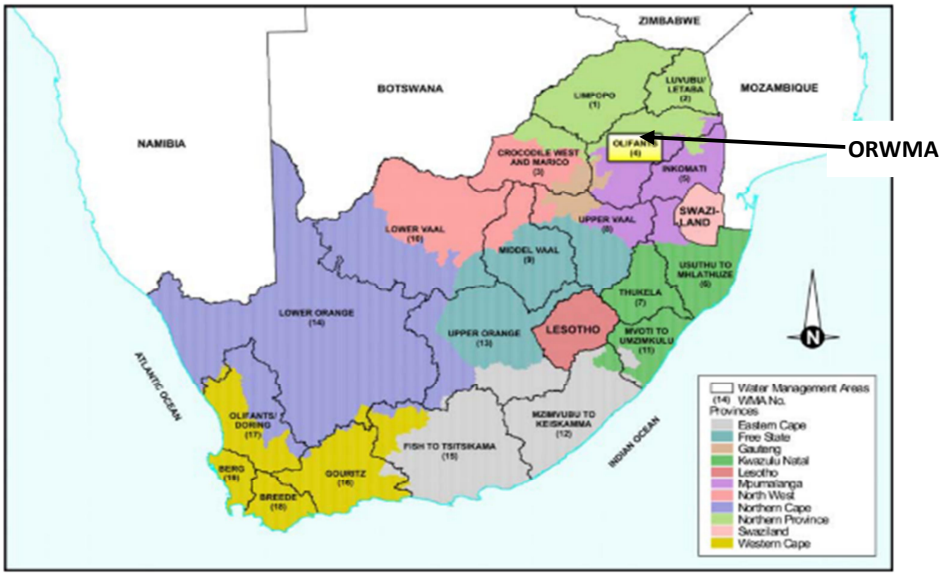


Figure 4.2: Location of the Olifants River WMA out of 19 WMA's and 3 Provincial Governments (DWAF, 2004a)

4.1.2 Social and economic overview of the Olifants River WMA

The ORWMA is classified as one of the most economically important WMA in South Africa, with mining, power production, commercial agriculture, and tourism as the

dominant economic drivers. The economy is driven mainly by the mining activities, with a large coal deposit, followed by platinum, copper, phosphate, chrome, diamonds and vanadium deposits (DWAF, 2004). There are also several large thermal power stations from which large portions of the country's energy is produced. There are agricultural activities at both subsistence, and commercial scales, in addition to tourism, mostly in the Kruger National Park area (DWA, 2011). The ORWMA contributes approximately 6% of South Africa's gross domestic product (GDP), which makes the catchment one of country's most significant WMA owing to its importance to the national economy (IWMI, 2008).

The population of the ORWMA constitute about 7% of total South Africa's population, with approximately 67% of the people living in rural areas (IWMI, 2008). According to the Magagula *et al*., (2006) about 60% of the population live in the former homeland areas that cover 26% of the Olifants area, while the remaining 40% occupies 74% of the land. The catchment is also characterised by a low literacy level, in which 33% of the 49% of the school-going age population are without formal education. Besides, about 29% are employed, 24% unemployed and 47% are economically inactive, with nearly 85% categorised as Very Poor and Poor (DWA, 2011).

4.1.3 Water infrastructures and ecological overview of the Olifants River WMA

Water infrastructures are greatly developed in the ORWMA, with several large, medium, and small dams. There are nine major dams within the Olifants River, including the Witbank and Middelburg dams for domestic, and industrial supplies. The Bronkhorstspruit dam supplies Bronkhorstspruit and the Western Highveld Region for domestic, irrigation, and industrial use. The Mkhombo and Rust De Winter dams are for domestic supply to the Western Highveld Region, and irrigation purposes. Loskop dam is primarily used for irrigation through the Loskop Irrigation Board, with some supply to the Western Highveld Region for domestic use. Flag Boshielo dam is for irrigation, domestic use, and transfer to Polokwane for domestic use. Blyderivierspoort dam, supplies water for irrigation, industrial and domestic demands (DWAF, 2004; DWA, 2011). The water is predominantly used by irrigation users, which

amount to over 60%; power generation consumes about 19%, while domestic, industrial and mining consume 19% (IWMI, 2008).

There are vital natural resource conservation areas within the ORWMA. The most economically important, and well-known natural resource conservation area is the Kruger National Park, which is situated in the Lower Olifants region. There are many wetlands in the Olifants River, and many of these wetlands are under threat due to the evaporation of saline mine water (DWA, 2011). Because ORWMA is water stressed, with an annual water deficit of about 181.9 Mm^3, the ecological needs are not adequately met (Magagula *et al*., 2006). There is also substantial sewage treatment plant return flows in the Klipspruit, and Witbank Dam down to Loskop Dam, which causes eutrophication in the upper reaches of the Loskop Dam, and the Klein Olifants River. The problems of salinity and eutrophication are not only due to mining and sewage treatment plant discharges, but also due to irrigation return flows (DWAF, 2006; Ashton & Dabrowski, 2011; Pollard & Retief, 2017).

4.1.4 Institutional arrangement and stakeholders' involvement in the Olifants River WMA

The institutional arrangement of ORWMA is comprised of a wide range of stakeholders that are involved in the management of the water resources. The Olifants River Forum is a platform that involves a wide range of stakeholders, including public agencies, private service providers, civil societies, water user associations, and other institutional stakeholders (DWA, 2011). The major stakeholders include three Provincial Governments (Gauteng; Mpumalanga and Limpopo.), Water Boards, Water Users Associations (WUAs), Mining and Industry Representatives, and Other Institutions such as Kruger National Park, and Eskom. The summary of the Olifants River Forum stakeholders is as presented in Table 4.1 (DWAF, 2006).

Table 4.1: Olifants River Forum stakeholders

Category of Stakeholders	Organisations
Department of Water & Sanitation (DWS)	ORWMA, water management regions, Dam managers & operators
Water Boards	Rand Water; Magalies Water; Ikangala Water and Lepelle Water.
Provincial Government	Gauteng; Mpumalanga and Limpopo.
Local Government (District Municipalities)	Drakensberg; Greater Marble Hall; Greater Thubatse and Phalaborwa.
Main User Municipalities	Middelburg; Witbank; Polokwane etc.
Water User Associations (WUA)	Lebalelo WUA and Blyde WUA etc.
Mining and Industry	Metallurgic Industries: Coal, Platinum mining etc.
Other Institutions	Eskom; Sanparks (Kruger National Park)

4.1.5 The state of water use rights in the Olifants River WMA

The South African National Water Act, 36 of 1998 described water use rights based on existing lawful water use in a different perspective (Section 21). For example, a person may continue with a current lawful water use subject to a) obligations attached to that use, b) its replacement by a licence in terms of this Act, or c) any other limitation or prohibition by this act (NWA, 1998). In spite of such provisions in the NWA, more than 65% of the upstream water use in the ORWMA have not yet been verified (DWA, 2011c). It is probable that a considerable percentage of this unverified water use could be unlawful, and could have been wrongly incorporated in reservoir yield analysis for the dams in the area. According to a report on the reconciliation strategy for the ORWMA (DWA, 2011b), if the current annual estimated total irrigation water use (1,677 Mm^3) is verified, the actual use could reduce to about 60% of this estimate.

However, in spite of such unreliable existing lawful water use data, most dam yield calculations have for long been based on these data, and relied on for water resource planning, development, and operational analysis. Therefore, dam yield calculations are expected to be more reliable if conducted based on an improved upstream irrigation water use data. Hence, there is a need for the DWS to urgently undertake such verifications to determine the correct water use for all WMAs to accurately identify the amount of water that has been lawfully used by irrigators, otherwise reliable yield analysis cannot be undertaken (DWA, 2011c).

In line with this proposal, the DWS is in the process of validating, and verifying water use in the ORWMA to ensure that all the available water is accounted for. The DWS

stressed the importance of water use verification, and validation as South Africa is a water scarce country, and, hence, water needs to be used equitably, efficiently and wisely for a sustainable future (DWS, 2016a). This process has been started by engaging and enlightening water users of the Olifants catchment to understand the country's water status, and water demand management strategy, as well as the water use verification processes (DWS, 2016a). The process entails validation of water use, thereby ascertaining the extent of authorised, and unauthorised water use.

Thus, WMAs that face water scarcity with high levels of unverified water use such as ORWMA, require prudent water management decisions that account for not only hydrological and physical constraints, but also for human behaviour-related influences.

4.1.6 Reservoir systems selected for the case study

The reservoir operation socio-hydrological model was applied to two reservoir systems within ORWMA. A system of two reservoirs in the Elands River of the upper middle Olifants, and a system of five reservoirs in the upper Olifants River were selected for the study. Figure 4.3 shows the map of the ORWMA showing the two case study regions (DWAF, 2006).

Figure *4.4* is the schematic of the positioning, and connections between the eight major dams, and the overall hydrological summary as provided in the Olifants Water Availability Assessment Study report (OWAAS) (DWA, 2010a).

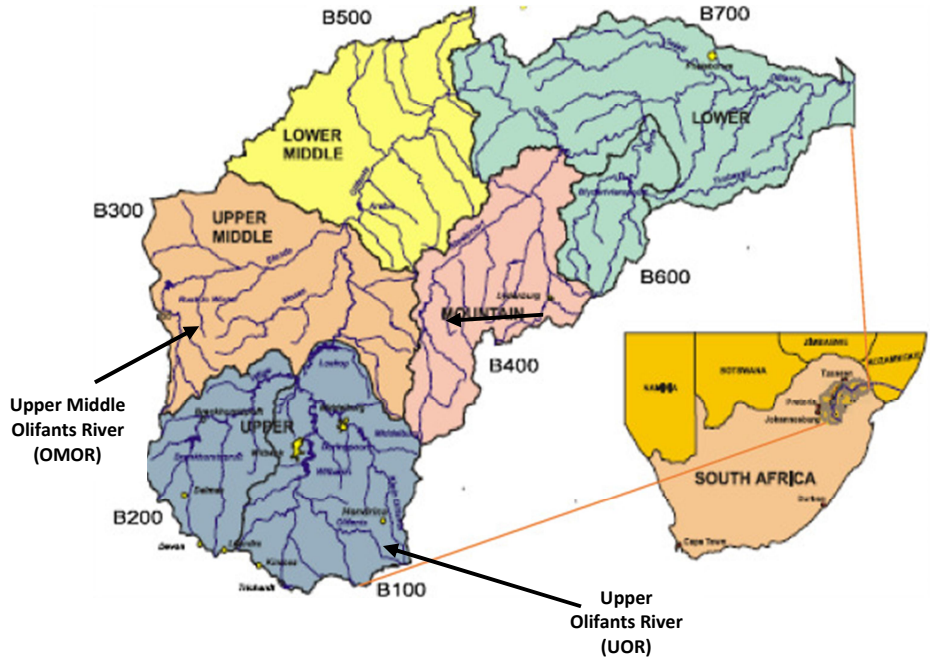


Figure 4.3: Map of South Africa showing the ORWMA and 2 study areas (DWAF, 2006)

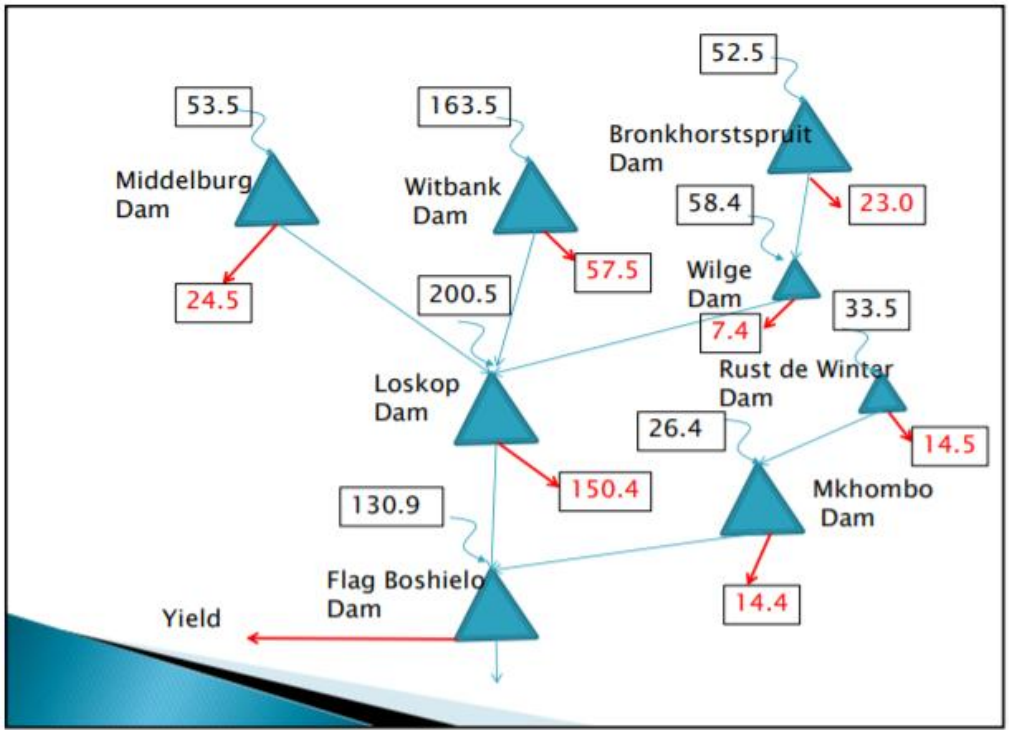


Figure 4.4: Schematic of the 8 major dams and their hydrological characteristics (DWA, 2010a)

Table 4.2 summarise the hydrological, geographical, climatic, and physical characteristics of the eight major dams. This information was gathered from various reports (Lange *et al*., 2003; Magagula *et al*., 2006; BS, 2012; DWA, 2011; WR2012, 2018; DWS, 2013; DWS, 2014; Middleton & Bailey, 2008).

4.2 Elands River System Case Study

The Elands River is a tributary of the Olifants River, and its sub-area is part of the Olifants River basin. The Elands River system comprises of two major dams, Rust de Winter, and Mkhombo dams, and both are located within the Upper Middle Olifants River. The primary purpose of the Rust de Winter dam is to supply water for irrigation and municipal, industrial and mining uses. Mkhombo dam was initially known as Rhenosterkop dam, and is located downstream of Rust de Winter dam, purposely to supply for irrigation and municipal use. One case study was based on the system of two reservoirs, and is schematically shown in *Figure 4.5*.

Table 4.2: Summary of the hydrological, geographical, climatic and physical characteristics of the eight major dams

Dams / Characteristics	Middelburg	Witbank	Bronkhorstspruit	Wilge	Loskop	Rust de Winter	Mkhombo	Flag Boshielo
Location of the dams (Lat.°S /Long.°E)	25.77/29.55	25.89/29.32	25.89/28.73	26.08/29.25	25.42/29.36	25.23/28.53	25.27/28.58	24.80/29.43
Water Man. Region of the dams	UOR	UOR	UOR	UOR	UMOR	UMOR	UMOR	UMOR
Secondary catchment(s) of the dams	B1	B1	B2	B2	B1 and B2	B3	B3	B3 and B5
Quaternary catchments draining to the dams	B11A, B12A, B12B, B12C	B11B, B11C(sd2), B11D(sd1), B11E(sd1), B11F, B11G	B20A, B20B, B20C	B20D, B20E, B20F	B11H, B11J(EWR1), B11K, B11L, B12D, B12E(EWR3), B20G, B20H, B20J(EWR4), B32A(EWR2)	B31A, B31B, B31C	B31D, B31E B31F, B31G(EWR6)	B31H, B31J, B32D(EWR5, B32F, B32G, B32H, B32J, B51A, B51B
River on which dams located	Klein Olifants	Olifants	Olifants	Wilge	Olifants	Elands	Elands	Elands
Quaternary in which dams located	B12C	B11G	B20C	B11B	B32A	B31C	B31F	B51B
Catchment area of the dams (Km^2)	46.8	121.12	86.09	30.00	242.77	47.33	362.40	128.77
Storage Capacity of the dams (Mm^3)	48.435	104.02	57.91	13.00	374.31	27.21	205.00	105.00
Mean Annual Precipitation (mm)	682	682	682	682	621	621	621	621
Nearby rain gauge stations	0516201W	0515270W	0513836W	0478546W	0516096W	0551120W	0551511W	0553151W
Mean Annual Evaporation (mm)	2013.7	2013.7	2117.0	2117.0	2117.0	2179.4	2179.4	2121.0
Mean Annual Potential ET (mm)	1377.2	1377.2	1460.4	1460.4	1460.4	1513.7	1513.7	1486.6
Mean Annual Runoff (mm)	36.2	36.2	38.3	38.3	38.3	22.1	22.1	12.5
Mean Annual Runoff (Mm^3)	257.12	257.12	166.93	166.93	166.93	248.64	248.64	121.21
Mean altitude (m above sea level)	1588	1588	1501	1501	1501	1174	1174	1097
Purpose of the dams	Irrigation Domestic Industrial Mining Fishing	Domestic Industrial Mining	Irrigation Domestic Industrial Mining	Mining, Municipal	Irrigation Domestic	Irrigation Domestic	Irrigation Domestic	Irrigation Domestic Industrial Recreation Transfer (Polokwane)

UOR = Upper Olifants River; UMOR = Upper Middle Olifants River; sd = small dams; EWR = environmental water requirement sites; %EWR1 = 18.6%; %EWR2 = 23.8%; %EWR3 = 27.0%; %EWR4 = 29.9%; %EWR5 = 19.09%; %EWR6 = 17.9%; masl = meters above sea level

4.2.1 Characteristics of the Elands River system

The total quaternary catchment area contributing to the Rust de Winter, and Mkhombo dams are 47.33 km^2 and 362.30 km^2 respectively. The mean annual precipitation, runoff, total storage capacity ,and storage surface area of the Rust de Winter dam are 605 mm, 19.8 mm, 27.21 Mm^3 and 373.3 ha respectively. The mean annual precipitation and runoff from the incremental quaternary catchment area to Mkhombo dam are 243 mm and 3.9 mm and Mkhombo dam has a storage capacity and surface area of 205 Mm^3 and 3,624 ha respectively (Ndiritu, 2005; DWA, 2011). Other details are as summarised in Table 4.2. The study assumed unlawful activities relating to water abstractions could occur at five locations (A to E) as schematically shown in Figure 4.5.

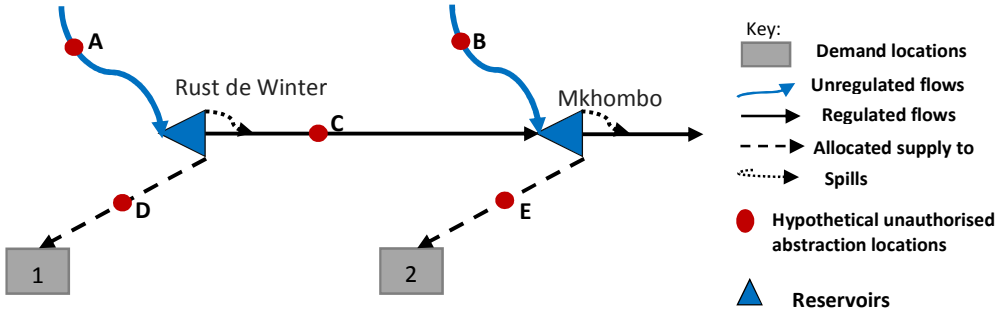


Figure 4.5: Schematic of the Eland River system case study

4.2.2 Human behaviour scenarios

The human behavioural impact was incorporated, while simulating the system using the scenarios developed in Section 3.2.2 of chapter three. The scenarios are formulated to enable assessment of changing users' compliance, and management competence on reservoir system yield, using the socio-hydrological model developed in chapter three. Nine scenarios are created from different combinations of three categories of users' compliance, and management competence as shown in Table 4.3. The system was also simulated, and optimised without incorporating the human behaviour scenarios as conventionally assumed in reservoir system yield analysis. This served as a reference to the scenarios incorporating human behaviour, and was used to determine the water loss due to unlawful abstractions for each of the nine scenarios.

Table 4.3: Summary of the human behaviour scenarios

Scenarios	UC and MC scenarios		Mean value of the distributions	
	UC	MC	UC	MC
1	High	Effective	0.75	0.75
2	Moderate	Effective	0.50	0.75
3	Low	Effective	0.25	0.75
4	High	Moderately effective	0.75	0.50
5	Moderate	Moderately effective	0.50	0.50
6	Low	Moderately effective	0.25	0.50
7	High	Ineffective	0.75	0.25
8	Moderate	Ineffective	0.50	0.25
9	Low	Ineffective	0.25	0.25
0	Conventional (without incorporating human behaviour impact)			

UC: users' compliance
MC: management competence

The probability density function (PDF) of the 3 levels of management competence (MC) are as illustrated in Figure 4.6. The other variable users' compliance (UC) was also modelled similarly.

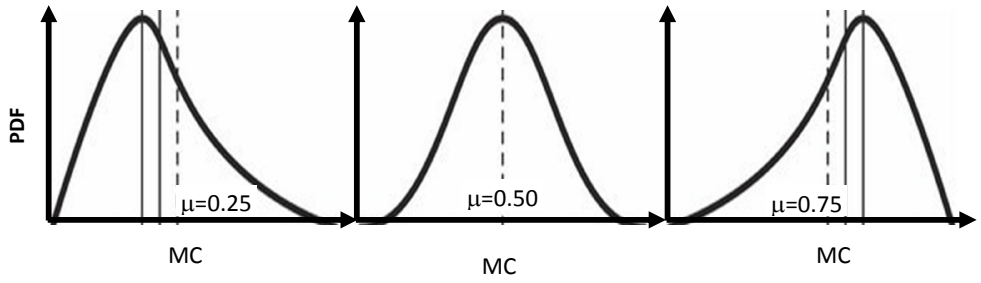


Figure 4.6: Probability density functions for the 3 levels of management competence and users' compliance

4.2.3 Simulation-optimisation modelling for the Elands reservoir system

Simulation-optimisation (S-O) modelling was employed to optimise the objective (yield) by linking the developed reservoir operation socio-hydrological simulation model with the shuffled complex evolution (SCE-UA) optimisation method. Section 2.1.4.3 reviews simulation-optimisation applications to water resource systems analysis, including a detailed description of the SCE-UA method. The simulation-optimisation setup for the case study is described in the next sub-sections.

4.2.3.1 Simulation modelling

The reservoir system operation was simulated using a 90-year (1920 - 2009) monthly dataset provided by the Water Resources of South Africa - 2012 Study (WR2012,

2018). The 90-year data were considered to contain adequate levels of annual, and decadal variability of hydro-climatic conditions for the study. The area–capacity relationships for each reservoir were modelled using the second-order polynomials, as they had been found to fit better than the classic power-law model (Ndiritu, 2005). The Symon's pan evaporation is factored by 0.85 to obtain evaporation rates from the reservoirs, and used to compute the net evaporation losses from each reservoir (Equation 4.1).

$$Ne_t = \frac{1}{2}(A_t + A_{t+1})(0.85Ev_t - Pr_t) \qquad 4.1$$

Where: Ne_t Ev_t and Pr_t are the net evaporation losses, average Symon's evaporation rate and point rainfall respectively. A_t and A_{t+1} are the surface area of the reservoir in time t and t + 1 respectively.

The reservoir socio-hydrological simulation model was developed by incorporating an unlawful abstractions impact model into reservoir mass balance variables, as expressed in Equation 3.9 and 3.10. The simulation was conducted at a monthly time interval, and three variables were computed at each simulation time step: i) monthly storage levels of each reservoir, and total storage level ii) allocated supplies to demands from each reservoir, based on operating rules and iii) actual delivered supplies at demand sites, which may be less than the allocated supply due to unlawful abstractions. The mass balance of each reservoir, in this case coupled with the effect of unlawful water abstractions, is as described in Equation 4.2.

$$S_{i,j+1,k} = S_{i,j,k} + \left(1 - UI_{u,i,j,k}\right)Q_{i,j,k} - \left(1 - UI_{d,i,j,k}\right)R_{i,j,k} - NE_{i,j,k} - SP_{i,j,k} \qquad 4.2$$
$$0 \leq S_{i,j,k} \leq C_k$$

Where: $S_{i,j,k}$ and $S_{i,j+1,k}$, is the storage of reservoir k at the beginning of the month j and $j + 1$ of year i respectively. $Q_{i,j,k}$ is the natural inflow to reservoir k in the month j of year i; $R_{i,j,k}$ is the allocated supply to demand from reservoir k in the month j of year i. $UI_{u,i,j,k}$ and $UI_{d,i,j,k}$ are the unlawful abstractions impact in the month j of year i at the upstream and downstream of reservoir k respectively. $NE_{i,j,k}$ and $SP_{i,j,k}$are the net evaporation losses and spills out of reservoir k in the month j of year i. C_k is the capacity of reservoir k.

The reservoir system operating rules are based on the concept of ensuring upstream reservoirs remain as full as possible, which is the common practice in South Africa

(Mckenzie & Allen, 1990; Ndiritu *et al.*, 2017; Ndiritu, 2005). The operation is based on shortage rule curves, which define zones within which specified proportions of the demand are supplied (Basson *et al.*, 1994). Three rule curves that provided four supply zones, were applied in this study. The detailed quantitative description of the operating rules as applied to two case study systems, is presented in this chapter.

The system was simulated using the operating rules that maintain high water volume in the upstream reservoirs, and which is commonly used in South Africa (Mckenzie & Allen, 1990; Oliveira & Loucks, 1997; Ndiritu, 2005). The rules were allowed to change within a year once the storage state changes (Ndiritu *et al.*, 2017). Also, the monthly allocated supply from each reservoir, and the regulated supply from the upstream to the downstream reservoir depended on the monthly demand, the month of the year, total storage state, and storage of each reservoir. The reservoir operation was based on four restriction zones, within which supply allocations of 100, 80, 50 and 30% of the monthly demand could be made. This required the specification of three rule curves each for the storage in each reservoir, and for the total storage. The role of the optimisation was to obtain the reservoir operating rule curves that would maximise the yield. Figure 4.7 illustrates the optimised operating rule curves for a given reservoir with four supply restriction zones for a complete water year.

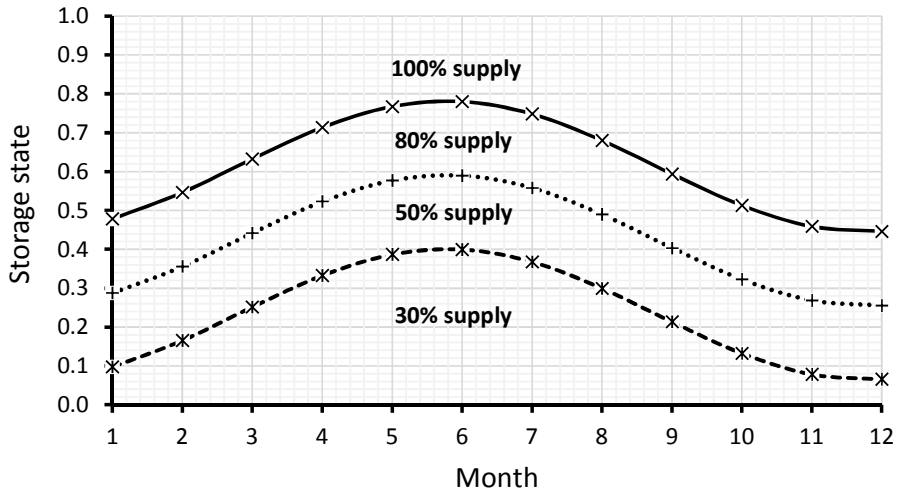


Figure 4.7: Reservoir operating rule curves for a complete water year (month 1 = April)

The monthly demands were set to vary for the two reservoirs to reflect the seasonal variation in irrigation water demand. Therefore, the monthly demand distribution of

each reservoir was obtained as a fixed percentage of the optimised annual demand value. The allocated supply from each reservoir, and the regulated supply from reservoir 1 (upstream reservoir) to reservoir 2 (downstream reservoir), were obtained as summarised below, and quantitatively described in Equation 4.3 to 4.5 (Ndiritu, 2005).

- If the storage of each reservoir and that of total system are in the same supply zone, the supply from each reservoir is allocated without regulated supply from reservoir 1 to 2.
- When the storage of downstream reservoir is in a lower zone than that of the total storage, and the upstream reservoir is in a zone, or higher than that of total storage, then a regulated supply is made from upstream to the downstream reservoir. Also, the regulated supply should be equal to the extra demand that the downstream reservoir would fail to supply, so that the downstream reservoir can allocate a corresponding supply to the zone of total storage.
- If no regulated supply from upstream to the downstream reservoir is made, and the downstream reservoir is in a lower zone than the total storage, the downstream reservoir provides allocated supply based on its supply zone.
- Whenever the upstream reservoir is in a lower zone than that of total storage, the allocated supply from that reservoir is based on its zone.
- If any of the reservoirs are in a higher zone than that of the total storage, the allocated supply is based on the total storage supply zone.

$$IF \quad tL_{j,l+1} < \frac{tS_{i,j}}{tC} \leq tL_{j,l} \; AND \; L_{j,l+1,k} \leq \frac{S_{i,j,k}}{C_k}; \; THEN \; Ra_{i,j,k} = \frac{P_{l,k}}{100} * D_{j,k} \tag{4.3}$$

$$IF \quad tL_{j,l+1} < \frac{tS_{i,j}}{tC} \leq tL_{j,l} \; AND \; L_{j,l+1+m,k} \leq \frac{S_{i,j,k}}{C_k} \leq L_{j,l+m,k}; \; THEN \; Ra_{i,j,k} = \frac{P_{l+m,k}}{100} * D_{j,k} \tag{4.4}$$

$$IF \quad tL_{j,l+1} < \frac{tS_{i,j}}{tC} \leq tL_{j,l} \; AND \; L_{j,l+1+m,2} < \frac{S_{i,j,2}}{C_2} \leq L_{j,l+m,2} \; AND \; L_{j,l+1,1} < \frac{S_{i,j,1}}{C_1}; \; THEN$$
$$rf_{i,j,1} = \frac{(P_{l,k} - P_{l+m,k})}{100} * D_{j,2} \; AND \; Ra_{i,j,2} = \frac{P_{l,k}}{100} * D_{j,2} \tag{4.5}$$

$i = 1,2,3, \ldots \ldots N \quad j = 1,2,3, \ldots \ldots 12 \quad k = 1,2 \quad l = 1,2,3 \quad m = 1,2$

Where: $tL_{j,l}$= Lth operating rule curve value for total storage for month j; $tS_{i,j}$ = total storage at the beginning of month j of year i ($tS_{i,j} = S_{i,j,1} + S_{i,j,2}$). $S_{i,j,k}$ = storage volume in reservoir k at the beginning of month j of year i; tC = total system capacity ($tC = C_1 + C_2$) and C_1 and C_2 = capacities of reservoir 1 and 2 respectively. $L_{j,l,k}$ = Lth

operating rule curve value for reservoir k for the month j; $P_{l,k}$ = L[th] percentage supply of the demand $D_{j,k}$ for reservoir k in month j. $rf_{i,j,1}$ = regulated supply from reservoir 1 to 2 in the month j of year i.

For each complete simulation period (90 years), a yield indicator is used to assess performance, and to optimise system operation. The system yield performance index is defined as the proportion of the actual supply delivered to the total streamflows (runoff) into the system for the entire simulation period, as expressed in Equation 4.6. The total runoff for the entire simulation period is as shown in Equation 4.7. The loss due to unlawful abstractions is computed as the ratio of the difference between yields (Y) when there was no and when there was unlawful abstractions impact to the when there was no unlawful abstractions impact as expressed in Equations 4.8.

$$Y = \frac{\sum_{i=1}^{T}\sum_{j=1}^{12}\sum_{k=1}^{N} R_{i,j,k}^{d}}{TR} \quad 4.6$$

$$TR = \sum_{i=1}^{T}\sum_{j=1}^{12}\sum_{k=1}^{N} Q_{i,j,k} \quad 4.7$$

$$L = \frac{Y_{nUI} - Y_{UI}}{Y_{nUI}} * 100 \quad 4.8$$

Where: Y is the yield, $R_{i,j,k}^{d}$ is the delivered supply from the reservoir k in the month j of year i for reservoir k. TR is the total runoff into the reservoirs for the entire simulation period; $Q_{i,j,k}$ is the natural runoff into the reservoir k in the month j of year i. N and T are the number of reservoirs and years of simulation respectively i. L is the unlawful abstractions loss, Y_{nUI} and Y_{UI} are the yield when there was no unlawful abstractions and when there was unlawful abstractions.

4.2.3.2 Optimisation modelling

The study optimised yield for each of the nine scenarios. An optimum yield depends on the well-defined operating rule curves, and the optimum annual demand, hence the optimisation modelling was set to define reservoir rule curves that can provide optimum annual demand, hence, the yield. The study adopted an evolutionary optimisation method of shuffled complex evolution (SCE-UA) (Duan *et al*., 1992, 1994). The SCE-UA method is selected owing to its ability to use multiple complexes and shuffling, which provide a more effective search of the parameter space (Thyer *et al*., 1999). Section 2.1.4.3.2 provides a detailed description of the SCE-UA, and other

evolutionary methods, including genetic algorithms, and their applications in water resource systems analysis. The flow algorithm of the SCE-UA, and the parameterisation was implemented as provided by Duan *et al*., (1992) and Duan *et al*., (1994) (Figure 2.3 and Table 2.1). Also, the reservoir operation simulation-optimisation modelling was conducted as described by Ngo, (2006) (Figure 2.5).

Moreover, the study opted to employ an approach to defining operating rule curves that can reduce the number of decision variables without compromising the optimisation result. Ngo (2006), recommended such an approach of reducing the number of decision variables, provided it does not compromise the accuracy of the objective. Ndiritu & Sinha (2009), developed a simple approach. This approach reduces the number of decision variables considerably. The function is defined such that it allows the rule curves to have a vast range of shapes, to enable a vigorous search. The function was applied to a system with two reservoirs, and found to be effective, although the obtained results revealed no need for employing such a function in a system of two reservoirs with similar objective functions (Ndiritu & Sinha, 2009). The study further recommended the need to apply such a simple trigonometric function to more complex systems, and to multi-objective optimisations. Ndiritu *et al*., (2017) applied the trigonometric model with SCE-UA optimisation to effectively simulate the observed historic behaviour of a reservoir over a 40-years period. Thus, this function was adopted for this study. The adopted trigonometric function for defining the operating rule curves developed by Ndiritu & Sinha, (2009) is shown in Equation 4.9.

$$L_{j,l,k} = tp_k + wp_k(3 - l) + ap_k\left[sin\left(2\pi\left(\frac{j}{12} - lp_k\right)\right)\right] \qquad 4.9$$

Where: $L_{j,l,k}$= rule curve value for month j, level l and reservoir k. tp_k, wp_k, ap_k and lp_k are the translational, width, amplitude and lag parameter respectively for the rule curves for reservoir k. $j = 1,2,3, \ldots.12;\ l = 1,2,3;\ k = 1,2$.

Unlike in the free specification methods for defining operating rules curves, which require 36 parameters for a single reservoir which increases the optimisation task, the trigonometric function uses only four (4) parameters for each reservoir (tp_k, wp_k, ap_k and lp_k). The simple trigonometric function has been found to be versatile, as

different varieties of rule curve shapes were obtained for the various combinations of the 4 parameters when $l = 2$ (the second rule curve), as illustrated in Figure 4.8. With the aim to assess the need for the use of the simple trigonometric function, the function was applied in two ways:

i) With all the four parameters (simple trigonometric rule curves)
ii) With a very low value of amplitude parameter, ap_k (simple linear rule curves). This is just like only translational (tp_k) and width parameter (wp_k) were used since deactivating amplitude (ap_k) deactivates the lag parameter (lp_k). The curve with very low ap_k ($ap = 0.02$) in Figure 4.8 shows a typical example of simple linear rule curves.

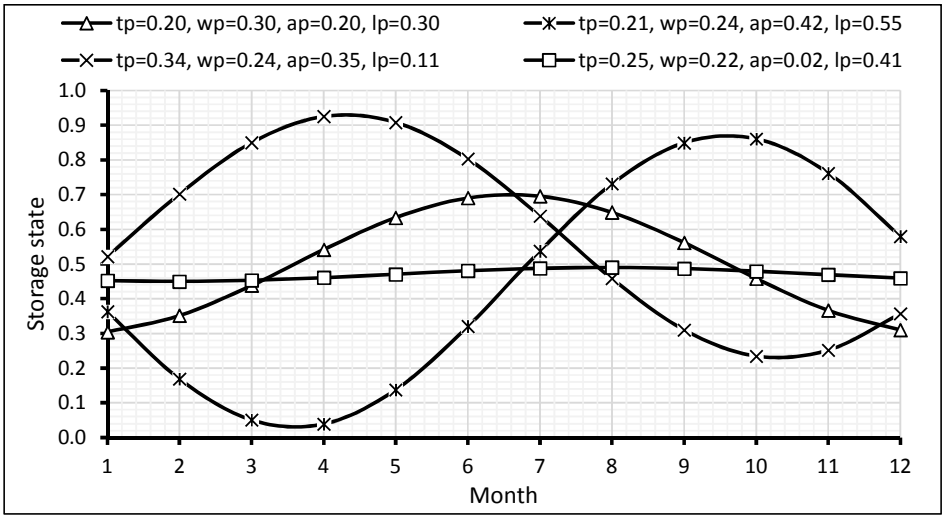


Figure 4.8: The versatility of the simple trigonometric function (Ndiritu & Sinha, 2009)

Since the ratio of the total annual inflows to the total reservoir capacity of each reservoir differs, a weighting parameter (w_g) was introduced by Ndiritu (2005) to effect such differences in obtaining the operating rule curves for the total storage. The operating rule curves for the total storage was obtained as the weighted linear average of the two reservoir rule curves, as shown in Equation 4.10 (Ndiritu, 2005; Ndiritu & Sinha, 2009), and is adopted in this study. The weighing parameter, w_g is also optimised.

$$tL_{j,l} = \sum_{k=1}^{N} \left(w_k L_{j,l,k} \right) \quad 4.10$$

$$\sum_{k=1}^{N} w_k = 1$$

Where: $tL_{j,l}$ is the Lth operating rule curve value for the total storage for month j. $L_{j,l,k}$ = L[th] operating rule curve value in month j for reservoir k. N is the number of reservoirs, w_k is the weight for reservoir k.

Therefore, the optimisation entailed linking the SCE-UA optimiser with the reservoir operation socio-hydrological simulation model to determine rule curves that maximise yield (Y). The parameters to be optimised include the four trigonometric function parameters for each reservoir, the weighting parameter (w_k), and annual demands for each reservoir, making a total of eleven (11) parameters, as shown in Table 4.4. The objective was to defined operating rule curves that maximise yield (Y), as expressed in Equation 4.11. The monthly allocated and delivered supplies were obtained, as described in Equation 4.12, and 4.13 respectively. Given the search ranges of the parameters in Table 4.4, it is possible that some parameter combinations could lead to rule curve that violates the constraint that this value lies between 0 and 1.0 ($0 \leq L_{j,l,k} \leq 1$). If this occurred, the objective function for that solution was reduced to a value of 1 x 10^{-10}.

$$maximize \quad Y = \frac{\sum_{i=1}^{T} \sum_{j=1}^{12} \sum_{k=1}^{N} R_{i,j,k}^{d}}{TR} \quad 4.11$$

$$R_{i,j,k}^{a} = \frac{P_{l,k}}{100} * d_{j,k} \quad 4.12$$

$$R_{i,j,k}^{d} = (1 - UI) R_{i,j,k}^{a} \quad 4.13$$

Where: Y = system yield, $Ra_{i,j,k}$ and $Rd_{i,j,k}$ = allocated and delivered supplies for the reservoir k in the month j of year i. TR = total inflows into the system for the entire simulation period. $P_{l,k}$ = supply percentage for the storage zone l for reservoir k, $d_{j,k}$ = monthly water demand for month j from reservoir k, $UI_{i,j,k}$ = unlawful abstractions impact on reservoir k in the month j of year i (to be obtained as described in chapter four). N = number of years of simulation.

Table 4.4: Selected parameters and their respective search ranges

Parameters	Units	Search Range Limits	
tp_1	None	0.00	1.00
wp_1	None	0.00	0.50
ap_1	None	0.00	1.00
lp_1	None	0.00	1.00
tp_2	None	0.00	1.00
wp_2	None	0.00	0.50
ap_2	None	0.00	1.00
lp_2	None	0.00	1.00
w_s	None	0.00	0.99
td_1	Mm^3/year	0.01	14.5
td_2	Mm^3/year	0.01	15.5

tp_k: Translational parameter for reservoir k
wp_k: Width parameter for reservoir k
ap_k: Amplitude parameter for reservoir k
lp_k: Lag parameter for reservoir k
w_s Weighing parameter for obtaining rule curves for the total storage
td_k: Annual demand for reservoir k

4.3 Olifants River Reservoir System Case Study

The Olifants Rivers system, also referred to as the Loskop sub-system, is comprised of five major dams; the Middelburg, Witbank, Bronkhorstspruit, Wilge and Loskop dams, and is located within the Upper Olifants River water management region. The schematic of the five major dams as provided in the Olifants Water Availability Assessment Study report (DWA, 2010a), is shown in Figure 4.9.

4.3.1 Characteristics of the Olifants River system

The hydrological, geological, and physical characteristics, as well as the purposes of all the five dams, are as summarised in Table 4.2. The study assumed unlawful abstractions could be taking place in thirteen locations (A to M) as schematically shown in Figure 4.9. Regulated flow from Middelburg to Loskop is a closed conduit (DWA, 2010a), and considered to have no unlawful use.

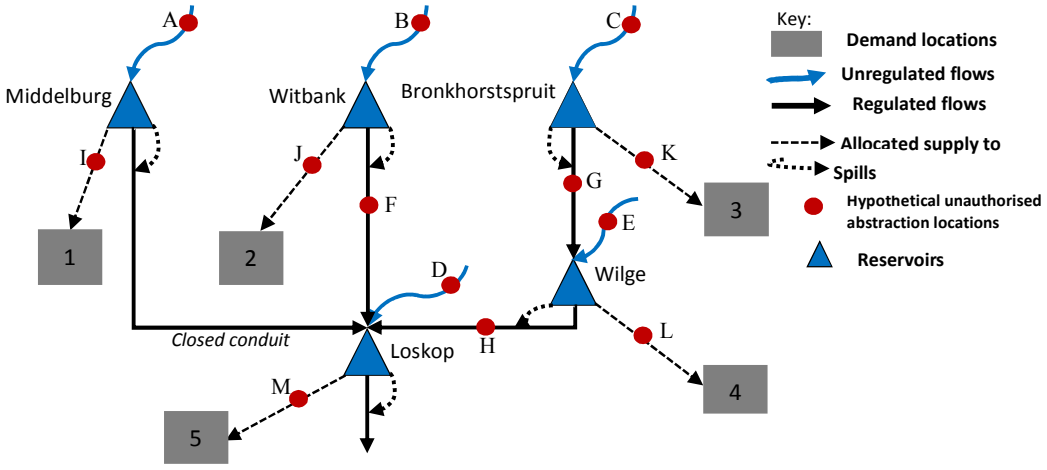


Figure 4.9: Schematic of the Loskop reservoir system.

4.3.2 Human behaviour scenarios

The scenarios are formulated to enable the assessment of changing users' compliance, and management competence on reservoir system yield, using the socio-hydrological model developed in chapter four. The scenarios applied for this case study are similar to those applied in the Elands River system case study (Section 4.2.2).

4.3.3 Simulation-optimisation model for the Olifants River reservoir system

The simulation and optimisation modelling setups are similar to that of the Elands River case study and, therefore, only features that differ from that case study are presented here. The allocated supply from each of the five reservoirs to their respective demand sites, and the regulated supply from reservoir 1 to 5, 2 to 5, 4 to 5 and 3 to 4, are set to be governed as follows:

4.3.3.1 Simulation modelling

The system operation is simulated in the same way as in the Elands River case study (4.2.3.1). Only about 58% of the total annual inflows into reservoir 1 (Middelburg dam) are dedicated for irrigation, and municipal uses, whereas 42% is for the regulated flows to reservoir 5 (Loskop Dam), and is conveyed using a closed conduit. About 78% of the 58% supply from Middelburg dam is allocated to municipal use, while the remaining 22% is for irrigation use (DWA, 2010a). The simulation assumed

uniform monthly demand distribution for reservoirs 1, 2, and 4 as these reservoirs are mainly used for municipal supply, whereas reservoirs 3 and 5 are considered to have varying monthly demand to mimic the seasonal variations of irrigation demand.

The allocated supply from each of the five reservoirs to their respective demand sites, and the regulated supply from reservoir 1 to 5, 2 to 5, 4 to 5, and 3 to 4 are governed as follows.

- 42% of the total inflows to reservoir 1 is supplied as a regulated flow to reservoir 5, using a closed conduit.
- If the storage state of each of the five reservoirs, and that of the total storage, are in the same supply zone, the allocated supply from each reservoir is provided without regulated supply.
- If reservoir 4 is in a lower zone than that of the total storage and reservoir 3 is in a zone or higher than that of total storage, then a regulated supply is made from reservoir 3 to 4. This regulated supply is equal to the extra demand that reservoir 4 would fail to supply.
- If reservoir 5 is in a lower zone than that of the total storage, and reservoir 2 and/or 4 are in the same zone or a zone higher than that of total storage, then a regulated supply is made from reservoir 2 and/or 4 to 5. This regulated supply should be equal to the extra demand that reservoir 5 would fail to supply. The proportion of the regulated supply contributed from reservoirs 2 and 4 to reservoir 5 depends on the supply zone of each reservoir.
- If no regulated supply from any of the upstream reservoir to the downstream reservoir is made, and the downstream reservoir is in a lower zone than the total storage, that downstream reservoir provides allocated supply based on its supply zone.
- If any of the upstream reservoirs (1, 2 or 3) is in a lower zone than that of total storage, the allocated supply from these reservoirs is based on their respective supply zones.
- If any of the reservoirs are in a higher zone than that of the total storage, the allocated supply from that reservoir is based on the total storage supply zone.

The simulation was also conducted at a monthly time interval, and yield performance was computed for each complete simulation period (90 years), as in Equations 4.6.

4.3.3.2 Optimisation modelling

System yield (Y) was optimised using the SCE-UA method, as for the Elands River system, and the rule curves were defined using the simple trigonometric function as in Eland River case study. The weighting parameters (w_{g1}, w_{g2}, w_{g3}, w_{g4} and w_{g5}) for computing the operating rule curves for total storage from the rule curves of the individual reservoirs, were also optimised). Therefore, the operating rule curves of the total storage are obtained as the weighted linear average of the rule curves of all five reservoirs as shown in Equation 4.10.

Thus, the parameters to optimise include four trigonometric function parameters for each of the five reservoirs, annual demands for each reservoir, and weighting parameters for each reservoir, making a total of 30 parameters as shown in Table 4.5. The decision variables to be optimised, and their respective search range limits, are as shown in Table 4.5.

Table 4.5: Variables to be optimised for Loskop system and their search ranges

Parameters	Units	Search Range Limits	
tp_k	None	0.00	1.00
wp_k	None	0.00	0.50
ap_k	None	0.00	1.00
lp_k	None	0.00	1.00
td_1	Mm^3/year	0.001	24.5
td_2	Mm^3/year	0.001	57.5
td_3	Mm^3/year	0.001	23.0
td_4	Mm^3/year	0.001	7.7
td_5	Mm^3/year	0.001	150.4
w_k	None	0.01	0.25

tp_k: Translational parameter for reservoir k
wp_k: Width parameter for reservoir k
ap_k: Amplitude parameter for reservoir k
lp_k: Lag parameter for reservoir k
td_k: Annual demand for reservoir k
w_k weighting parameters for obtaining rule curves for the total storage

4.4 Yield Analysis Implementation

This section briefly informs how the reservoir operation socio-hydrological simulation model was coded, the source of the SCE-UA optimisation algorithm code, and how reservoir operation was simulated, and linked with SCE-UA optimisation algorithm.

The reservoir socio-hydrological simulation model was coded using the Python programming language (Spider - Python 2.7). The SCE-UA optimisation algorithm (Duan *et al.*, 1992) was implemented using Python by Van Hoey, (2012), and adopted in this study. The reservoir operation socio-hydrological model, and the SCE-UA optimisation algorithm, was linked using the inbuilt *import* module in the Python. The import statement allows the use of pre-defined variables and functions from other files using an import statement (*from NameOfFile import* *). Since the location of a global optimum solution is not guaranteed in an evolutionary optimisation method such as SCE-UA, five randomly initialised optimisation runs were conducted.

CHAPTER FIVE

5.0 RESULTS AND ANALYSIS FOR ELANDS RIVER CASE STUDY

This chapter presents the results, and analyses obtained from the Elands River Reservoir System (Figure 4.5). The results of the optimisation are first presented, and discussed, followed by the simulation results. The result of the optimised yield for the scenario with no human behaviour incorporated (scenario 0) is presented first, and discussed. The results of this scenario are then used as a reference to the results obtained from the other nine scenarios that have varied levels, and combinations of human behaviour. The optimised yields for the scenarios with the highest unlawful abstractions impact (scenario 9), and least impact (scenario 1) are also presented and analysed, while those for the other seven scenarios (2 to 8) are presented in Appendix A1. Similarly, the optimised parameter values, the operating rule curves, and the losses in yield due to unauthorised abstractions, are presented, and analysed for the nine scenarios. A comparison of the effects of users' compliance and management competence (the two human behaviour inputs into the simulation) on system yield is also carried out.

The results from the simulation runs were used to analyse the trajectories of the storage state, yield-demand ratio, and storage-yield trade-offs. Since weighting parameters were used to compute the total reservoir system storage, the analysis of the simulation result was limited to the total reservoir system as it provided the needed information on all the reservoirs in the system, whereas, results from the individual reservoirs are presented (tables and graphs) in Appendices. The discussions and analyses are mostly based on the two performance indices; system yield, and unauthorised abstractions loss, as defined in Section 4.2.3.1.

5.1 Optimisation Results

The results presented in this section were obtained from the optimisation runs.

5.1.1 Optimised yield

Table 5.1 presents the optimised reservoir system yield, and the number of model simulations for the five randomly initialised optimisation runs. The table contains the

yield for the scenarios 0, 1 and 9 (see Table 4.3) for the two cases; trigonometric rule curves (with the 4 trigonometric parameters), and linear rule curves (with a very low value of amplitude parameter) as explained in Section 4.2.3.2. For each scenario, all the five initialised optimisation runs gave almost identical optimised yield with the maximum value being less than 2% higher than the minimum value. The low differences in optimised yields indicate that SCE-UA is an effective, and efficient optimiser, as Ndiritu & Sinha, (2009) had also found. Although deactivating amplitude parameters (very low amplitude) significantly reduces the number of model simulations, and computation time, the yield was found to be slightly higher when the amplitude parameter was deactivated in most of the five optimisation runs. The computation time for the five randomly initialised optimisation runs for the activated and deactivated amplitude case, lasts for about 25 to 35 minutes, and 15 to 20 minutes respectively. In scenario 0, the best yield of 0.4970 was obtained when the amplitude parameter was activated, and this took 6,253 model simulations. On the other hand, the best yield of 0.4967 was achieved with 5,822 model simulations when the amplitude parameter was excluded (simple linear rules).

The average optimised yield when the amplitude parameter was activated and deactivated for the scenarios 0, 1 and 9, were 0.4940 and 0.4963, 0.4829 and 0.4835, and 0.4497 and 0.4510 respectively. The corresponding computed difference between the averages of the optimised yield for the cases with activated and deactivated amplitude parameter were +0.3%, +0.1% and +0.5% respectively. In all the scenarios, the average yield was found to be slightly higher when the amplitude parameter was deactivated, than when the amplitude parameter was activated. The result suggest that there was no need to use the trigonometric functions for the two reservoirs system. This is in agreement with the suggestion that a simple model (without amplitude parameter) that defines rule curves as straight horizontal lines, with slight or no monthly variations, can be adequate (Ndiritu & Sinha, 2009).

When the amplitude parameter was activated, the optimised yield of all the five optimisation runs for scenario 0 were higher, compared scenarios 1 and 9 with an average yields of 0.4940, 0.4829 and 0.4497 respectively. When the amplitude was

deactivated, a similar trend was observed with a yield for scenario 0 averaging to 0.4963, compared with 0.4835 and 0.4510 for scenarios 1 and 9 respectively.

Table 5.1: Optimised yield for scenarios 0, 1 and 9

Run	Scenario 0		Scenario 1		Scenari 9	
	With Amplitude Parameter (Simple trigonometric rules)					
	No. of Sim.	Yield	No. of Sim.	Yield	No. of Sim.	Yield
1	6253	0.4970	6336	0.4840	5512	0.4510
2	7950	0.4931	6497	0.4821	6230	0.4472
3	7901	0.4932	5821	0.4828	6807	0.4535
4	6041	0.4908	6287	0.4863	6029	0.4484
5	7566	0.4961	6461	0.4793	6191	0.4483
Average		**0.4940**		**0.4829**		**0.4497**
Run	**Without Amplitude Parameter (Simple linear rules)**					
	No. of Sim.	**Yield**	**No. of Sim.**	**Yield**	**No. of Sim.**	**Yield**
1	4168	0.4962	5966	0.4799	5804	0.4501
2	5237	0.4966	5526	0.4855	5603	0.4532
3	5058	0.4966	5446	0.4856	5863	0.4493
4	5822	0.4967	5677	0.4816	5836	0.4521
5	4907	0.4956	5541	0.4846	5824	0.4502
Average		**0.4963**		**0.4835**		**0.4510**

5.1.2 Impact of human behaviour on the optimised yield

The optimised yields achieved from each of the nine scenarios that incorporated human propensity to unlawful water abstractions were found to be less than the yield obtained from scenario 0 (scenario without incorporating human propensity to unlawful water abstractions). Table 5.2 shows the average yields, and the losses in yield as a result of unauthorised abstractions for the 9 scenarios. The losses ranged from 2.3 to 9.0% for the more complex operating rule (trigonometric rule curves) that allows the rule curves to vary on a monthly basis, and 2.7 to 9.2% for the simpler operating rule (linear rule curves) that specified a single rule curve level across the year. This approximate the obtained annual water-scarcity probability of 10% (90% reliability) as a result of upstream water abstractions (van Oel *et al.*, 2008). van Oel *et al.*, (2008) defined reliability as the ratio of the difference between the number of simulation years, and the number of years without meeting the target yield (due to upstream abstractions) to the number of simulation years. This revealed that the obtained annual water losses due to unlawful abstractions in this study, is realistic. With an aim to approximate the computed water loss to a single value, an overall

average loss of all the nine scenarios was computed. The overall average losses for the optimisation runs with the activated and deactivated amplitude, were 5.8% and 5.6% respectively.

Table 5.2: Average of the optimised yields of the 5 initialised optimisation runs

Scenarios	Amplitude Activated		Amplitude Deactivated	
	Yield	Loss (%)	Yield	Loss (%)
1 – UC_1MC_1	0.4829	2.3	0.4835	2.7
2 – UC_2MC_1	0.4707	4.7	0.4707	5.2
3 – UC_3MC_1	0.4614	6.6	0.4642	6.5
4 – UC_1MC_2	0.4710	4.7	0.4757	4.2
5 – UC_2MC_2	0.4610	6.7	0.4673	5.9
6 – UC_3MC_2	0.4581	7.3	0.4654	6.3
7 – UC_1MC_3	0.4683	5.2	0.4750	4.4
8 – UC_2MC_3	0.4636	6.2	0.4684	5.7
9 – UC_3MC_3	0.4497	9.0	0.4510	9.2
Overall average	0.4652	5.8	0.4690	5.6
Scenario 0	0.4940	0.0	0.4963	0.0

Figure 5.1 illustrates the optimised yield for the scenarios 0 to 9. The optimised yield was found to reduce as users' compliance (UC), and management competence (MC) declined. For example, when the amplitude parameter was deactivated (linear rule), and UC was constant (UC_1), the yields for declining management competence (MC_1, MC_2 and MC_3) were 0.4835, 0.4757, and 0.4750 respectively. Also, for activated amplitudes case (trigonometric rules), the yields for a constant management competence (MC_2), for declining user compliance (UC_1, UC_2 and UC_3) were 0.4710, 0.4610, and 0.4581 respectively.

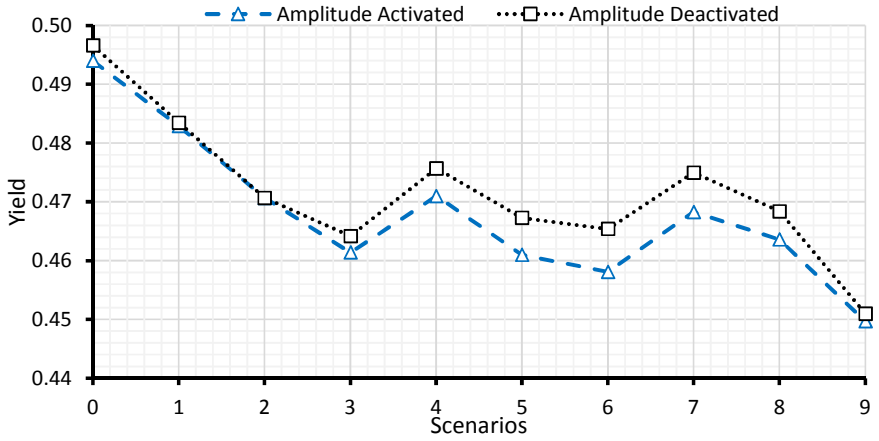
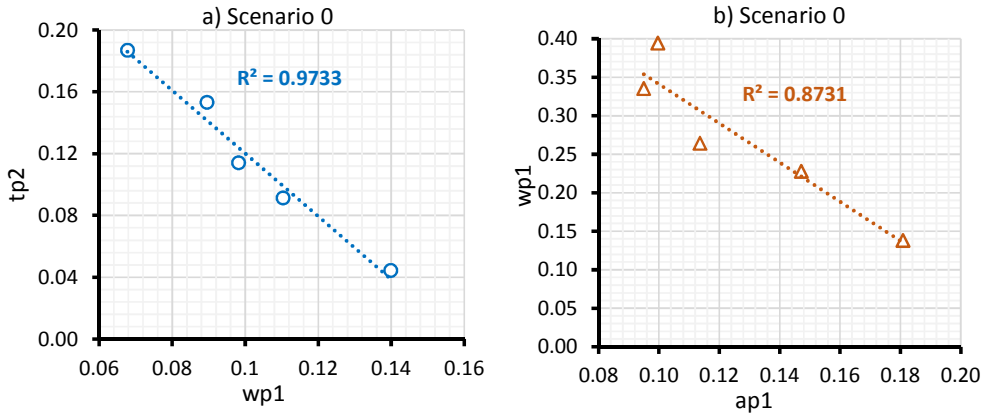


Figure 5.1: Average yield for the simple trigonometric and linear operating rules

5.1.3 Optimised parameter values

The adopted simple trigonometric function uses four parameters (translation - tp, width - wp, amplitude - ap and lag - lp) to define three rule curves for a single reservoir. A weighing parameter (w_g) was used to compute the rule curves for the total system, and the weight parameter was optimised. Also, the annual demands (td) for each reservoir was optimised. For the Elands system case study, eleven parameters were, therefore, optimised. In order to assess the adequacy of optimisation method (SCE-UA), analysis of some of parameter values from the multiple runs was carried out.

All the optimised parameters from the five initialised optimisation runs were observed to possess a reasonable level of consistency. The optimised parameter values for scenarios 0 to 9 for activated and deactivated amplitude are presented in Appendix B1 and C1. The optimised parameters also reveal parameter inter-dependence as Figure 5.2 shows strong correlations of some randomly selected parameters. The ability of the SCE-UA to obtain almost identical yields from multiple runs (Table 5.1), and to also capture strong parameter interdependencies (Figure 5.2) is considered an indication of its effectiveness as an optimiser. This observed effectiveness, and reliability of the SCE-UA was in agreement with the findings by Ndiritu & Sinha (2009). For the purposes of this study, the SCE-UA was, therefore, considered a reliable optimiser.



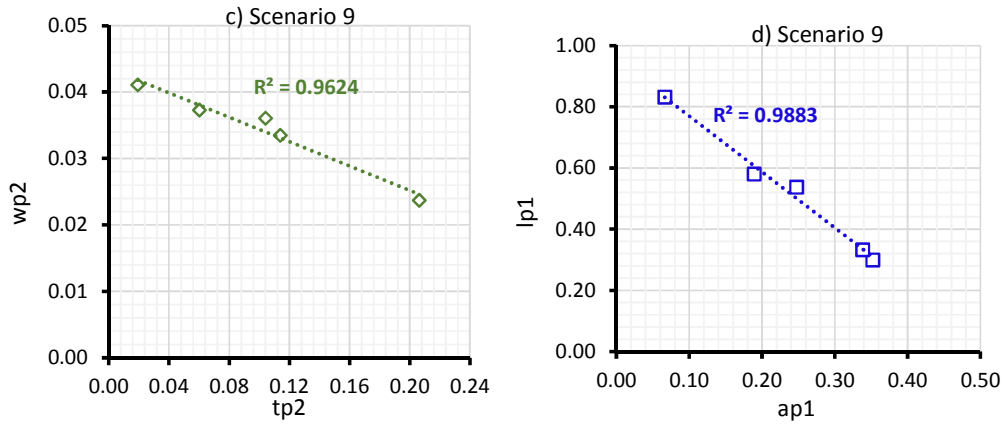


Figure 5.2: Cross correlation of some of the optimised parameters

5.1.4 Optimised reservoir operating rule curves

This section presents, and analyses the optimised operating rule curves for each reservoir, and the total storage. The analysis was presented in two ways:

i) Impact of amplitude parameter on the optimised operating rule curves;

ii) Impact of human behaviour on the optimised operating rule curves.

5.1.4.1 Effect of amplitude parameter on the optimised operating rule curves

Figure 5.3 and Figure 5.4 present the optimised reservoir operating rule curves obtained from the optimisation runs that gave the best objective functions for scenarios 0 and 9 respectively. The upper and lower optimised rules curves with activated amplitude parameter (trigonometric rule curves) were found to reach the upper and lower limits of 1.0 and 0.0 respectively for different months of the year, indicating that the amplitude values were high.

However, the trigonometric operating rules (non-linear), where amplitude is activated, obtained practically the same yield as when the linear operating rule was used by deactivating amplitude (see Table 5.1). The results are in agreement with what was earlier observed by Ndiritu & Sinha (2009), that trigonometric rule curves are not more effective than simpler linear rule curves. Ndiritu & Sinha (2009), found the linear rule performed better than the non-linear trigonometric rule if monthly-varying reliability constraints were imposed on reservoir operation.

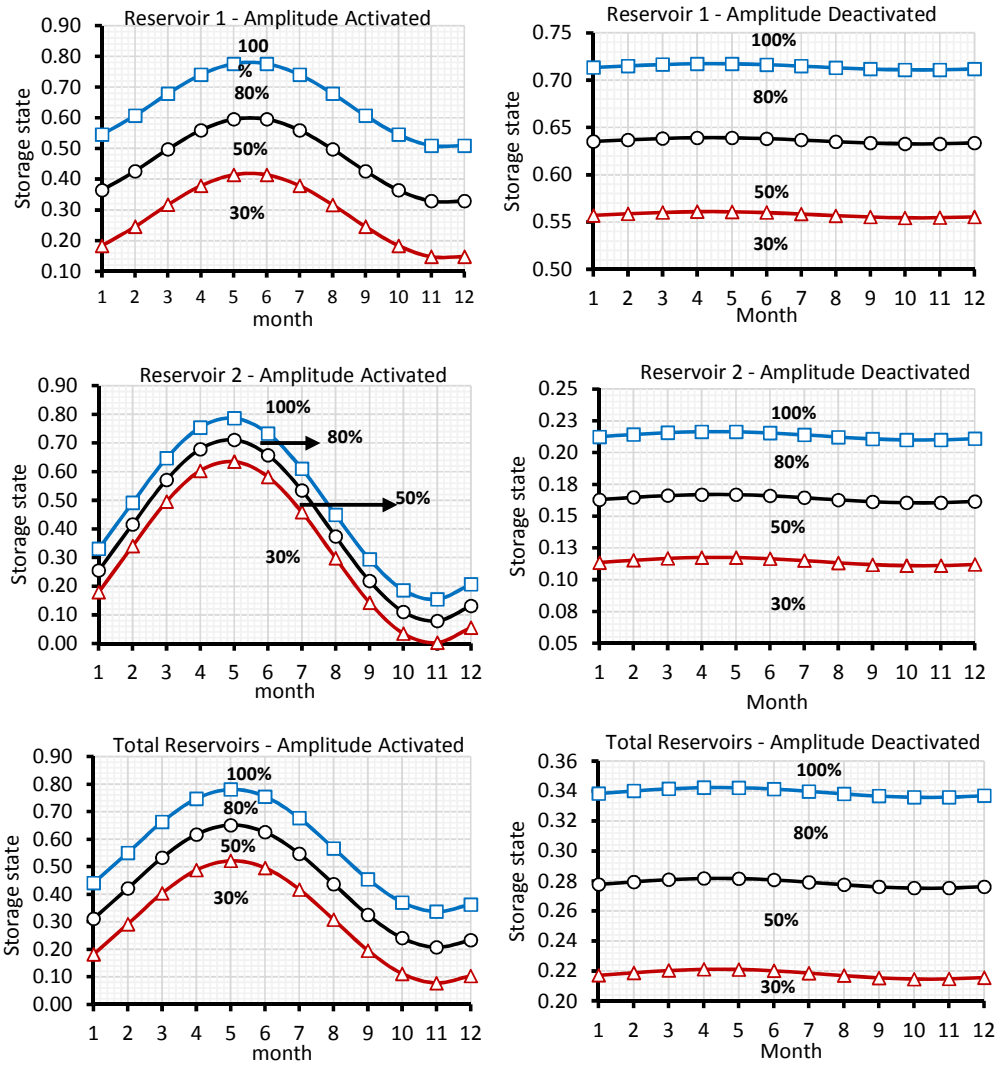


Figure 5.3: Optimised operating rule curves for the simple trigonometric and linear rules for scenario 0.

Figure 5.4 shows the optimised reservoir operating rule curves for scenario 9 for the optimisation runs, which gave the highest yields. The optimised non-linear rule curves include a considerable amplitude like for scenario 0. Nevertheless, the yield of 0.4472, using the non-linear rule curves, is slightly lower than that of 0.4501, obtained using the linear rule (see Table 5.1). This result again indicates that the simpler linear rule curves are more effective than the trigonometric non-linear rule curves.

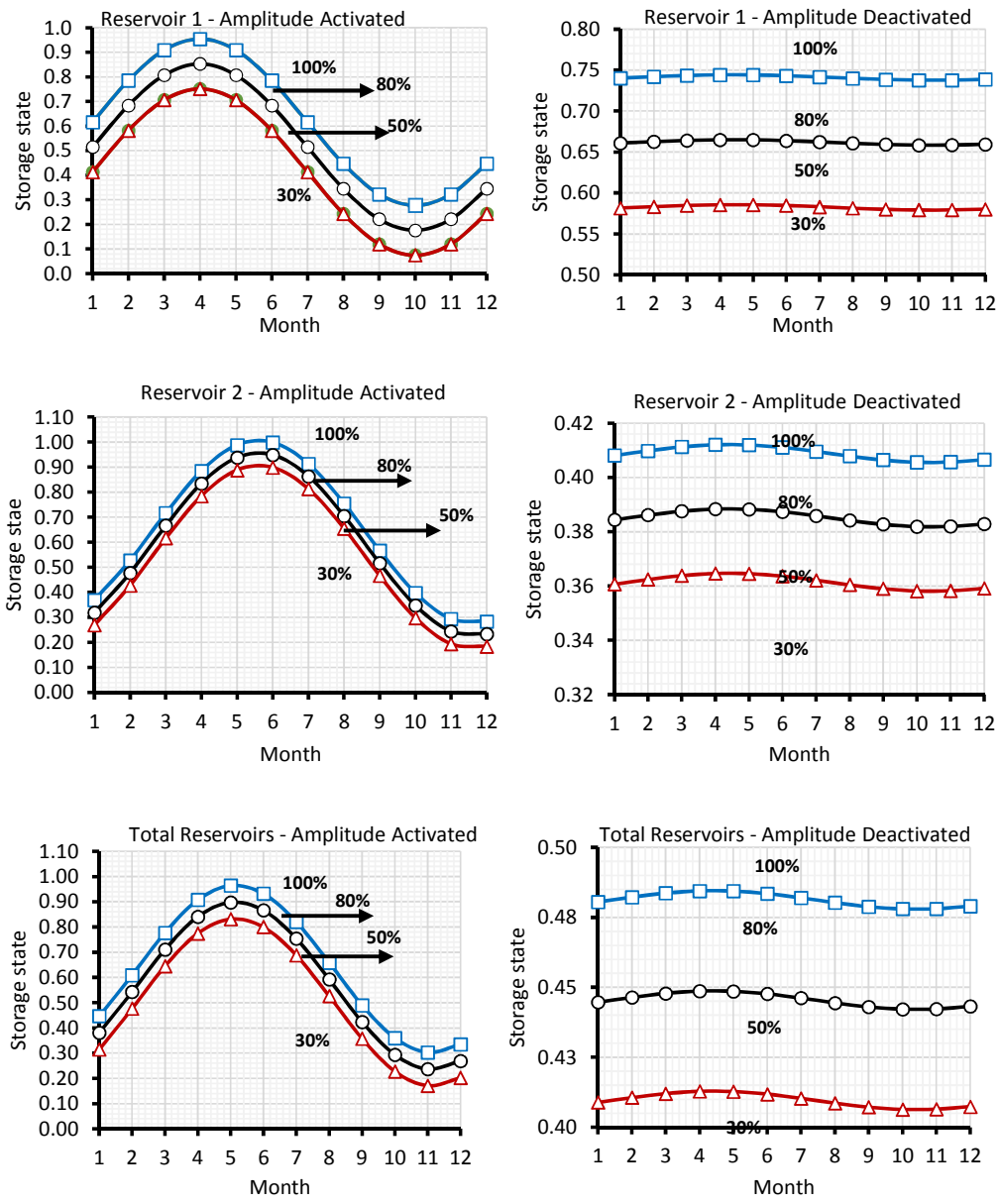


Figure 5.4: Optimised rule curves for simple trigonometric and linear rules for scenario 9.

5.1.4.2 Effect of human behaviour on the optimised operating rule curves

This subsection analyses the rule curves obtained from the optimisation runs that gave the best objective functions for scenarios 0 and 9. Figure 5.5 presents the optimised operating rule curves obtained from the optimisation runs that gave the best objective functions. For reservoir 1, the upper rule curve at the beginning of the water year (month 1 which is April) were 0.55 and 0.62 for scenarios 0 and 9

respectively. The relatively higher upper rule curve of 0.62 in scenario 9 with a difference of 0.07, indicated a rule curve shift. This was attributed to unlawful abstractions along the streamflows during the rainy season, which reduces the storage. Thus, when the storage decreases due to illegal abstraction, the operating rule curves will rise, and subsequently increase the possibility of implementing supply restrictions. The curves also continues to rise progressively with the highest minimum storage level to supply 100% of 0.78 and 0.95 for scenarios 0 and 9 respectively. The yield is, thus, expected to be higher in scenario 0 when compared to scenario 9. About 50% and 30% of the monthly distribution will be released in the 5th month at a storage state of 0.50 for scenarios 0 and 9 respectively. This revealed how human behaviour can negatively affect operating rule curves, and hence the yield performance.

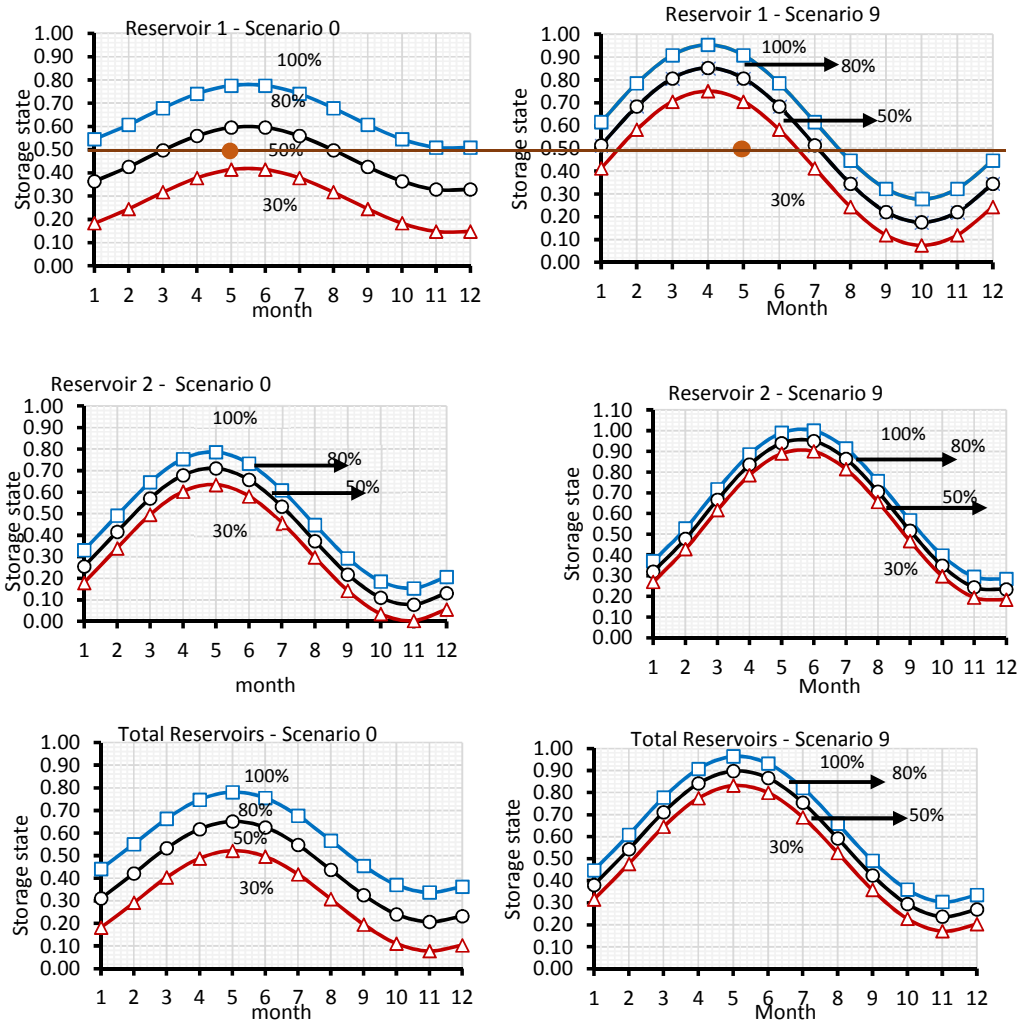
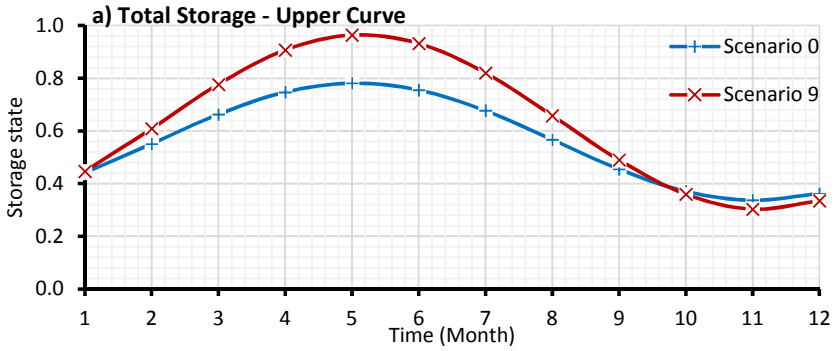


Figure 5.5: Optimised rule curves for trigonometric rules for scenario 0 and 9.

Such discrepancies between the rule curves for scenarios 0 and 9 could be the reason for higher yields in scenario 0 (0.4908) than scenario 9 (0.4472) with a yield difference of 9%. Hence, reservoir operating rules developed without incorporating the impact of upstream abstractions can lead to unexpected system failure. This indicated the need to incorporate the impact of water abstractions, while developing reservoir operating rules. Similar trends were also observed for reservoir 2, and the total storage as illustrated in Figure 5.5.

Figure 5.6 illustrates the levels of the optimised rule curves for the total system storage for the 12 months (water year calendar) for scenarios 0 and 9 with activated amplitude. The curves for the upper, middle and lower are separately shown in Figure 5.6a, Figure 5.6b and Figure 5.6c respectively. In all the three Figures, the level of the curves were found to be higher in scenario 9 compared to scenario 0, which indicates a shift in the rule curves. The area between scenarios 0 and 9 curves represent the operation zones where the supply for scenario 0 would be higher than that for scenario 9. Thus, the rule curves for scenario 9 restrict supply more than the rule curves for scenario 0. Whenever the total system storage falls within that area, the supplies in that month will be reduced from 100% to 80%, 80% to 50%, or even 50% to 30% for the upper, middle or lower levels respectively. The area between the two curves in Figure 5.6c (lower curve) is more noticeable, compared to that of the middle and upper curves, indicating higher water loss possibilities due to unauthorised abstractions at lower storage state. The change in the rule curves between scenarios 0 and 9 for reservoir 1 and 2 are presented in Appendix D1-1 and D1-2.



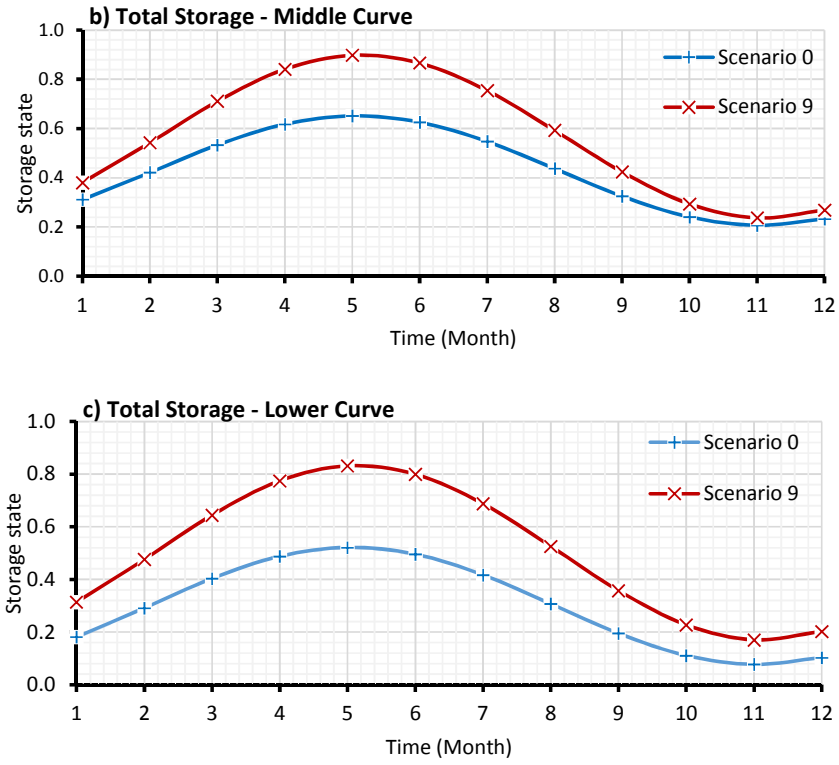


Figure 5.6: Optimised rule curves for the total storage for triginimetric rules for scenario 0 and 9.

Figure 5.7 presents the optimised operating rule curves obtained from the optimisation runs that gave best yield when amplitude was deactivated for scenarios 0 and 9. From reservoir 1, the upper rule curves at the beginning of the water year for scenarios 0 and 9 were 0.71, and 0.74 respectively. The relatively lower level of the storage state of 0. 71 above which 100% of the annual target draft can be released in scenario 0, is linked to the absence of unlawful abstractions along the streamflows. The storage state below which only 30% of the target draft will be supplied for scenario 0 is 0.55, whereas for scenario 9 it is 0.58 with a difference of about 0.03, and this indicates a shift of rule curves, which could lead to decrease in supply. Another example is when the storage state was 0.65 in scenario 0, 80% of the target draft can be released, whereas only 50% can be released in scenario 9 for the same level of storage. This could be the reason for the higher yield (0.4967) for scenario 0 compared to scenario 9 (0.4501), with a yield difference of about 9.4%. Similar trends were also observed in reservoir 2, and total storage, as illustrated in Figure 5.7.

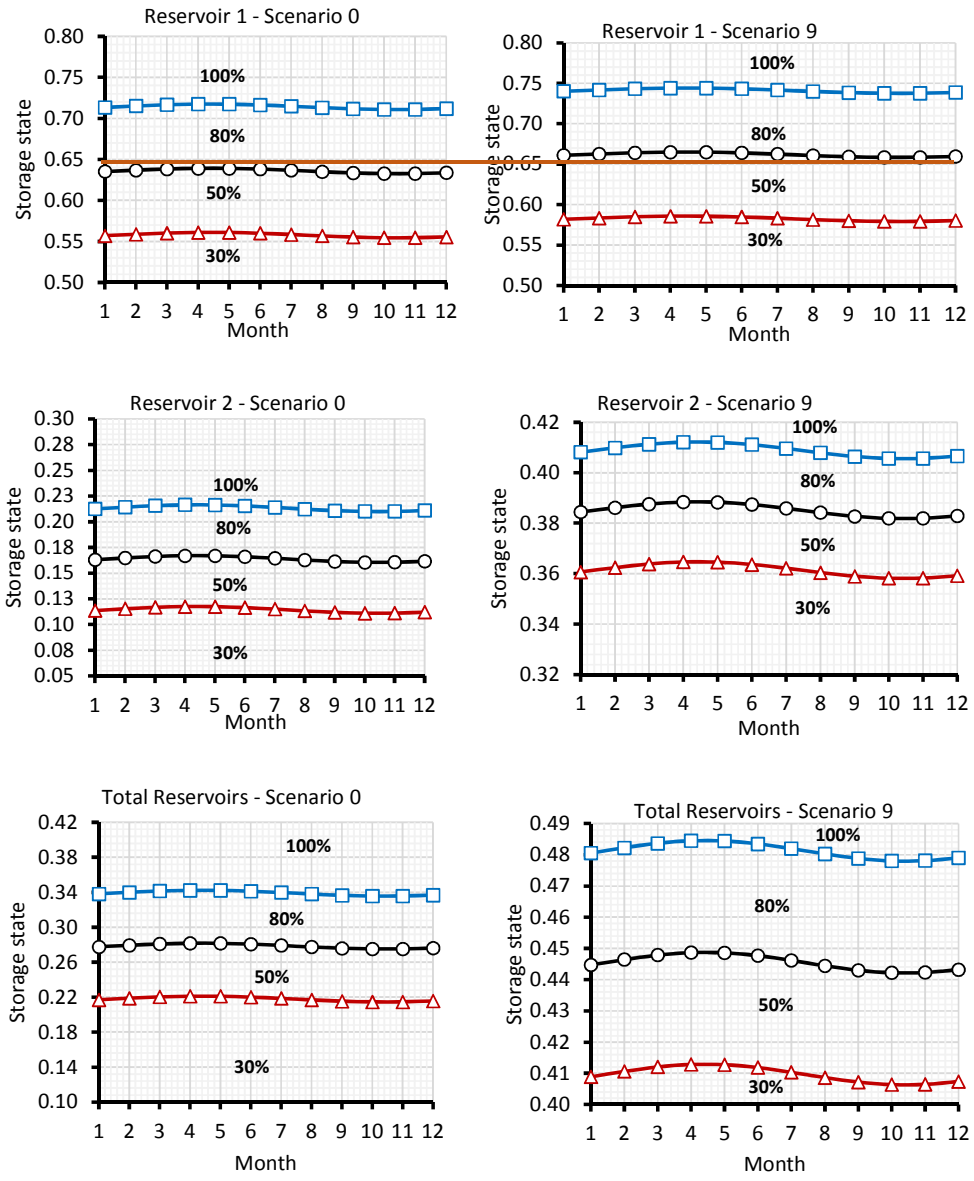


Figure 5.7: Optimised rule curves for linear rules for scenarios 0 and 9.

Figure 5.8 illustrates the levels of the optimised rule curves for the total system storage for scenarios 0 and 9 with deactivated amplitude for the complete water year. The upper, middle and lower curves are separately shown in Figure 5.8a, Figure 5.8b, and Figure 5.8c. In all the three Figures, the curves' levels were found to be higher in scenario 9 as compared to scenario 0 (rule curves shift), and the yield is again expected to be higher in scenario 0 than compared to scenario 9. Also, the area between scenario 0 and 9 curves represent the operation zones where the supply level for scenario 0 would be higher than that for scenario 9. Hence, the rule curves

for scenario 9 restrict supply more than the rule curves for scenario 0. Depending on the month, whenever the total system storage falls within the rule curve shift area, the supplies in that month will be reduced from 100% to 80%, 80% to 50%, or 50% to 30% for the upper, middle or lower rule curve levels respectively. The levels of the optimised rule curves for reservoirs 1 and 2 can be found in Appendix D1-3 and D1-4 respectively.

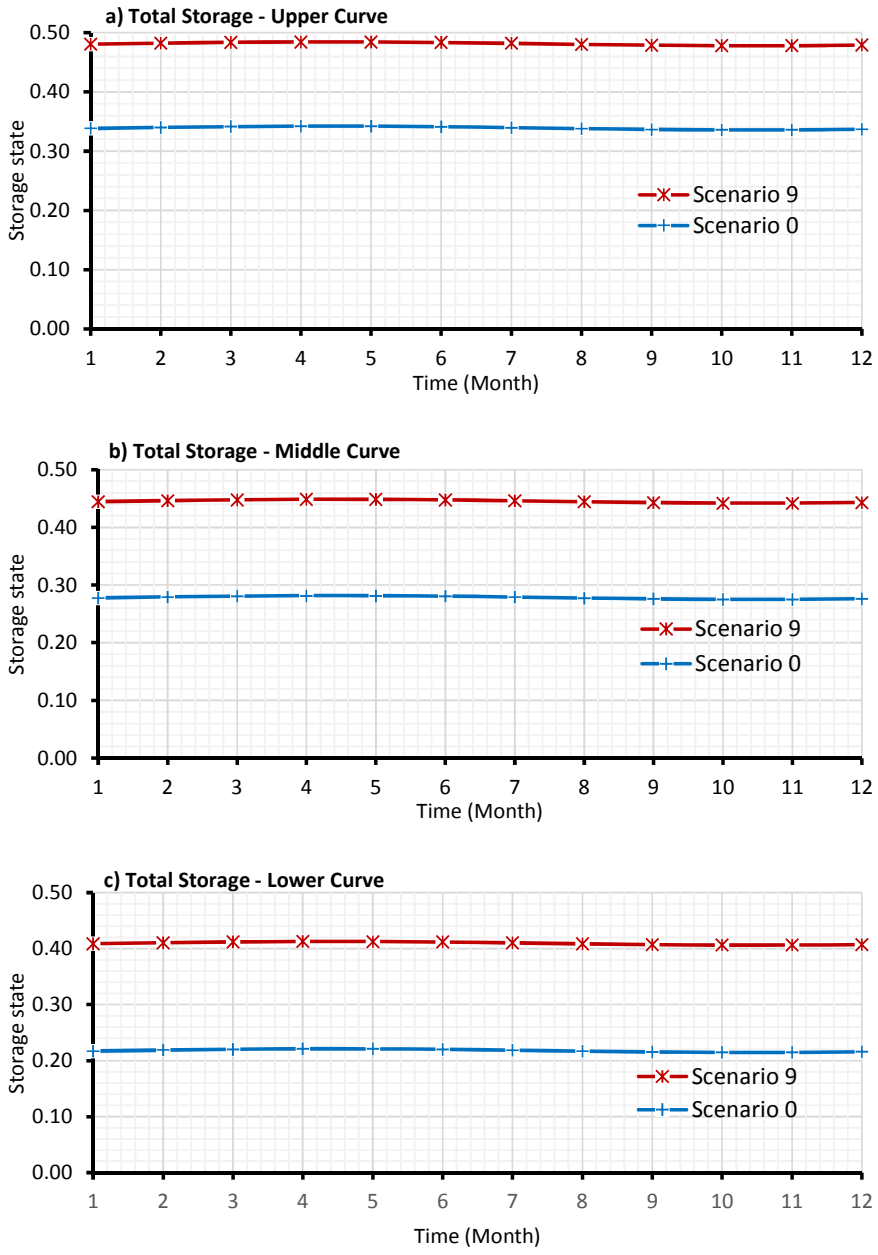
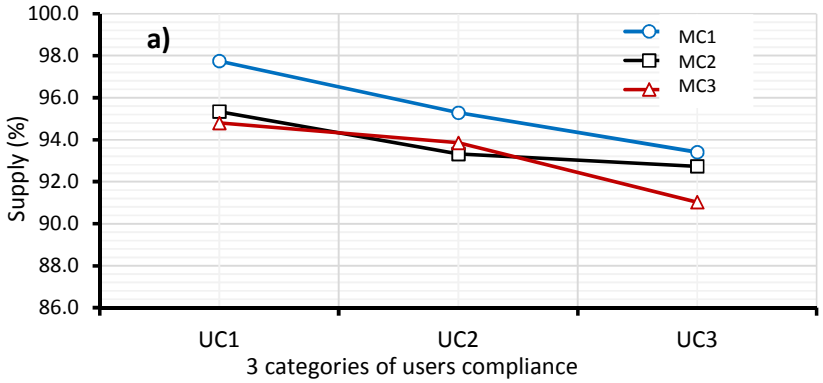


Figure 5.8: Optimised rule curves for the total storage for linear rules for scenario 0 and 9.

5.1.5 Comparative effect of users' compliance and management competence

This section presents the trade-off between the effect of users' compliance and management competence on the optimised yield for the activated amplitude case. Figure 5.9 shows the relative change in optimised yield due to changing users' compliance at constant management competence (Figure 5.9a), changing management competence at constant users' compliance (Figure 5.9b), and the average values (Figure 5.9c). These figures represent the relative decrease of yield (%) from what has been obtained in scenario 0, with 100% supply and 0.0% loss due to the absence of unauthorised water abstractions. In all the figures, the yield decrease as human behaviour (users' compliance and management competence) deteriorates. However, the yield drops drastically with a reduction in users' compliance (constant management competence), since the reduction in yield becomes more pronounced as users' compliance declines. Based on the computed impact ratio, both users' and management were found to have a significant impact on the optimised yield. However, users' impact is about 1.5 times higher than that of management. Thus, the problem of unlawful water abstractions can be minimised, not only due to the level of management effectiveness in preventing the problem, but also the level of compliance behaviour by the users.



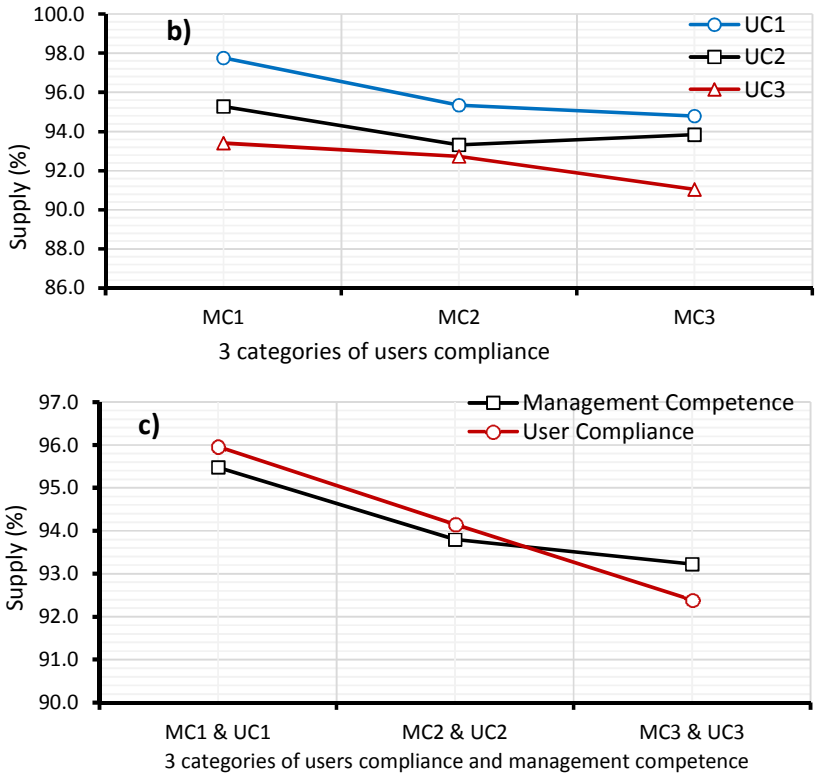


Figure 5.9: Relative change in yield due to changing users' compliance and management competence levels

5.2 Simulation Results

This section discusses the results obtained from the simulation runs by analysing the trajectories of the storage states, yields, and how the storage and yield are related under different human behaviour scenarios. The aim of analysing the trajectories of these variables was to quantitatively assess the impact of human behaviour on the storage state and yield over the 90-year long simulation period, and also to get insight in the co-evolutionary dynamics between the societal norms and values (behaviour), and reservoir system operation for an extended period. The analysis presented is mainly restricted to scenarios 0, 1 and 9 as these can cover the complete range of human behaviour impacts incorporated into the analysis. Also, the analysis is conducted and presented on an annual, and monthly basis.

5.2.1 Impact of human behaviour on reservoir storage state

The analysis gives more emphasis to the annual storage state because of the following reasons.

I) The storage state at the beginning of the water year typically used to decide on the amount of water to be allocated for that year.
II) The storage state at the beginning of the water year can also inform on the amount of water that has been abstracted illegally.

Figure 5.10 shows the annual total storage state trajectories for scenarios 0, 1 and 9, and the time series of the annual unlawful abstractions for scenarios 1 and 9. The effect of unlawful abstractions on the storage state was observed, as the total storage state for scenarios 1 and 9 were found to be lower than that of scenario 0. There were about ten major occurrences in which unlawful water use affected storage significantly. From the unlawful abstractions time series, massive unlawful water abstraction cases were found to occur in 21 and 29 years out of the 90 years of the simulation for scenarios 1 and 9 respectively, whereas no unlawful abstraction cases occurred in scenario 0. More water was abstracted without authorisation in scenario 9 than in scenario 1, and this reflected the fact that the effectiveness of management competence was higher in scenario 1 than in scenario 9. This could be the reason for higher yield in scenario 0 than scenarios 1 and 9, and higher yield in scenario 1 than in scenario 9 (see Table 5.1). Moreover, years in which human behaviour affected storage were also observed to correspond with years that experienced massive unlawful water abstractions. Yield can thus be reduced whenever massive unlawful abstractions occurred. In addition, most of the years in which the storage state differ due to changing human behaviour are the years with poor storage state, therefore, unlawful abstractions are more likely to occur during poor hydrological states. The storage trajectories for the individual reservoirs at different scenarios were found to have similar patterns (Appendix E1).

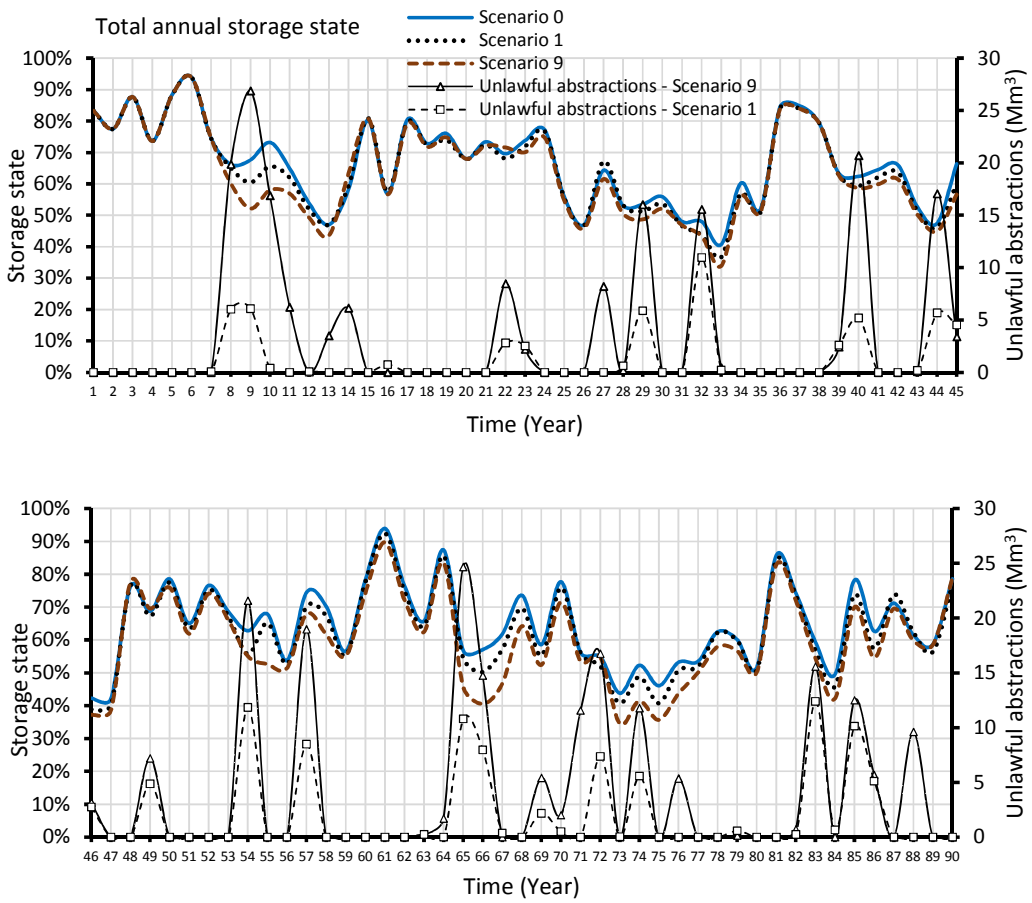


Figure 5.10: Annual total storage state trajectory and annual unlawful abstractions for scenario 0, 1 and 9

Figure 5.11 shows the trajectories of the total storage state, and the amount of water abstracted without authorisation on a monthly basis. The Figure is for 5 years, affected by drought (1929 to 1933). Although the storage states were predominantly low during these drought-affected years, the unlawful abstractions were found to have happened in a few months. The model is, thus, realistic as it mimics the fact that the unlawful abstraction is not expected to occur in every month. The adverse impact of the unlawful use was also found to be higher in scenario 9 than in scenario 1, because scenario 9 has the worst human behaviour and ineffective management.

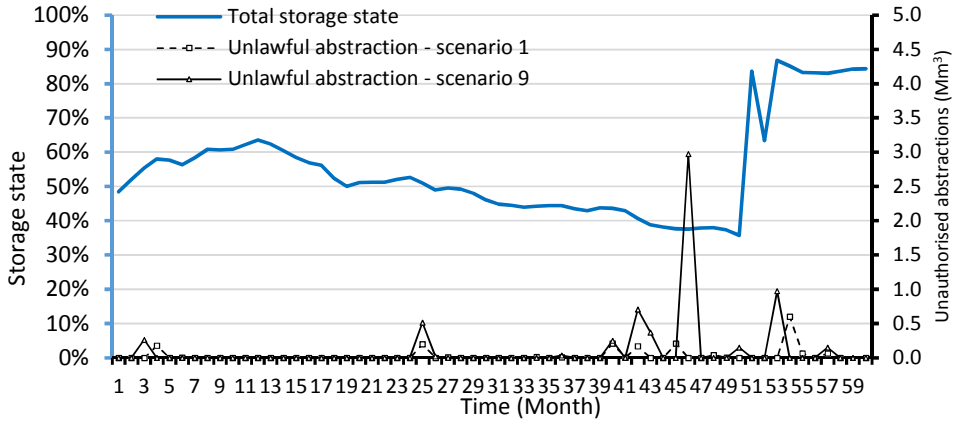


Figure 5.11 : Monthly trajectories of total annual storage and unlawful abstractions

5.2.2 Effect of human behaviour on yield and yield-demand ratio

This section presents the trade-off of the annual yield-demand ratio, and unlawful abstractions. The analysis was also restricted to the total system yield-demand ratio, and unlawful abstractions as this represent and provides an accurate picture of the two reservoirs in the system. Figure 5.12 shows the trajectories of the percentage of the annual target draft that has been delivered for scenarios 0, 1 and 9, and the unlawful abstractions for scenarios 1 and 9. From Figure 5.12, most of the years in which the yield-demand ratio differs significantly due to human behaviour, are years affected by unlawful abstraction cases. The result indicates that whenever massive unauthorised water abstraction occurs, the total annual expected yield can be drastically reduced. For example, in the 44th year, marked **X**, about 65%, 55% and 29% of the total annual target draft were allocated in scenarios 0, 1 and 9 respectively. The trajectories of the yield-demand ratio for the individual reservoirs as affected by unlawful water abstractions, are presented in Appendix F1.

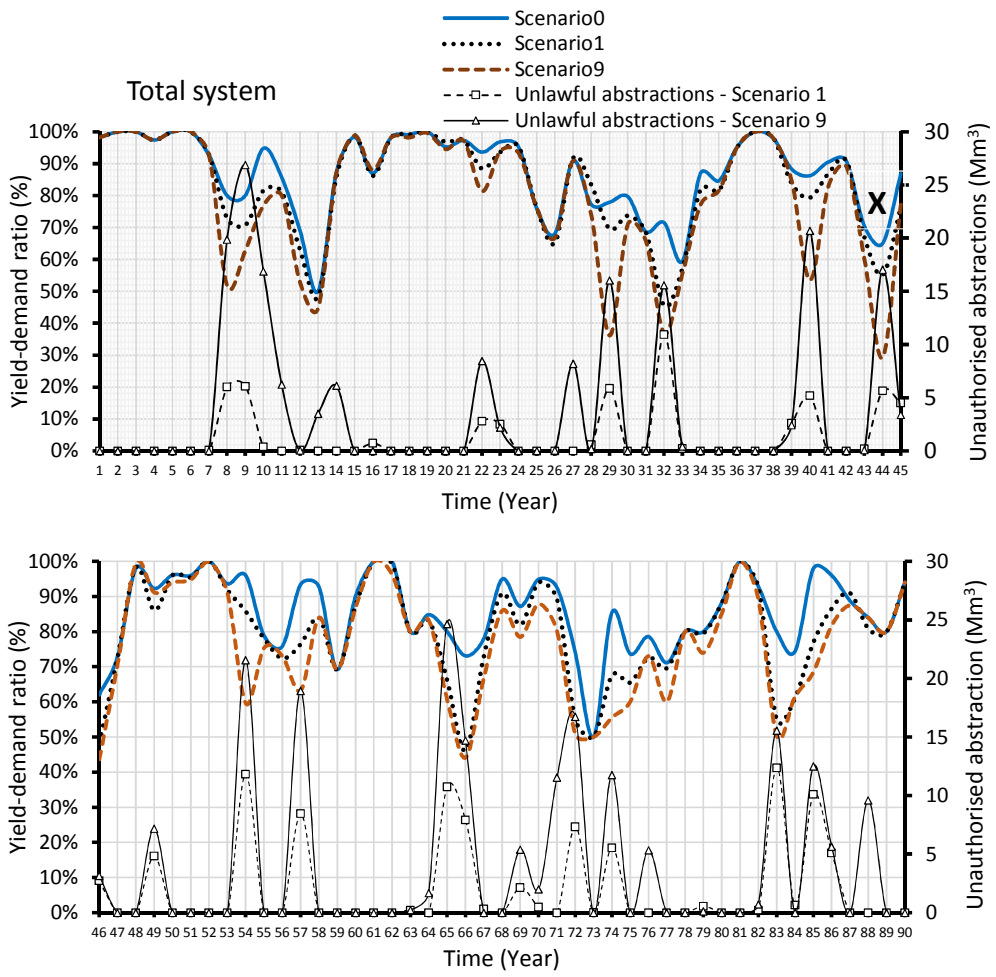
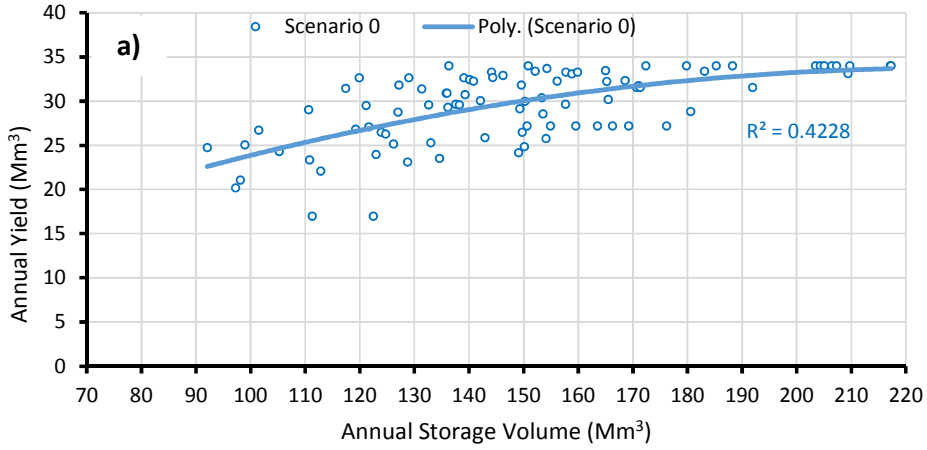


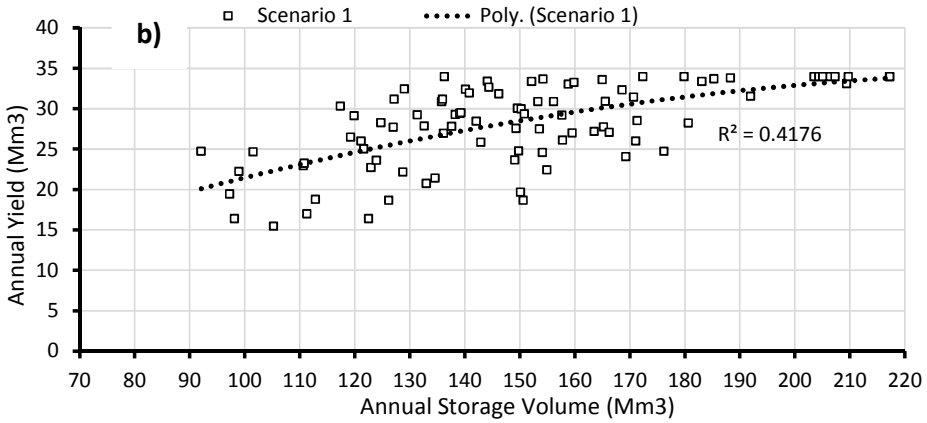
Figure 5.12: Annual yield-demand ratio and annual unlawful abstractions trajectory for scenario 0, 1 and 9.

5.2.3 Annual operating rule curves as affected by human behaviour

The simulation-optimization optimized yield and monthly operating rule curves for the purpose of assessing the impact of human behaviour on reservoir system performance. In practice however, decisions on how much water to allocate to irrigation users over a period of one year are required to enable them to plan their planting activities for the year. This is usually done using annual operating rule curves that inform how much water to allocate for the year given the storage state of the reservoir system. This section, therefore, presents the deviation of annual reservoir operating rules on the basis of the relationship between the annual storage volume (on decision date) and annual yield for scenarios 0, 1, and 9. Figure 5.13a, Figure 5.13b and Figure 5.13c illustrate the total annual storage-yield relationships for scenarios 0,

1, and 9 whereas, Figure 5.13d shows the storage-yield relationships for the three scenarios. The polynomial trend lines in Figure 5.13a to Figure 5.13c revealed how annual yield as the total annual storage volume increases. Figure 5.13d showed that at a given storage volume, the yield obtained in scenario 0 is higher than that of scenarios 1 and 9, due to adverse human behaviour of unauthorised water abstractions in scenario 0. For example, when the total annual storage volume was 120 Mm^3, the total yields were 26.7 Mm^3, 24.6 Mm^3 and 23.1 Mm^3 for scenarios 0, 1 and 9 respectively. The calculated reduction in yield between scenarios 0 and 1 was 2.1 Mm^3 (7.8%), and between scenarios 0 and 9 it was 3.6 Mm^3 (13.5%). Whereas, when the total storage volume reached 200 Mm^3 the total system yield for all three scenarios was nearly the same (33.5 Mm^3). The total system storage volume, and the yield can, therefore, be significantly affected by human behaviour.





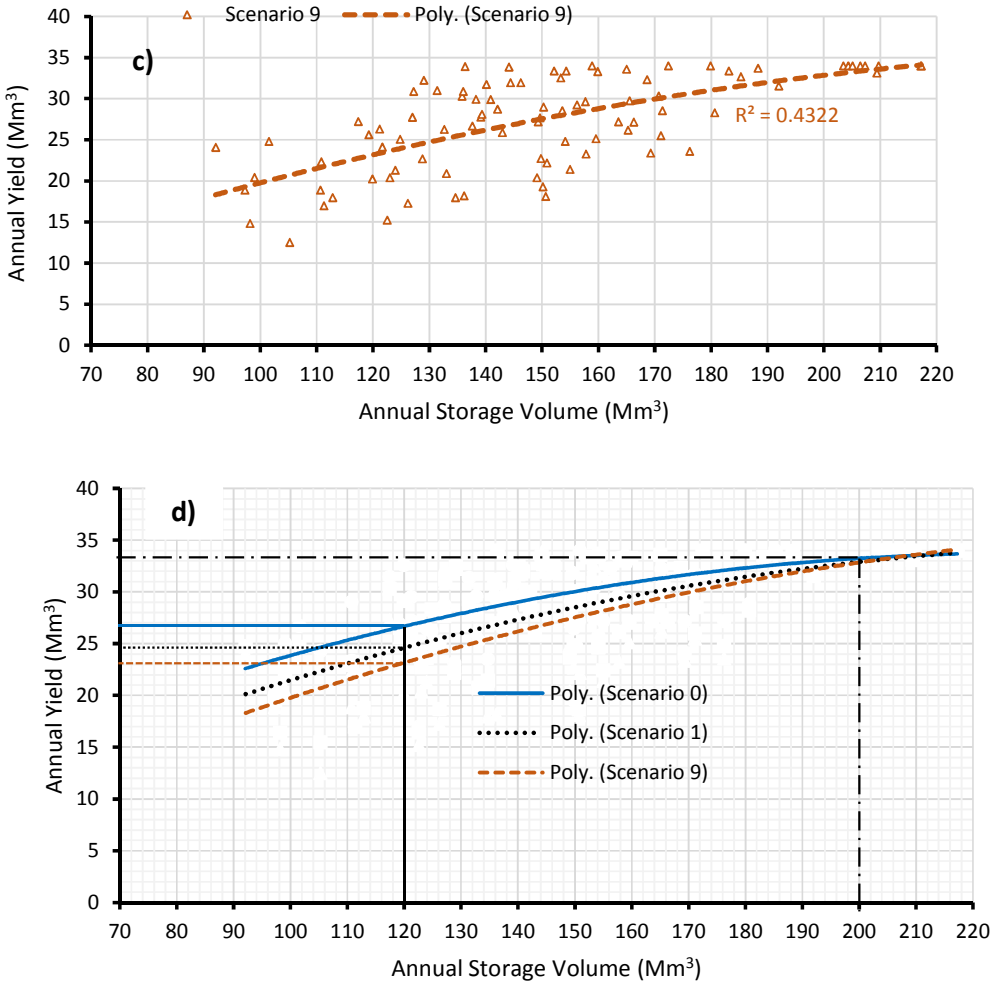


Figure 5.13 : Annual storage-yield relationships: a) scenarios 0, b) scenario 1, c) scenario 9 and d) for the 3 scenarios

The total annual yields obtained for the 90 years for scenarios 0, 1 and 9 were then ranked from highest to lowest, and the probability that a given annual yield is exceeded was computed using the Weibull plotting position formula. The computed probability of exceeded annual yield was considered as a percentage less in the total annual yield for scenarios 0, 1 and 9, as shown in Error! Reference source not found.. From the figure, the total annual yield is reduced as the exceedance probability decreases. This indicated that although there were fewer occurrences of unauthorised water use, the adverse impact on the yield increases with the decreasing probability of such occurrences.

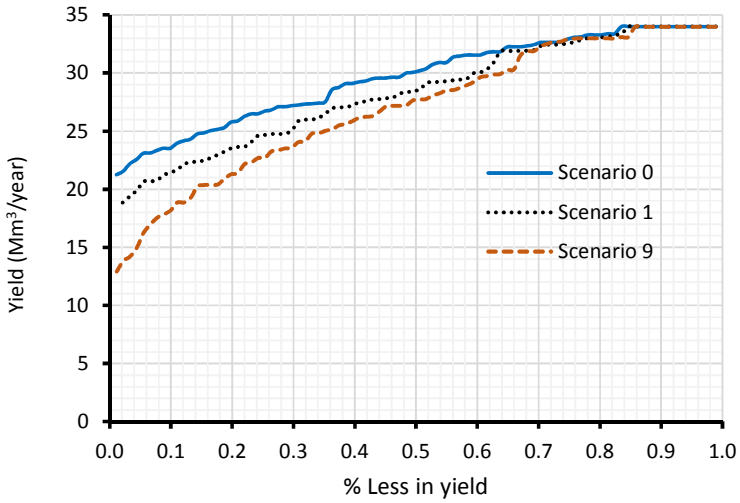


Figure 5.14: Total expected annual yield for scenario 0, 1 and 9

Since the total annual yield obtained from scenario 0 is the maximum expected yield, due to the absence of unauthorised abstractions, it was then used to compute the percentage reductions in total annual yield for scenarios 1 and 9 at different probabilities for unauthorised abstractions to occur. Table 5.3 and Figure 6.14 presents the percentage reduction in total annual yields for scenarios 0, 1, and 9 at different probabilities of exceedance, as extrapolated from Error! Reference source not found..

Table 5.3: Yield loss for scenario 0, 1 and 9 at different % less in yield

Scenarios	**Yield** (Mm³) *p=0.01*	**Loss (%)**	**Yield** (Mm³) *p=0.1*	**Loss** (%)	**Yield** (Mm³) *p=0.5*	**Loss** (%)	**Yield** (Mm³) *p=0.8*	**Loss** (%)	**Yield** (Mm³) *p=0.9*	**Loss** (%)
Scenario 0	21.3	0.0	23.5	0.0	29.2	0.0	33.0	0.0	34.0	0.0
Scenario 1	18.5	13.1	21.3	9.4	28.3	3.1	33.0	0.0	34.0	0.0
Scenario 9	12.9	39.4	18.2	22.6	27.8	4.8	33.0	0.0	34.0	0.0

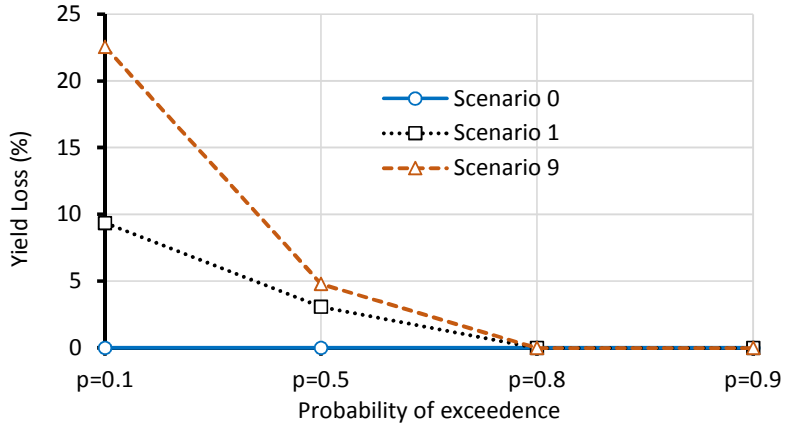


Figure 5.15: Yield loss for scenario 0, 1 and 9 at different probabilities of exceedance

5.2.4 Comparative analysis of the annual and monthly rule curves

Figure 5.16 illustrates the operating rules for reservoir 1. Figure 5.16a and Figure 5.16b are the defined monthly and annual operating rules respectively. For a given storage state, the monthly supply was observed to be higher or lower than the annual supply. This is quite possible, since an annual yield for a given water year is usually shared throughout that water year, based on the monthly demand distribution. For example, in a year with an annual yield of 80% of the annual target draft, this yield is shared across the year, such that monthly supply could vary from 30% to 100%, especially with seasonally varying demands, such as irrigation.

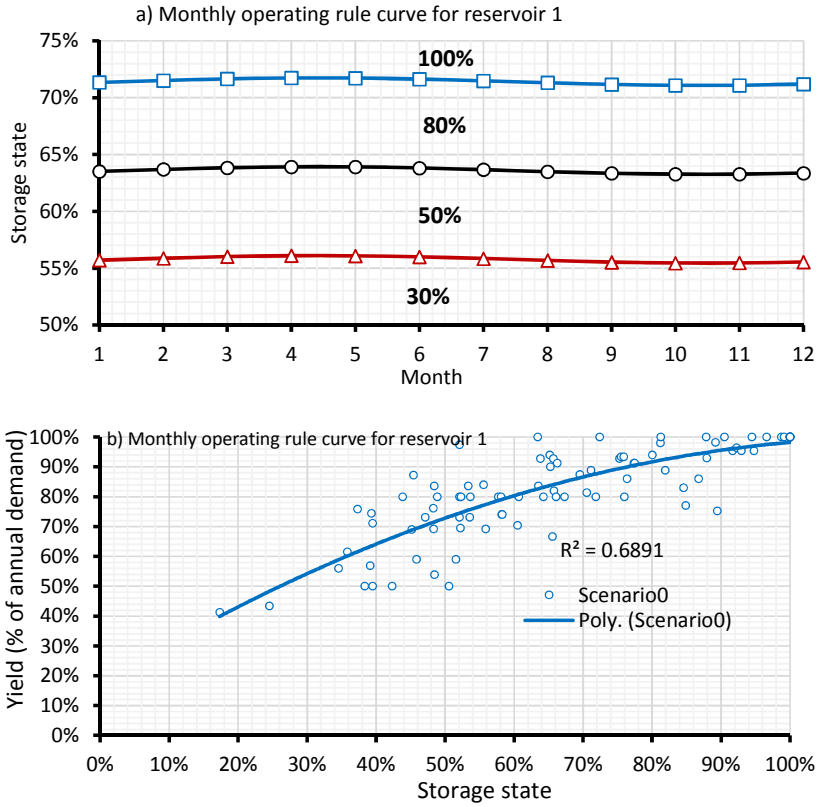


Figure 5.16: Operating rules for reservoir 1: a) monthly and b) annual

5.2.5 Incorporating reliability into annual and monthly operating rules

This study applies historic streamflows sequences, and the comprehensive probabilistic analyses that use stochastically generated streamflows to incorporate

reliability into reservoir operation (Basson *et al.*, 1994; Ndiritu *et al.*, 2017), are not applicable. In this section, a simpler approach of incorporating reliability that makes use of the variability of the optimised annual yields with storage, is formulated and illustrated, using an example.

Figure 5.17 illustrates the optimised annual storage-yield relationships over 90 years for reservoir 1, categorised into four zones. The zones were formed to each contain an equal number of years, and the respective number of years are 22, 23, 22 and 23 for zone1, zone2, zone3, and zone4. The total annual yields obtained for each of the four zones are then ranked independently, and the probability that a given annual yield is exceeded is computed using the Weibull plotting position formula. The resulting cumulative frequency distribution curves for the annual yields are shown in Figure 5.18. These curves can now be used to determine the annual reservoir operating rule curve for a specified reliability (or level of assurance) by assigning the yields at those levels of assurance to the average storage in that zone. Figure 5.18 shows the annual yields obtained at 50% and 95%, and these are used to obtain the respective annual rule curves as shown in Figure 5.19.

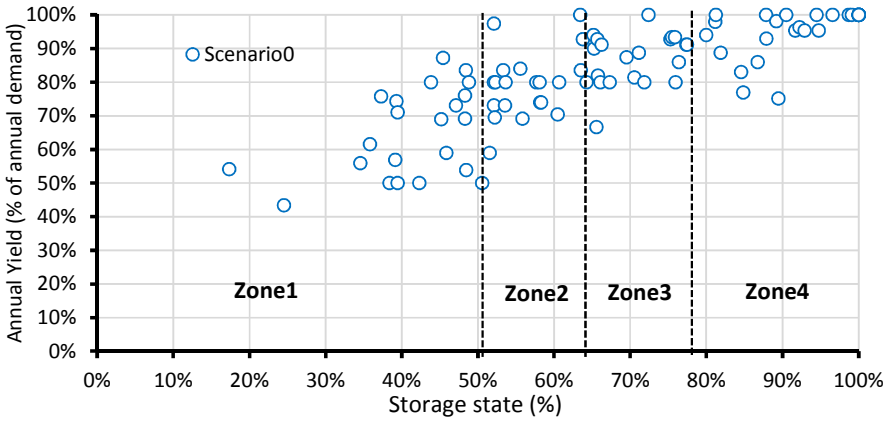


Figure 5.17: Storage-yield relationship and the four storage zones for reservoir 1

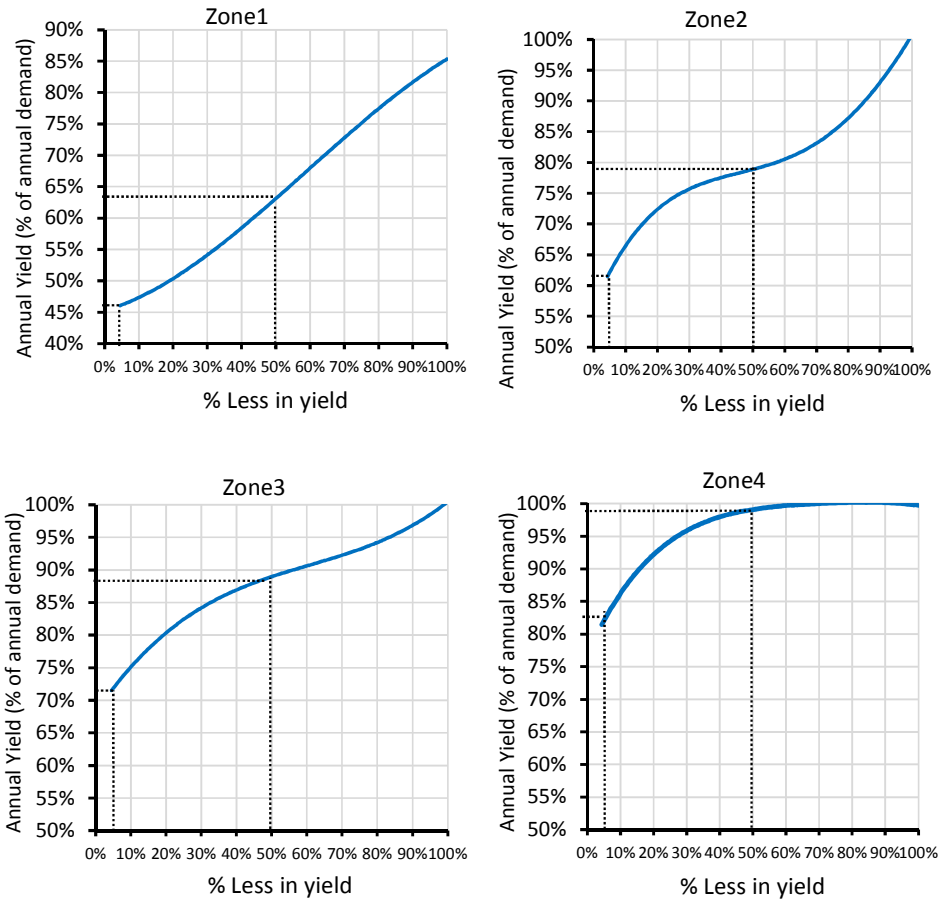


Figure 5.18: Expected annual yields to be obtained from the four storage zones

Table 5.4 and Figure 5.19 shows the yields obtained at 50% and 95% reliability of supply, and the average storage state obtained at each of the four storage zones (Figure 5.18). The yield obtained from the 95% reliability of supply curve ($Y_{95\%}$) is the safe-zone annual operating rule with which the system is not expected to fail. This is transformed annual operating rule curve with a 95% reliability of supply, and is considered as the safe operating rule for reservoir 1.

Table 5.4: Annual yields obtained at 50% and 95% reliability of supply and the average storage for each zone

Storage zones	Zone1	Zone2	Zone3	Zone4
Annual yield (50% reliability of supply)	63	78	88	98
Annual yield (95% reliability of supply)	46	62	73	84
Average storage (%)	41	58	73	94

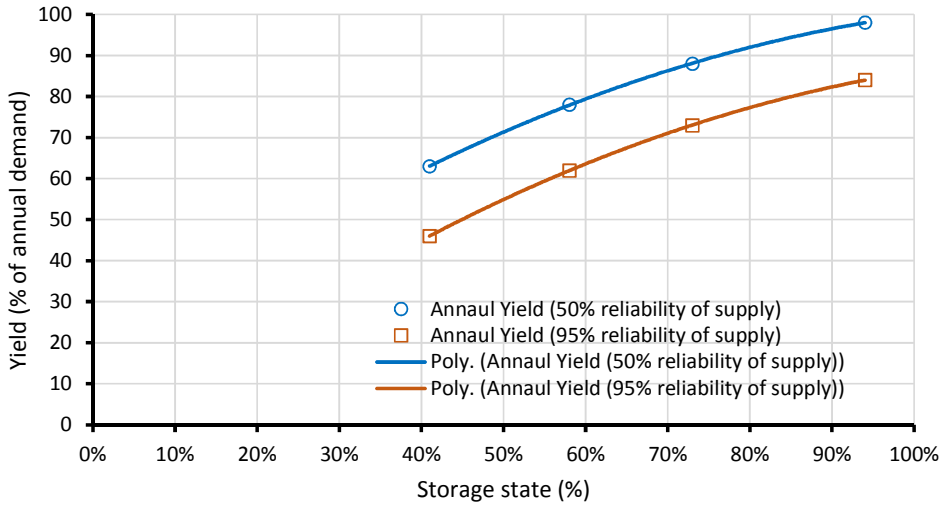


Figure 5.19: Annual yield and yield obtained at 5% less (95% reliability of supply)

The transformed annual yield ($Y_{95\%}$) was also extended to the monthly operating rules. Figure 5.20 shows the initial (Figure 5.20a) and transformed (Figure 5.20b) monthly operating rules for reservoir 1. The transformed operating rule was computed as the product of the initial monthly rule curve value, and the ratio of the yield obtained at 50% reliability of supply, to the yield obtained at 95% reliability of supply ($Y_{50\%}/Y_{95\%}$). The transformed rule curves rises to increase the probability of imposing supply restrictions that will conform to the 95% reliability of supply, as shown in Figure 5.20b.

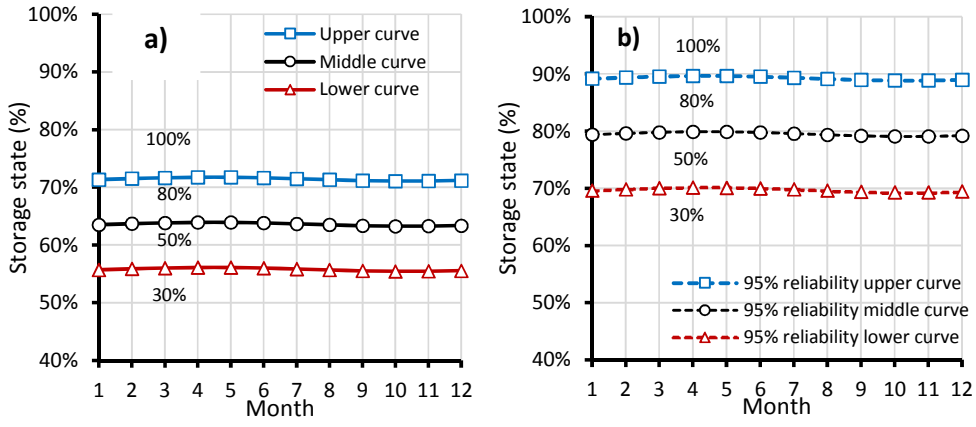


Figure 5.20: Monthly rule curves: a) Initial rule curves and b) transformed (95% reliability of supply) rule curves for reservoir 1

Figure 5.21 illustrates the annual and monthly operating rules based on the 95% reliability of supply. Both annual and monthly operating rule curves encourage higher

release, as the storage increases. The monthly operating rule found to be higher and lower than annual operating rule as storage increases and decreases respectively. This is possible since annual yield for a given water year is usually shared throughout that water year, based on the monthly demand distribution.

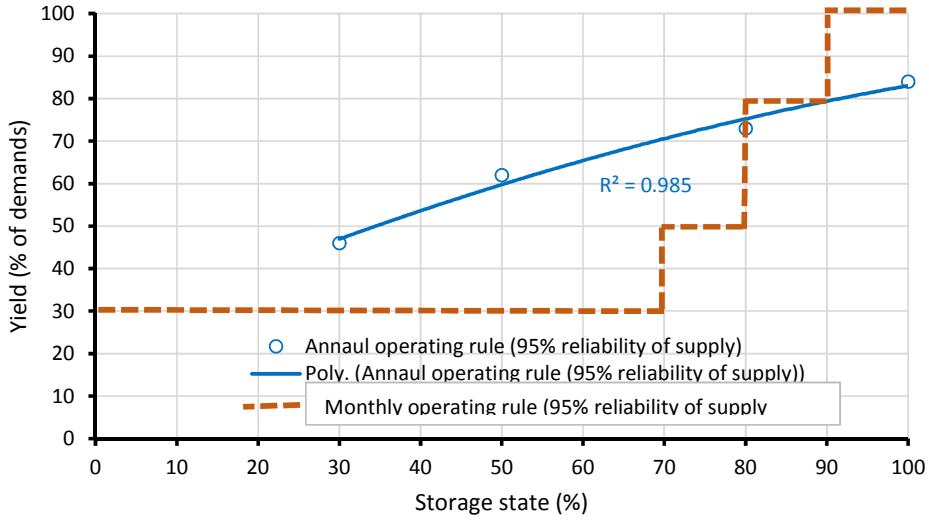


Figure 5.21: Annual and monthly operating rule at 95% reliability for reservoir 1

5.3 Summary of Chapter

Although human behavioural impacts were hypothetically incorporated into the reservoir operation simulation model, the results quantitatively provide an insight into the probable impact of unlawful water abstractions on reservoir performance. The calculated average loss due to illegal water use was found to approximate the reported annual water loss through unlawful use (6.4%) in South Africa (Mckenzie *et al*., 2012). It is, therefore, vital to consider the task of monitoring compliance via the enforcement unit (management competence), as well as continued awareness campaigns (to enhance users' compliance). This is to create an avenue whereby both water managers and users' will jointly work, and ensure effective compliance, particularly in years of drought. This study, therefore, introduces a novel approach to yield analysis that incorporates uncertainties of both hydrologic, and human behaviours. The study also highlighted the need to change the business-as-usual approach of ignoring the impact of human behaviour in the management of water resource systems.

CHAPTER SIX

6.0 RESULTS AND ANALYSIS FOR OLIFANTS RIVER CASE STUDY

This chapter presents the results and analyses obtained from the Olifants River Reservoir System (Figure 4.9). The results of the optimisation are first presented, and discussed, followed by the simulation results. The result of the optimised yield for the scenario with no human behaviour incorporated (scenario 0), is first presented, and discussed. The results of scenario 0 were then used as a reference to the results obtained from the other nine scenarios with varying levels of human behaviour. The optimised yields for the scenarios with the highest unlawful abstractions impact (scenario 9) and least impacted (scenario 1) are also presented, and analysed, while those for the other seven scenarios (2 to 8) are presented in Appendix A2. Similarly, the optimised parameter values, the operating rule curves, and the losses in yield due to unauthorised abstractions are presented, and analysed. A comparison of the effects of the two human behaviour inputs into the simulation (users' compliance and management competence) on yield performance, is also conducted.

The results from simulation runs were used to analyse the trajectories of the storage state, yield-demand ratio, and storage-yield trade-offs under different levels of human behaviour. The analysis of the simulation result was limited to the total reservoir system, as it provided the needed information on all the reservoirs in the system, because weighting parameters were used to compute the total reservoir system storage. Results from the individual reservoirs are presented (tables and graphs) in Appendices. The discussions and analyses are mostly based on the two performance indices; system yield, and unauthorised abstractions loss, as defined in Section 4.2.3.1.

6.1 Optimisation Results

The results obtained from the optimisation runs are presented in this section.

6.1.1 Optimised yield

Table 6.1 below presents the optimised reservoir system yield, and the number of model simulations for the five randomly initialised optimisation runs. The table

contains the yield for scenarios 0, 1 and 9 (Table 4.3) for the two cases; trigonometric rule curves (with the four trigonometric parameters), and linear rule curves (with a very low value of amplitude parameter) as explained in Section 4.2.3.2. For each scenario, all five the initialised optimisation runs gave almost matching optimised yield, with the maximum value being less than 3% higher than the minimum value. The low differences in optimised yields indicate that SCE-UA is an effective and efficient optimiser, as observed by Ndiritu & Sinha, (2009).

Deactivating the amplitude parameter was found to significantly reduce the number of model simulations, and computation time. The computation time for the activated and deactivated amplitude case is about 3 hours and 5 hours respectively. For the activated amplitude case, all five the initialised optimisation runs in each scenario gave almost similar yield. The maximum and minimum optimised yields for scenarios 0, 1 and 9 were 0.2754 and 0.2716, 0.2594 ,and 0.2523, and 0.2468 and 0.2431 respectively. The minimum yields were found to be 98%, 97% and 99% of the maximum yields respectively. Similarly, when the amplitude was deactivated, the minimum yields found to be 99%, 97% and 99% of the maximum values.

However, deactivating the amplitude parameter increases the yield with maximum and minimum yields of 0.4235 and 0.4218, 0.4002 and 0.3884, and 0.3745 and 0.3731 for scenarios 0, 1 and 9 respectively. The average of the optimised yields when the amplitude parameter was activated and deactivated for scenarios 0, 1 and 9 were 0.2740 and 0.4226, 0.2566 and 0.3938, and 0.2453 and 0.3740, with a yield difference of -35.2%, -34.8% and -34.4% respectively. The average yields were found to increase by about 35% when the amplitude was deactivated in all the scenarios. The optimised yields when amplitude was activated, are suspected to be the local optimum solutions, and the optimisation method (SCE-UA) can be said to fail to reach global optimum since the system becomes complex. Notwithstanding, since when amplitude was excluded, the yield increased, confirming that there is no need to use the trigonometric function to define the reservoir operating rules.

For the activated amplitude, the optimised yields of all five the optimisation runs for scenario 0 were higher, compared to scenarios 1 and 9, with an average yield of

0.2740, 0.2566 and 0.2453 respectively. Also, when the amplitude was deactivated, a similar trend was observed with the optimised yield for scenario 0 averaging 0.4226, compared with 0.3938 and 0.3740 for scenarios 1 and 9 respectively.

Table 6.1: Optimised yields for scenarios 0, 1 and 9

Run	No BE (scenario 0)		Least BE (scenario 1)		Highest BE (scenario 9)	
	Amplitude Parameter Activated (Trigonometric rules)					
	No. of Sim.	Yield	No. of Sim.	Yield	No. of Sim.	Yield
1	39692	0.2750	38671	0.2523	37859	0.2460
2	36974	0.2754	36809	0.2581	39801	0.2431
3	37678	0.2716	37886	0.2594	36671	0.2468
4	38822	0.2650	35988	0.2633	35532	0.2428
5	35981	0.2739	37411	0.2554	37011	0.2434
Average		0.2722		0.2577		0.2444
Run	Amplitude Parameter Deactivated (Linear rules)					
	No. of Sim.	Yield	No. of Sim.	Yield	No. of Sim.	Yield
1	33765	0.4218	29501	0.4002	30351	0.3745
2	30252	0.4224	29645	0.3884	29734	0.3731
3	32773	0.4235	29975	0.3928	28638	0.3743
4	33811	0.4229	32479	0.3909	32400	0.3738
5	31837	0.4224	29248	0.3913	30535	0.3728
Average		0.4226		0.3913		0.3737

6.1.2 Impact of behavioural effect on the optimised yield

The optimised yield obtained from scenario 0, was found to be higher than the yields obtained from each of the nine scenarios that incorporated different levels of human behaviour. Table 6.2 shows the average yields, and the losses in yield as a result of unlawful abstractions for the nine scenarios. The losses due to unlawful abstractions ranged from 5.3 to 10.2% for the trigonometric operating rule curves (activated amplitude), that allows the rule curves to vary on a monthly basis, whereas the losses ranged from 7.1 to 11.5% for the simple linear operating rule curves (deactivated amplitude) that specified a single rule curve level across the year. This could also lead to an annual water-scarcity probability of 10% (90% reliability) as obtained in the Elands River case study. The overall average loss of all the nine scenarios with the activated and deactivated amplitude were 7.3%, and 8.9% respectively.

Table 6.2: Average of the optimised yields for the 5 initialised optimisation runs

Scenarios	Amplitude Activated		Amplitude Deactivated	
	Yield	Loss (%)	Yield	Loss (%)
1 – UC_1MC_1	0.2577	5.3	0.3913	7.1
2 – UC_2MC_1	0.2562	5.9	0.3927	7.4
3 – UC_3MC_1	0.2489	8.6	0.3860	8.7
4 – UC_1MC_2	0.2581	5.2	0.3888	8.0
5 – UC_2MC_2	0.2521	7.4	0.3848	8.9
6 – UC_3MC_2	0.2472	9.2	0.3822	9.6
7 – UC_1MC_3	0.2546	6.5	0.3822	9.5
8 – UC_2MC_3	0.2522	7.3	0.3809	9.9
9 – UC_3MC_3	0.2444	10.2	0.3737	11.5
Overall average	0.2524	7.3	0.3847	8.9
Scenario 0	0.2722	0.00	0.4226	0.00

Figure 6.1 shows the optimised yield for scenario 0 to 9. The optimised yield was found to reduce, as users' compliance (UC) and management competence (MC) deteriorated. For the deactivated amplitude parameter case, when UC was constant (UC_1), the yields for declining management competence (MC_1, MC_2 and MC_3) were 0.3913, 0.3888, and 0.3822 respectively. Also, for activated amplitude cases the yields for a constant management competence (MC_3) for declining user compliance (UC_1, UC_2 and UC_3) were 0.2546, 0.2522, and 0.2444 respectively.

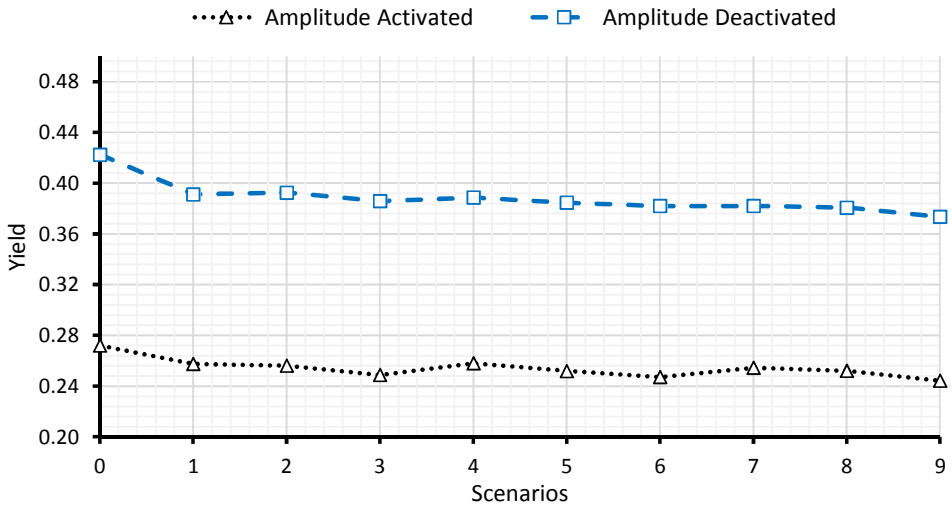
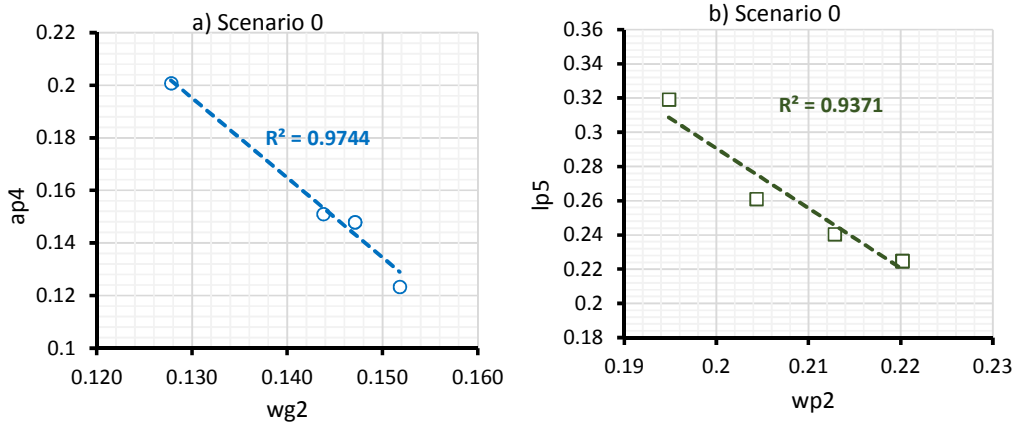


Figure 6.1: Average yield for trigonometric and linear operating rules

6.1.3 Optimised parameter values

In this case study, five randomly initialised optimisation runs were conducted for each scenario to identify the most optimum solution to the problem at hand. The adopted trigonometric function uses four parameters (translation - tp, width - wp, amplitude - ap and lag - lp) to define three rule curves for each reservoir. A weighing parameter (w_g) for each reservoir was used to compute the rule curves for the total system, and was optimised. Also, the annual demands (td) for each reservoir was optimised. For the Olifants River reservoir system case study, 30 parameters were, therefore, optimised. With as aim the assessment of the effectiveness of the optimisation method (SCE-UA), analysis of some of the parameter values from the multiple runs was conducted.

The optimised parameters from the five randomly initialised optimisation runs were observed to have a reasonable level of consistency. The optimised parameters also show parameter interdependence, as Figure 6.2 shows a strong correlation of some randomly selected parameters. The ability of the SCE-UA to obtain almost matching yields from multiple runs (Table 6.1), and to also capture strong parameter interdependencies (Figure 6.2), is considered an indication of its effectiveness as an optimiser. This observed effectiveness, and reliability of the SCE-UA were in agreement with the findings by Ndiritu & Sinha (2009). For the purposes of this study, the SCE-UA was, therefore, considered a reliable optimiser. The optimised parameter values for scenarios 0 to 9 were presented in Appendix B2 and C2.



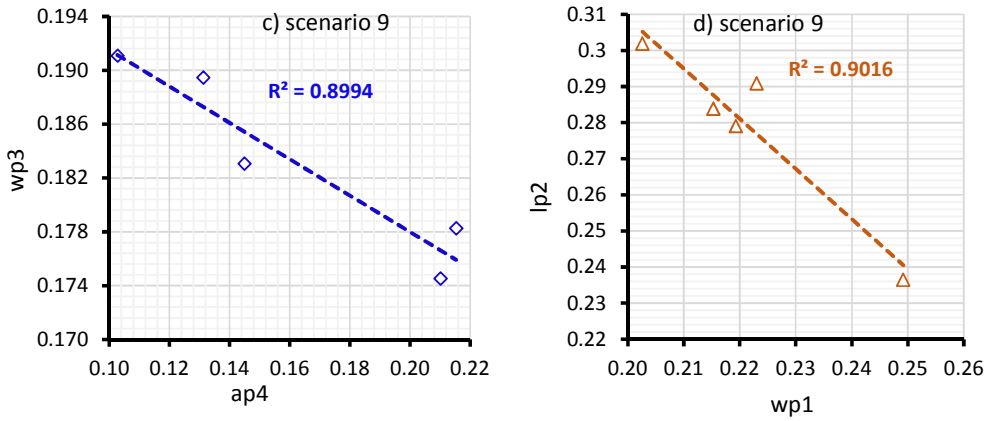


Figure 6.2 : Cross correlation of some of the optimised parameters

6.1.4 Optimised reservoir operating rule curves

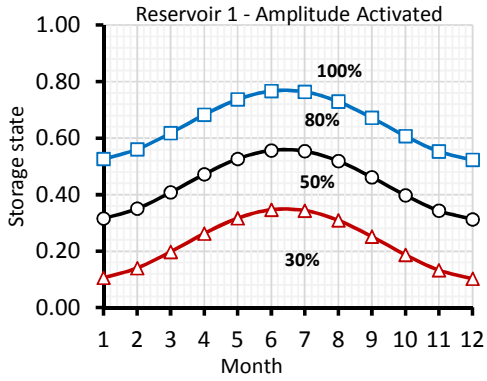
This section presents and analyses the optimised operating rule curves for the individual reservoir and the total system. The analysis was conducted in two ways:

i) Impact of amplitude parameter on the optimised operating rule curves;
ii) Impact of human behaviour on the optimised operating rule curves.

6.1.4.1 Effect of amplitude parameter on the optimised operating rule curves

Figure 6.3 presents the optimised rule curves obtained from the optimisation runs that gave the best objective functions for scenario 0. The upper and lower optimised rules curves with activated amplitude (trigonometric rule curves) were found to reach the upper (1.0), and lower (0.0) limits of the operating rules for different months within the water year, indicating that the amplitude values were high. Whereas, when the amplitude was deactivated (non-linear rule curves) the optimised rule curves for all the reservoirs, and the total system were found to have possessed negligible variation from the beginning to the end of the water year.

However, activating the amplitude parameter reduces the optimised yield drastically to 0.2754, compared to when the amplitude parameter was deactivated 0.4235 (see Table 6.1). The results indicate that when the amplitude parameter was activated, the optimiser (SCE-UA) failed to reach the global optimum (stop at local optimum), as previously suggested.


Reservoir 1 - Amplitude Activated
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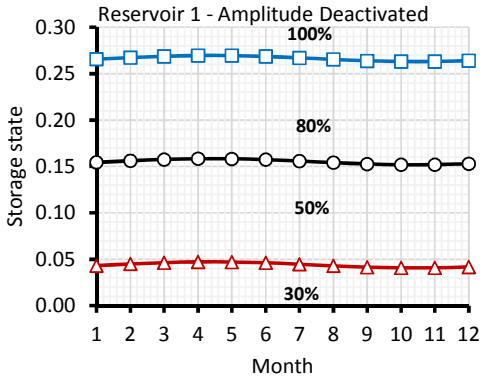
Reservoir 1 - Amplitude Deactivated
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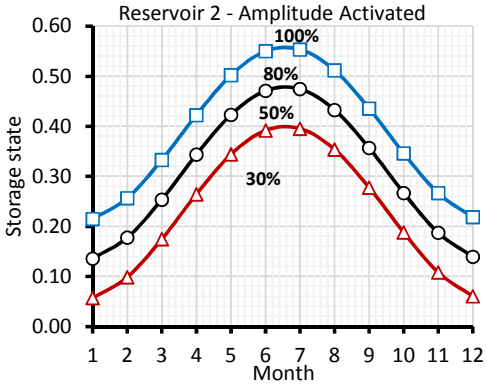
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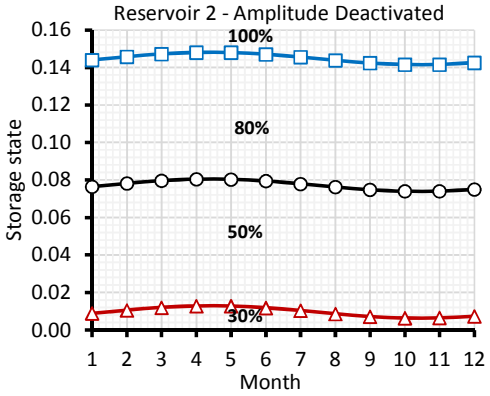
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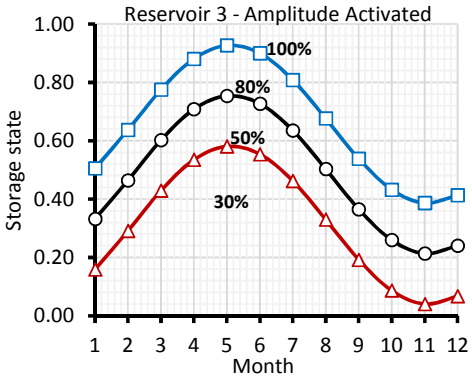
Reservoir 3 - Amplitude Activated
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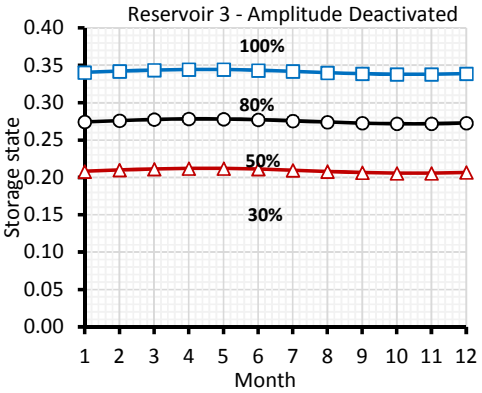
Reservoir 3 - Amplitude Deactivated
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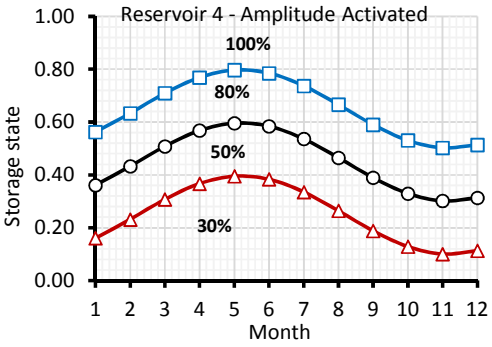
Reservoir 4 - Amplitude Activated
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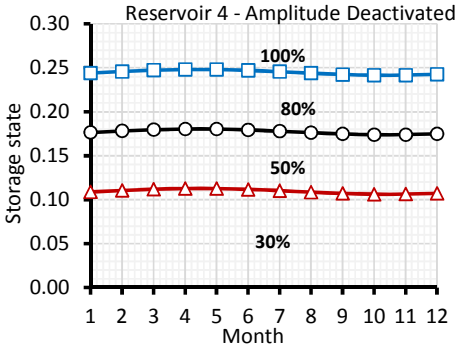
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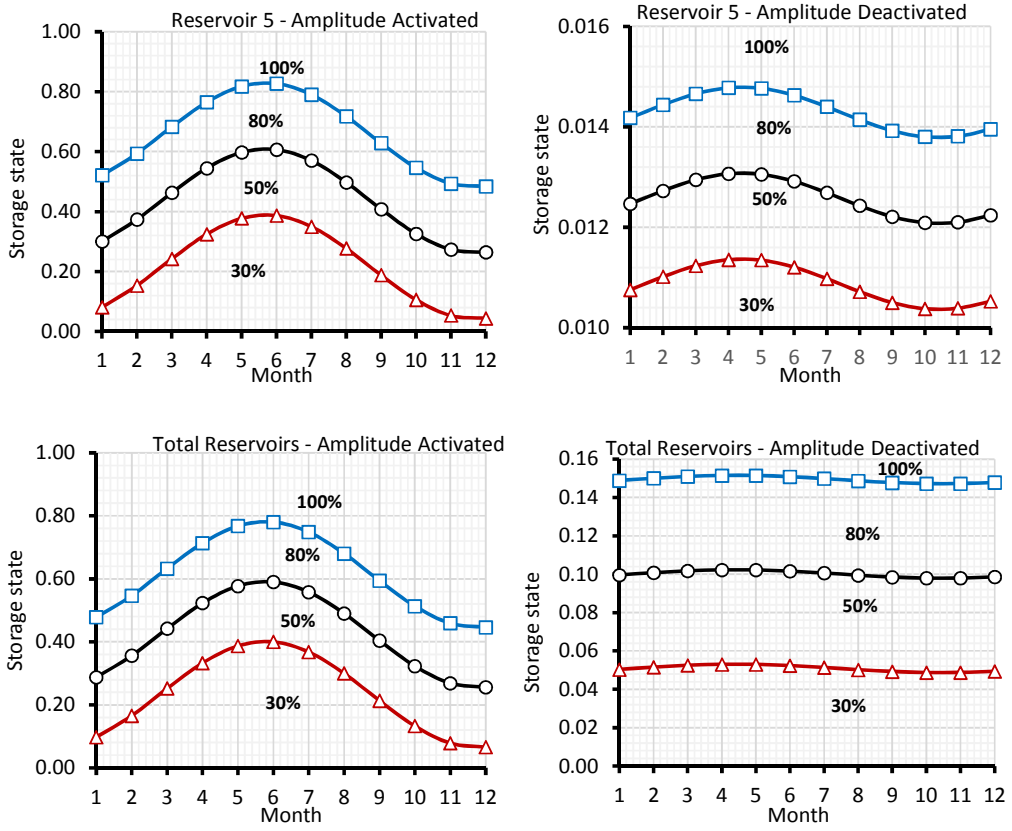
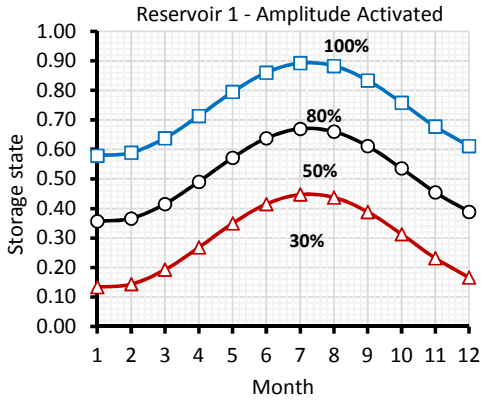


Figure 6.3: Optimised rule curves for trigonometric and linear rules for scenario 0.

Figure 6.4 shows the optimised reservoir operating rule curves for scenario 9 for the optimisation runs, which gave the highest yields. The optimised non-linear trigonometric operating rule curves include a considerable amplitude parameter, as in in scenario 0. Also, amplitude activation has a detrimental impact, with a yield of 0.2468, compared to 0.3745 when the amplitude parameter was deactivated, with a yield difference of about 34%. Thus, applying the trigonometric function to a more complex system (five reservoirs) yielded an even a poorer objective function than when applying it to the system of two reservoirs. Hence, there is no need to use the trigonometric function when defining reservoir system operating rule curves. Although this was suspected to be a problem with regard of the optimiser (SCE-UA) with regard to failure to reach the global optimum solution, which requires further investigation, as recommended in this study.


Reservoir 1 - Amplitude Activated
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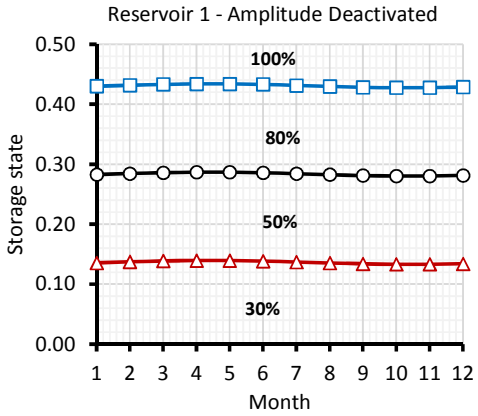
Reservoir 1 - Amplitude Deactivated
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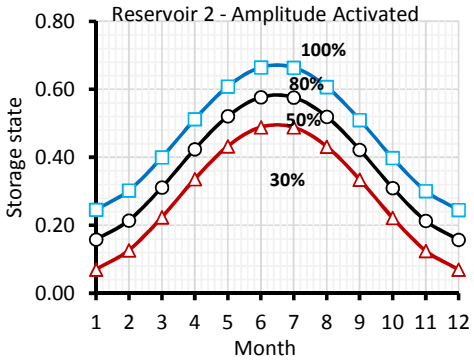
Reservoir 2 - Amplitude Activated
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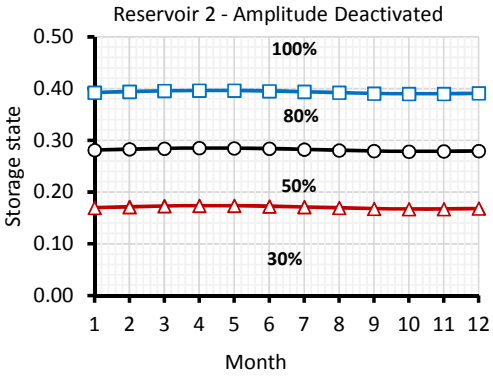
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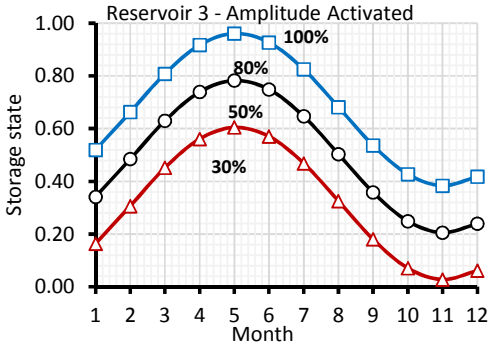
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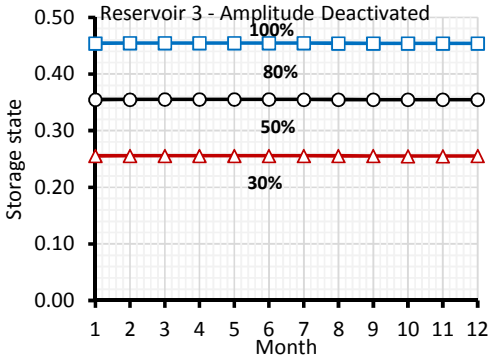
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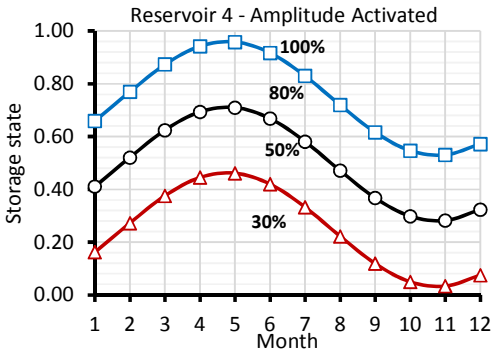
Reservoir 4 - Amplitude Activated
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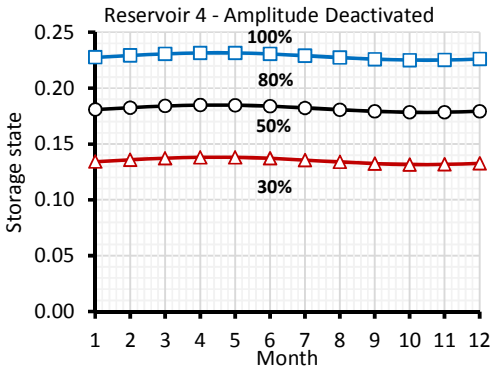
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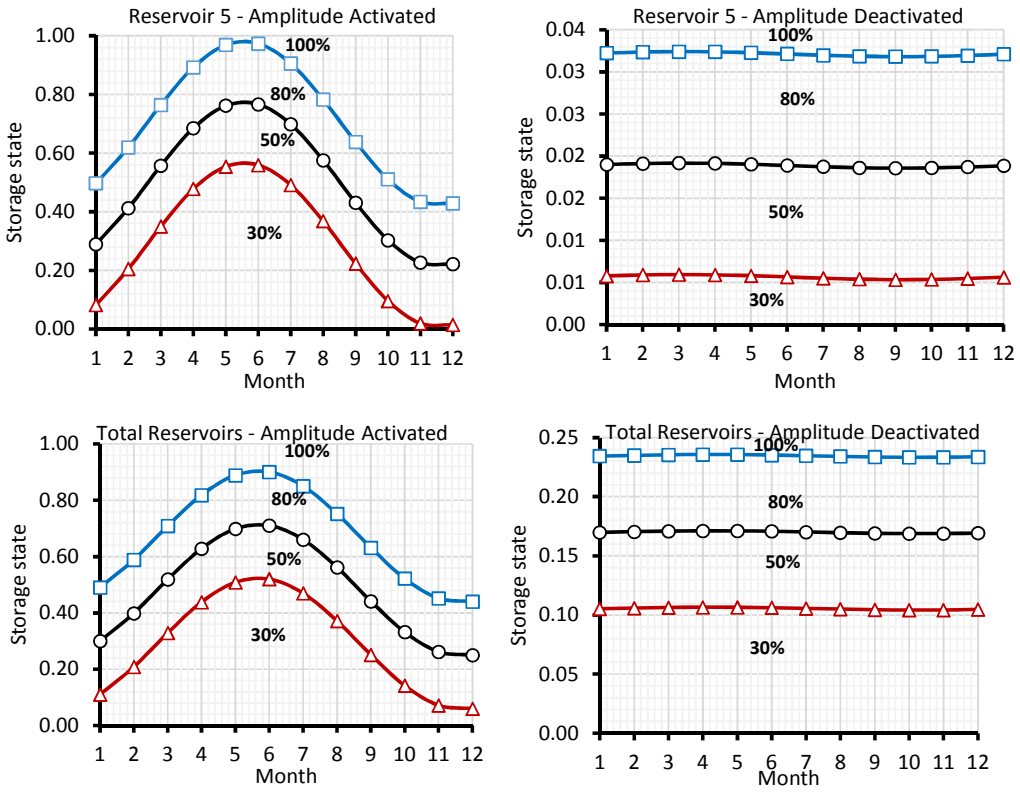


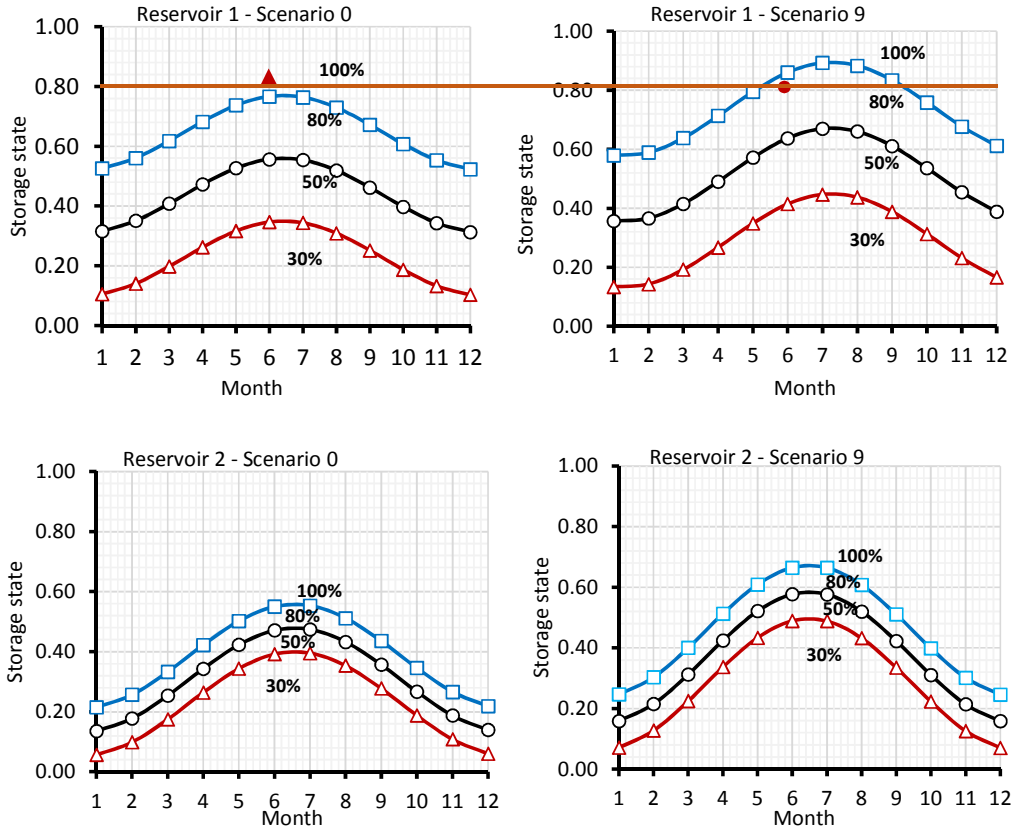
Figure 6.4: Optimised rule curves for trigonometric and linear rules for scenario 9.

6.1.4.2 Effect of human behaviour on the optimised operating rule curves

Figure 6.5 presents the optimised reservoir operating rule curves obtained from the optimisation runs, that gave the best objective functions (yield) for scenarios 0 and 9. For reservoir 1, the upper rule curve at the beginning of the water year (month 1) were 0.53 and 0.58 for scenarios 0 and 9 respectively. The relatively higher upper rule curve of 0.58 in scenario 9, with a difference of 0.05, indicated a rule curve shift. This could be attributed to unlawful abstractions along the streamflows during the rainy season, which reduce storage. Therefore, when the storage lowers due to unauthorised water abstractions, the reservoir operating rule curves will rise, thereby increasing the possibility of imposing of supply restrictions. The curves also continue to rise progressively with the highest minimum storage level to supply 100% of the monthly target draft of 0.77 and 0.90 for the scenarios 0 and 9 respectively. The yield is thus expected to be higher in scenario 0 compared to scenario 9.

The curves then begin to drop, which encourage more water release owing to increasing streamflows in the rainy season. The minimum storage state to supply

100% of the monthly target draft of 0.52, and 0.61 were respectively obtained for scenarios 0 and 9 in the last month of the water year. This indicates a rule curve shift of 0.09 in the last month of the water year. About 100% and 80% of the monthly demand distribution will be released in the 6th month at a storage state of 0.80 for the scenarios 0 and 9 respectively. Such differences between the rule curves for scenarios 0 and 9 could be the reason for higher yield in scenario 0 (0.2722) than scenario 9 (0.2444), with a yield difference of 10.2%. This revealed how human behaviour can adversely affect operating rule curves, and yield. Hence, the need to incorporate the impact of water abstractions quantitatively, while developing reservoir operating rules. Similar trends were also observed in the remaining four reservoirs with regard to the total storage, as illustrated in Figure 6.5.



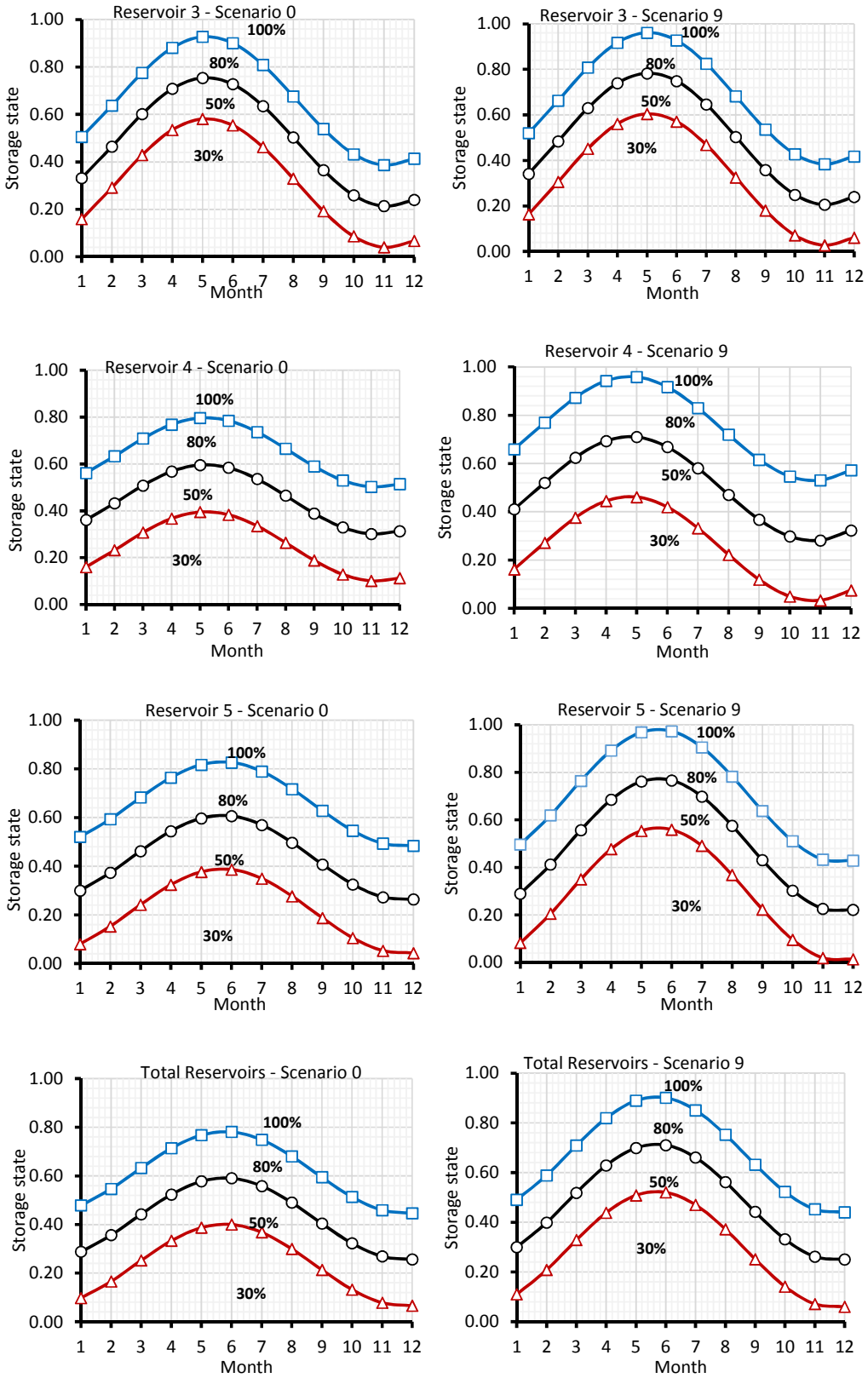
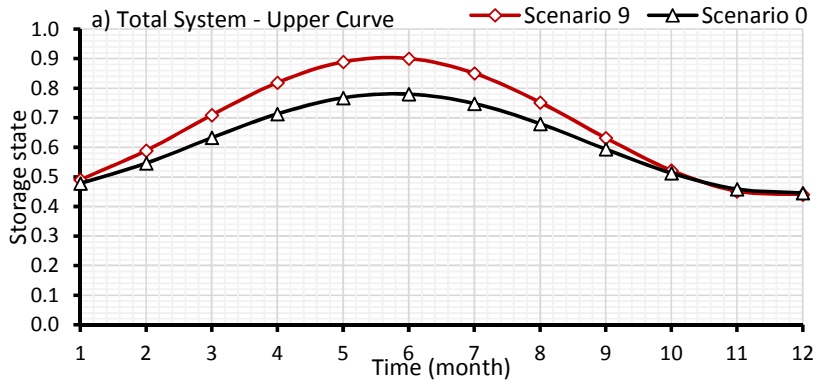
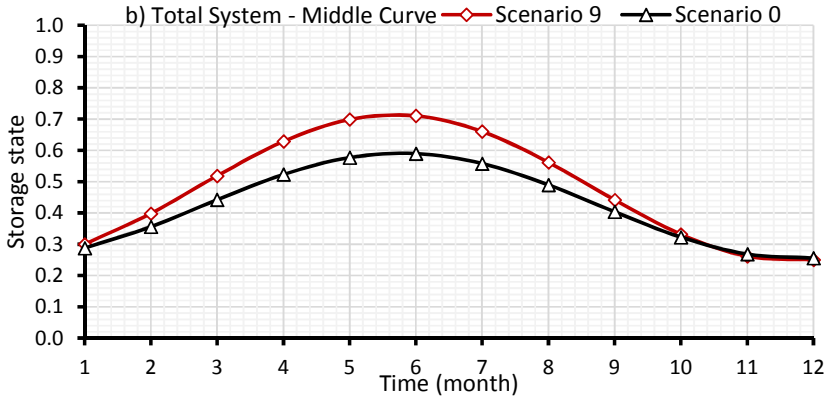


Figure 6.5: Optimised rule curves for trigonometric funtion for scenario 0 and 9.

Figure 6.6 illustrates the levels of the optimised rule curves for the total system storage for the 12 months (water year calendar) for scenarios 0 and 9 with activated amplitude. The curves for the upper, middle and lower are shown separately in Figure 6.6a, Figure 6.6b, and Figure 6.6c respectively. From the Figures, the level of the curves found to be higher in scenario 9, compared to scenario 0, which indicates a shift in the rule curves. The area between scenario 0 and 9 curves represent the operation zones where the supply for scenario 0 would be higher than that for scenario 9. The rule curves for scenario 9, therefore, restrict supply more than the rule curves for scenario 0. When the total system storage falls within this area, the supplies in that month will be reduced from 100% to 80%, 80% to 50%, or even 50% to 30% for the upper, middle or lower levels respectively. The change in the rule curves between scenarios 0 and 9 for the 5 reservoirs, are presented in Appendix D2-1 to D2-5.





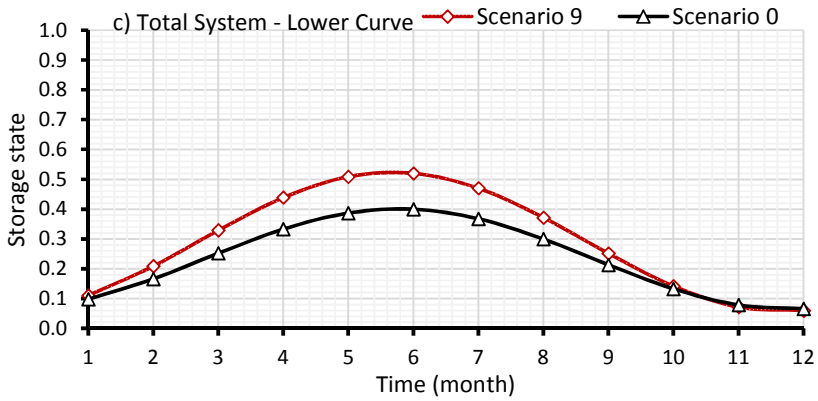
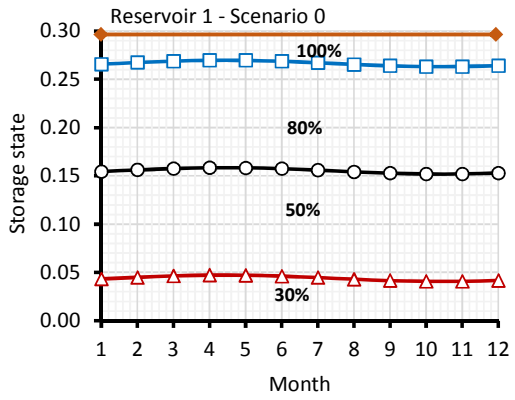
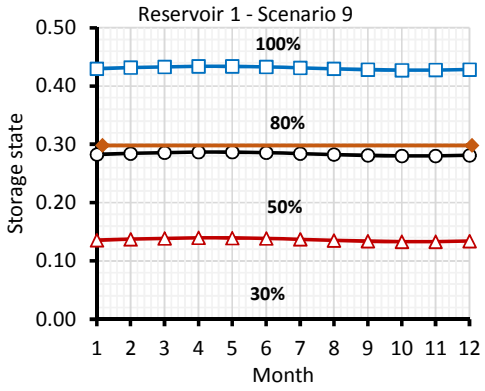
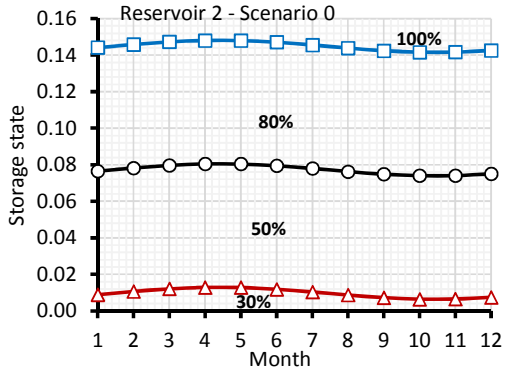


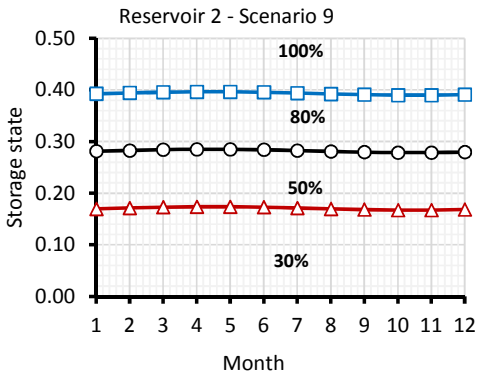
Figure 6.6: Optimised rule curves for the total storage for trigonometricrules for scenario 0 and 9.

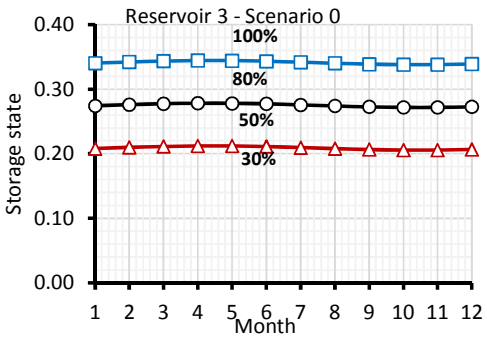
Figure 6.7Figure *5.7* presents the optimised reservoir operating rule curves obtained from the optimisation runs that gave the best objective functions when the amplitude was deactivated for scenarios 0 and 9. From reservoir 1, the upper rule curves at the beginning of the water year for scenarios 0 and 9 were 0.27, and 0.43 respectively. The relatively lower level of the storage state of 0.27 above which 100% of the monthly target draft can be released in scenario 0, is owing to the absence of unauthorised water abstractions along the streamflows. The storage state below which only 30% of the monthly target draft will be supplied for scenario 0 is 0.04, whereas for scenario 9 is 0.13, with a difference of about 0.09, and this indicates a shift of rule curves which could lead to a decrease in supplies. When the storage state was 0.3 in scenario 0, 100% of the monthly target draft can be released throughout the year, whereas only 80% of the monthly demand will be released for scenario 9 for the same storage state. These could also be the reasons for the higher yield of 0.4226 for scenario 0, compared to scenario 9 with a yield of 0.3737, with a yield reduction of 11.6%. Similar trends were observed in the other four reservoirs, and the total storage as shown in Figure 6.7.

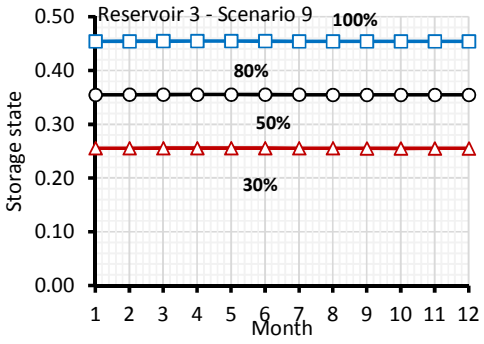

Reservoir 1 - Scenario 0
Storage state
Month
100%
80%
50%
30%

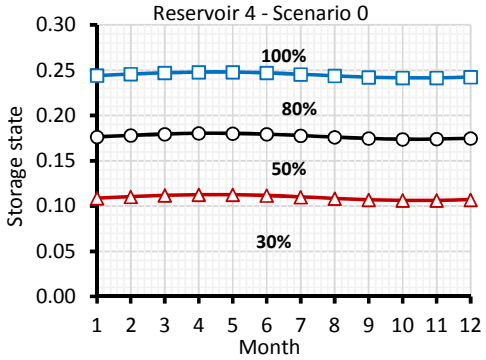

Reservoir 1 - Scenario 9
Storage state
Month
100%
80%
50%
30%

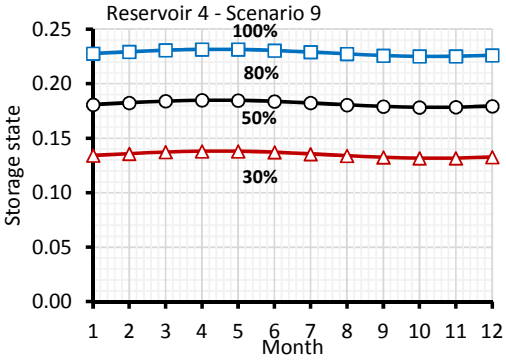

Reservoir 2 - Scenario 0
Storage state
Month
100%
80%
50%
30%


Reservoir 2 - Scenario 9
Storage state
Month
100%
80%
50%
30%


Reservoir 3 - Scenario 0
Storage state
Month
100%
80%
50%
30%


Reservoir 3 - Scenario 9
Storage state
Month
100%
80%
50%
30%


Reservoir 4 - Scenario 0
Storage state
Month
100%
80%
50%
30%


Reservoir 4 - Scenario 9
Storage state
Month
100%
80%
50%
30%

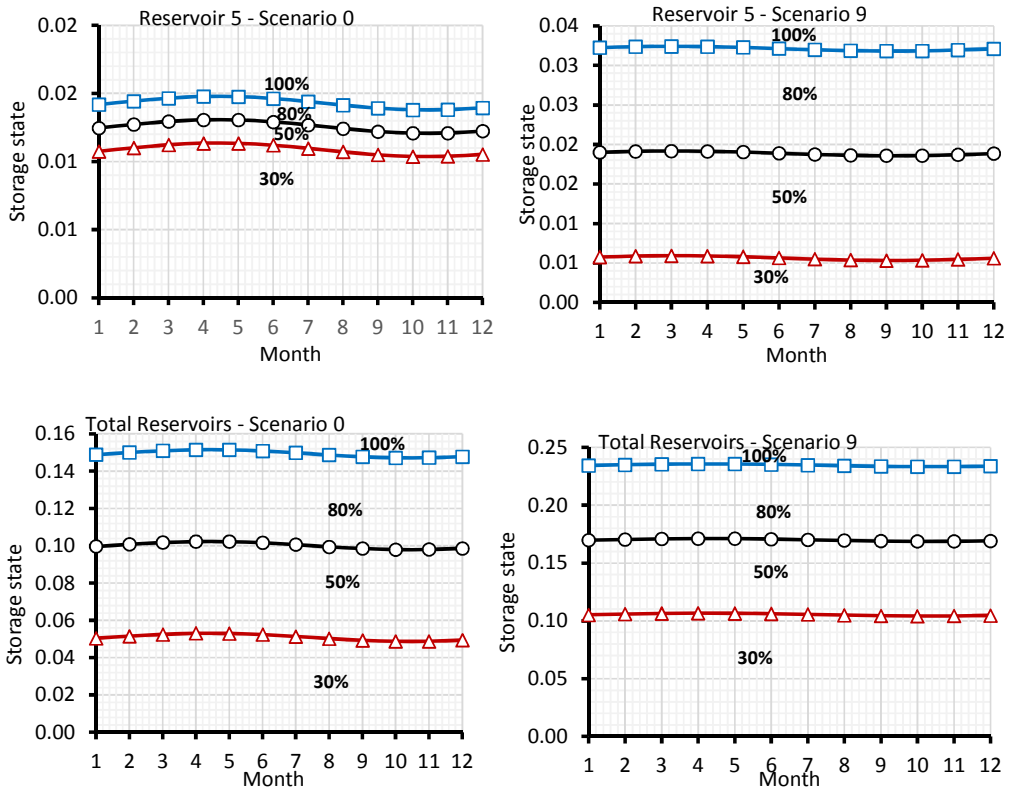


Figure 6.7: Optimised rule curves for simple linear rules for scenario 0 and 9.

Figure 6.8 illustrates the levels of the optimised monthly operating rule curves for the total system storage for scenarios 0 and 9, with deactivated amplitude for the complete water year. The upper, middle and lower curves are respectively shown in Figure 6.8a, Figure 6.8b, and Figure 6.8c. In all the three Figures, the curves were found to be higher in scenarios 9 as compared to scenario 0 (rule curves shift), and the yield is again expected to be higher in scenario 0 as compared to scenario 9. Hence, the rule curves for scenario 9 restrict supply more than that of scenario 0. Depending on the month, whenever the total system storage falls within the rule curve shift area, the supplies in that month will be reduced from 100% to 80%, 80% to 50%, or 50% to 30% for the upper, middle or lower rule curve levels respectively. The levels of the optimised rule curves for reservoirs 1 and 2 can be found in Appendix D2-6 to Appendix D2-10 respectively.

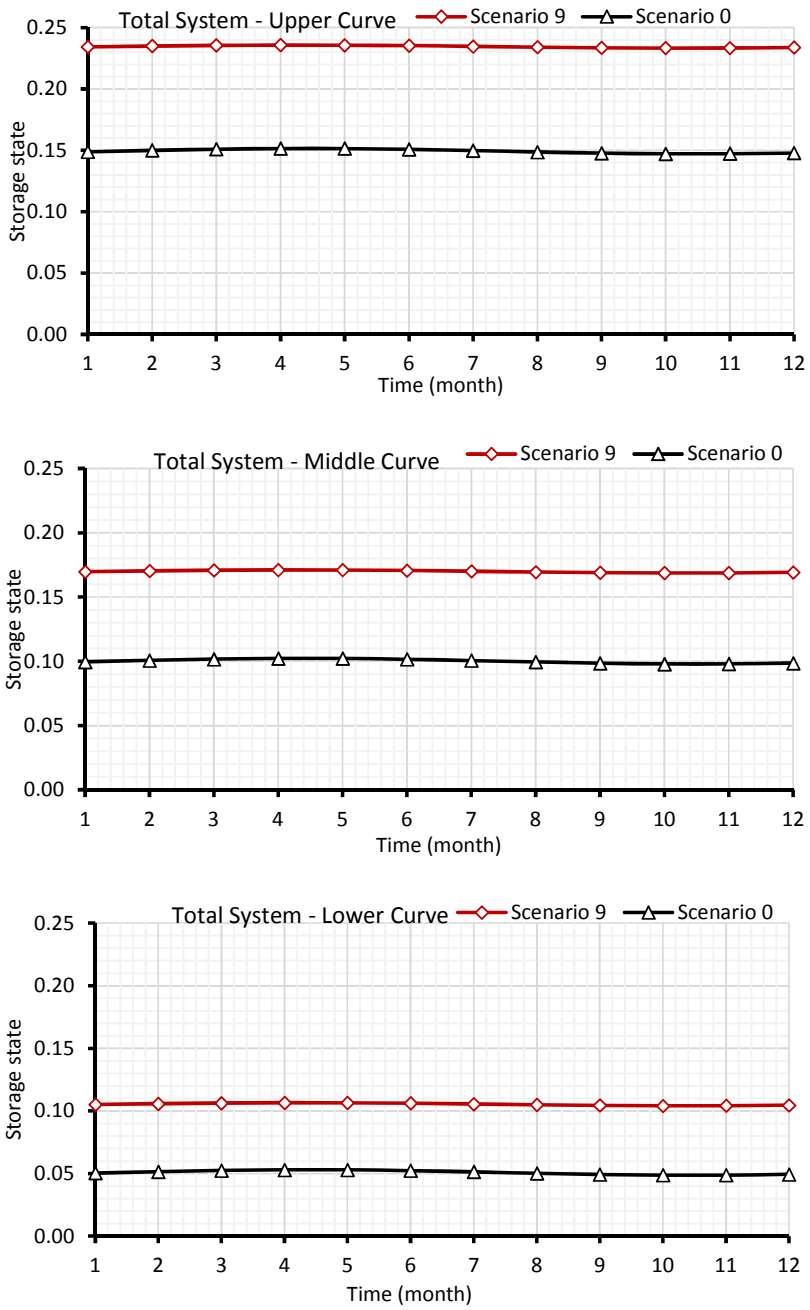
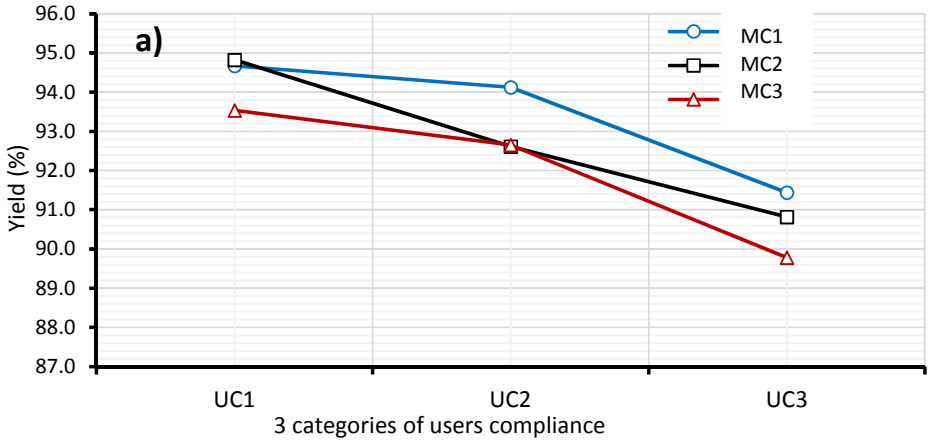


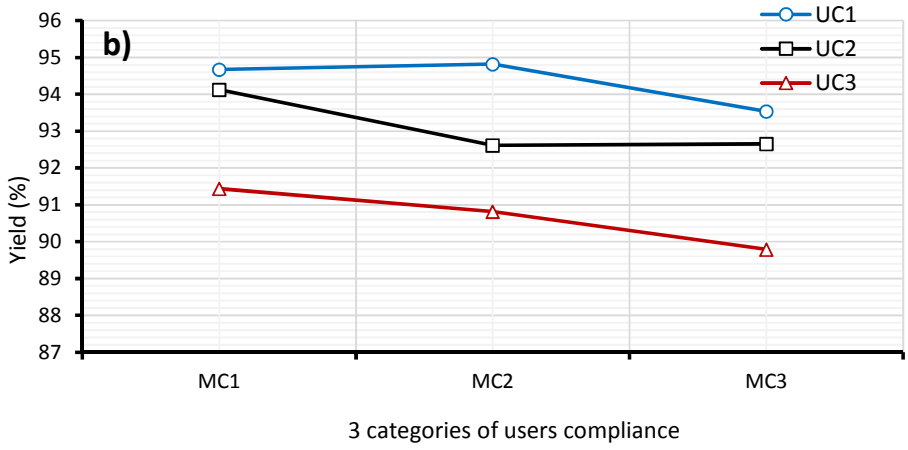
Figure 6.8: Optimised rule curves for the total storage for simple linear rules for scenario 0 and 9.

6.1.5 Comparative effect of users' compliance and management competence

This section presents the comparative analysis between the effect of users' compliance, and management competence on the optimised yield for the activated amplitude case. Figure 6.9a and Figure 6.9b show the relative change in optimised yield due to changing users' compliance at constant management competence, and

changing management competence at constant users' compliance respectively. The average values of the change of yield due to changing users' compliance, and management competence are shown in Figure 6.9c. These figures represent the relative decrease of yield (%) from what has been obtained in scenario 0 with 100% supply, and 0.0% loss due to the absence of unauthorised water abstractions. In all the figures, the yield decrease as human behaviour (users' compliance, and management competence) deteriorates. However, the yield drops drastically with a reduction in users' compliance (constant management competence), since the reduction in yield becomes more pronounced as users' compliance declines. Based on the computed impact ratio, both users' and management were found to have a significant impact on the optimised yield. However, users have an impact of about twice than that of management. Thus, the quest of minimising unlawful abstractions can be achieved, if the level of compliance behaviour by the users improve.





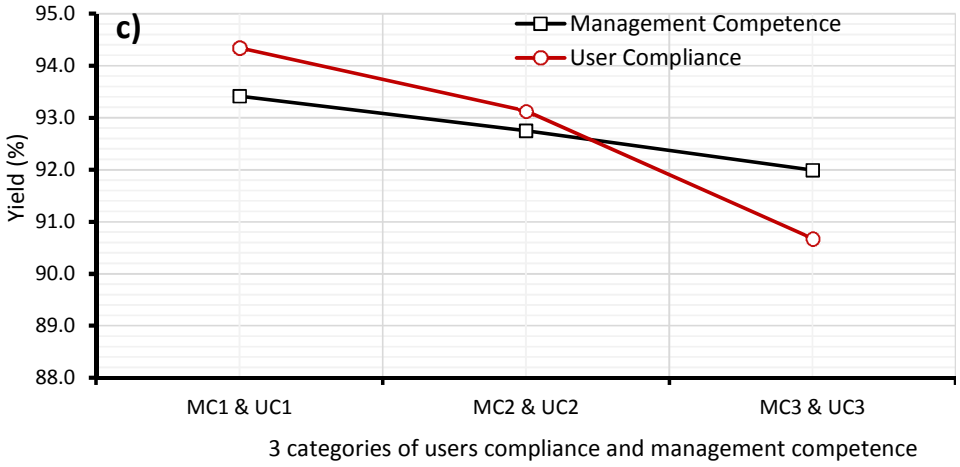


Figure 6.9: Relative change in yield due to changing users' compliance and management competence

6.2 Simulation Results

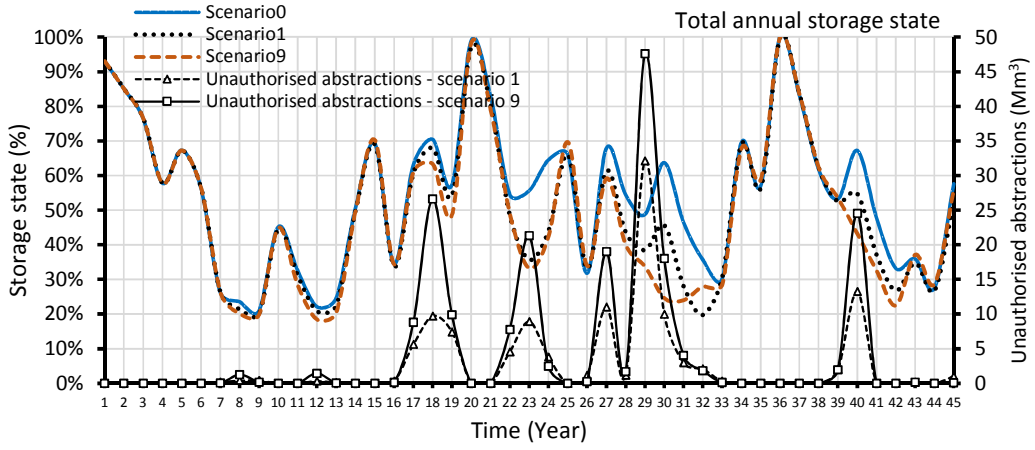
This section discusses the results obtained from the simulation runs. The analysis of the trajectories of the storage state, yield, and how the storage and yield relate, are also analysed. The aim of analysing the trajectories of these variables is to quantitatively assess the impact of human behaviour on the storage state and yield over the 90years-long simulation period. Also, to understand the co-evolutionary dynamics between the impact of human behaviour, and reservoir system operation for an extended period. The analysis presented is limited to scenarios 0, 1 and 9 as these can cover the complete range of human behaviour impacts incorporated into the analysis. Also, the analysis is conducted, and presented on an annual basis.

6.2.1 Impact of human behaviour on reservoir storage state

The analysis of the impact of human behaviour on storage gives more emphasis to the annual storage (storage state at the beginning of the water year). Because storage state at the beginning of the water year typically is used to decide on the amount of water to be allocated for that year, it can also inform on the amount of water that has been abstracted illegally.

Figure 6.10 shows the annual total storage state trajectories for scenarios 0, 1, and 9, and the time series of the annual unlawful abstractions for scenarios 1 and 9. The total storage state for scenarios 1 and 9 was found to be lower than that of scenario 0, and

this was as a result of the unlawful abstractions. There were about 12 major occurrences in which unauthorised water abstractions was found to have affected the total storage state significantly. From the unlawful abstractions time series massive unlawful water abstractions were found to have occured in 24 years out of the 90 years of the simulation for scenarios 1 and 9, whereas there were no unlawful abstraction cases in scenario 0. According to the unlawful abstractions trajectory, more water was abstracted without authorisation in scenario 9 than in scenario 1, and this reflected the fact that the management intervention is relatively more effective in scenario 1 than in scenario 9. This could be the reason for higher yield in scenario 0 than in scenarios 1 and 9, and higher yield in scenario 1 than in scenario 9. In addition, most of the years in which human behaviour affected the storage state were also observed to correspond with years with massive unauthorised water abstractions. Yield can, therefore, be reduced whenever a substantial amount of water was abstracted unlawfully. In addition, most of the years in which the storage state differ due to changing human behaviour are the years with poor storage state, thus, unlawful abstractions are more likely to occur during poor hydrologic states. The storage trajectories for the individual reservoirs at different scenarios were found to have similar patterns (Appendix E2).



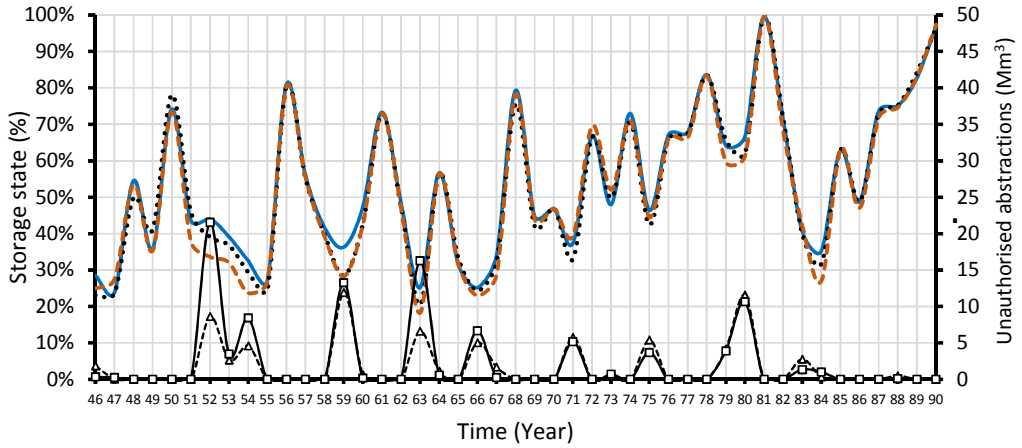


Figure 6.10: Annual total storage state trajectory and annual unlawful abstractions for scenario 0, 1 and 9

6.2.2 Effect of human behaviour on yield and yield-demand ratio

This section presents the trade-off of the annual yield-demand ratio, and unauthorised water abstractions. The analysis was also restricted to the total system yield-demand ratio, and unlawful abstractions as this provides an accurate picture of the five reservoirs in the system. Figure 6.11 shows the trajectories of the percentage of the annual target draft that has been delivered for scenarios 0, 1 and 9, and the time series of the water abstracted without authorisation for scenarios 1 and 9. From Figure 6.11, most of the years in which the yield-demand ratio differs significantly from one scenario to the other, are the years affected by unlawful abstraction cases. The result indicated that whenever massive unauthorised water abstraction occurs, the total annual expected yield can reduce drastically. For example, in the 30th year marked **Y**, about 89%, 67% and 37% of the total annual target draft was found to deliver in scenarios 0, 1, and 9 respectively. The trajectories of the yield-demand ratio for the individual reservoirs as affected by unlawful water abstractions, are presented in Appendix F2.

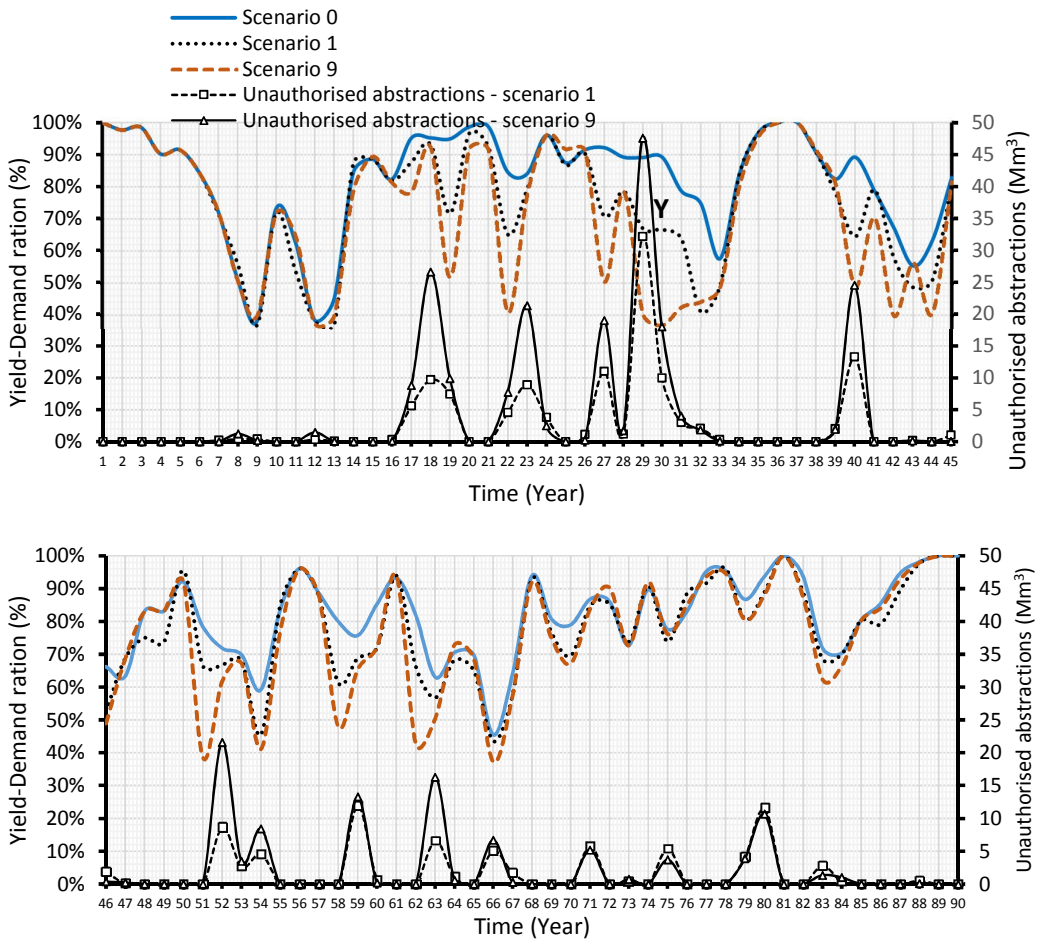
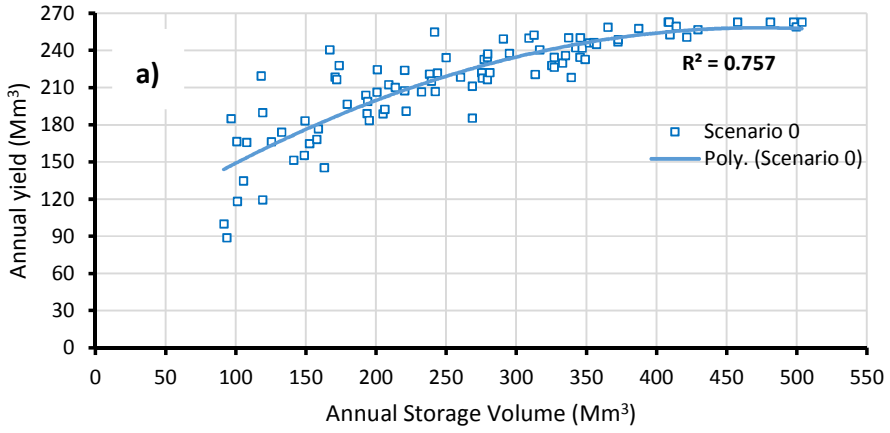


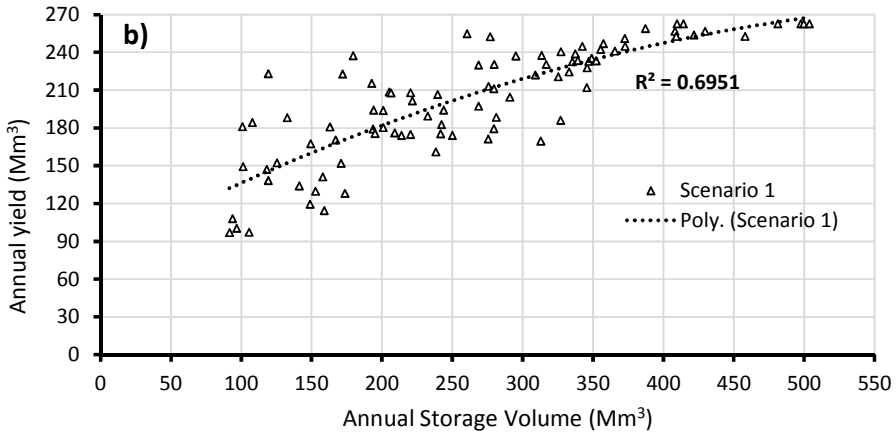
Figure 6.11: Annual yield-demand ratio and annual unlawful abstractions trajectory for scenario 0, 1 and 9.

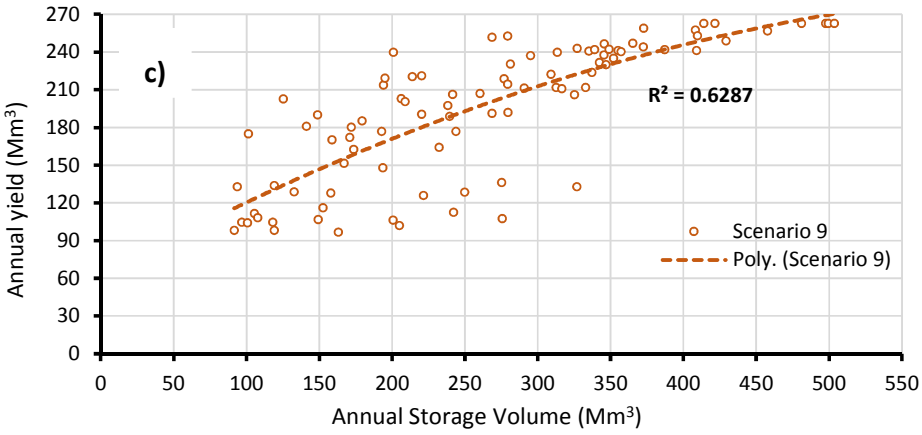
6.2.3 **Annual operating rule curves as affected by human behaviour**

As done in Section 5.2.3, this section derives annual operating rule curves for the Olifants reservoir system for scenarios 0, 1, and 9. Figure 6.12a, Figure 6.12b, and Figure 6.12c illustrate the total annual storage-yield relationships for scenarios 0, 1, and 9, whereas Figure 6.12d shows the storage-yield relationships for the three scenarios. The trend lines in these figures revealed how annual yield increases as the total annual storage volume increase. Figure 6.12d showed that at a given storage volume, the yield obtained in scenario 0 (scenario without incorporating the impact of unauthorised water abstraction) is higher than that of scenarios 1 and 9 due to the adverse impact of unauthorised water abstractions. For example, when the total annual storage volume is 150 Mm^3, the total system yields were 174 Mm^3, 162 Mm^3,

and 144 Mm^3 for scenarios 0, 1, and 9 respectively. The calculated reduction in yield between scenarios 0 and 1 is 12 Mm^3 (6.9%), and between scenarios 0 and 9 it is 30 Mm^3 (17.2%), whereas, when the total storage volume was 425 Mm^3, the total yield for all three the scenarios was nearly the same (255 Mm^3). The total system storage volume, and the yield can thus be significantly affected by human behaviour.







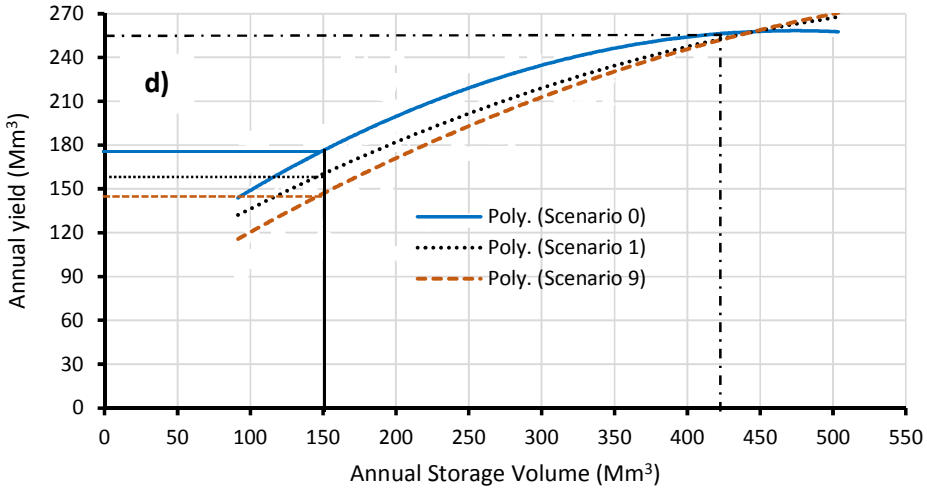


Figure 6.12: Annual storage-yield relationships: a) scenarios 0, b) scenario 1, c) scenario 9 and d) scenario 0, 1 and 9

The total annual yields obtained from scenarios 0, 1 and 9 for the 90 years were also ranked from highest to lowest, and the probability that a given annual yield is exceeded was computed using the Weibull plotting position formula. The computed probability of exceeded was used as a percentage less in the total annual yield for scenarios 0, 1, and 9 as shown in Figure 6.13. From the figure, the total annual yield also reduces as the exceedance probability decreases. This indicated that although there were fewer occurrences of unlawful water abstractions, the negative effect on the total annual yield increases with the decreasing probability of such occurrences.

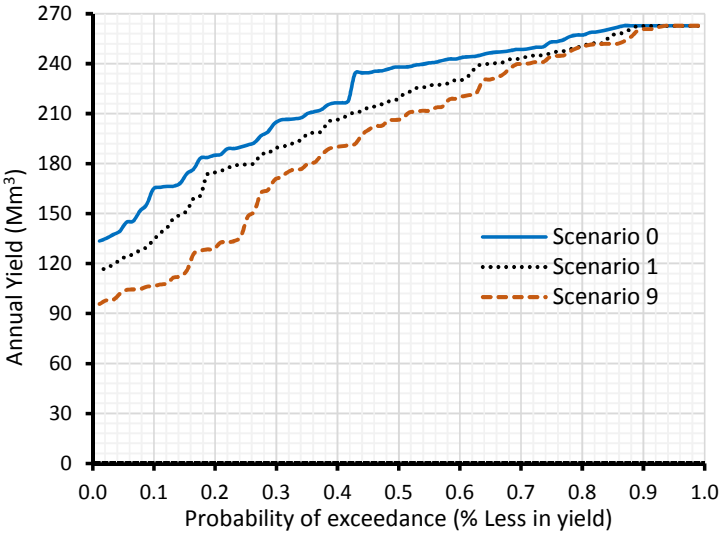


Figure 6.13: Total expected annual yield for scenario 0, 1 and 9

The total annual yield obtained from scenario 0 is the maximum obtainable yield owing to the absence of unauthorised water abstractions, and it was then used to compute the percentage reduction in total annual yield for scenarios 1 and 9 at different probabilities of unauthorised abstractions occurrence. Table 6.3 and Figure 6.14 presents the reductions in total annual yield for scenarios 0, 1 and 9 at the different probabilities of exceedance as extrapolated from Figure 6.13.

Table 6.3: Yield loss for scenario 0, 1 and 9 at different probability of exceedance

Scenarios	**Yield** (Mm^3) *p=0.01*	**Loss** (%)	**Yield** (Mm^3) *p=0.1*	**Loss** (%)	**Yield** (Mm^3) *p=0.5*	**Loss** (%)	**Yield** (Mm^3) *p=0.8*	**Loss** (%)	**Yield** (Mm^3) *p=0.9*	**Loss** (%)
Scenario 0	133.5	0.0	165.7	0.0	238.1	0.0	251.5	0.0	261.8	0.0
Scenario 1	117.3	12.1	134.1	19.1	218.2	8.4	250.6	0.4	261.8	0.0
Scenario 9	95.7	28.3	107.4	35.2	207.1	13.0	250.6	0.4	261.8	0.0

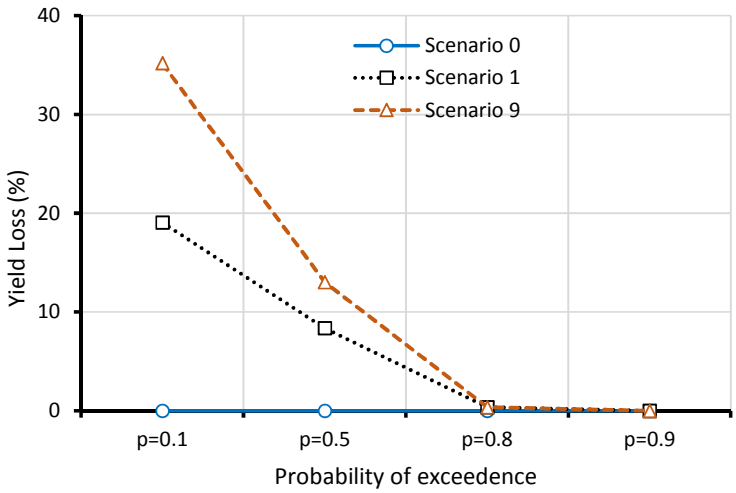


Figure 6.14: Yield loss for scenario 0, 1 and 9 at different probability of exceedance

6.2.4 Comparative analysis of the annual and monthly rule curves

Figure 6.15 shows the operating rules for reservoir 3. Figure 6.15a and Figure 6.15b are the monthly and annual operating rules respectively. For a given storage state, the monthly supply was observed to be higher or lower than the annual supply. This is also possible since an annual yield for a given water year is usually shared within that water year, based on the monthly demand distribution. For example, a year with an annual yield of 100% of the annual target draft is shared across the year, such that monthly supply will vary from 30% to 100%, particularly for the seasonally varying demands by such as the irrigation sector.

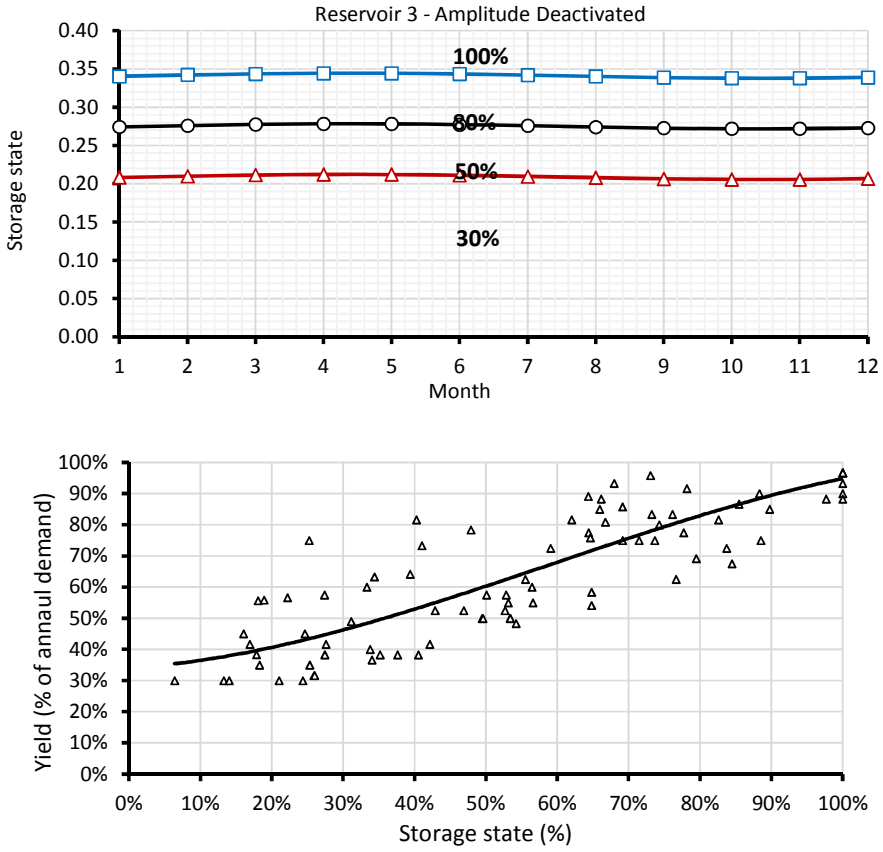


Figure 6.15: Operating rules for reservoir 1: a) monthly and b) annual

6.2.5 Incorporating reliability into annual and monthly operating rules

The concept of reliability was also incorporated using a simpler approach similar to that of the Elands case study. The approach makes use of the variability of the optimised annual yields with storage state.

Figure 6.16 shows the optimised annual storage-yield relationships for 90 years for reservoir 1, and categorised into four zones. The zones were formed to each contain an equal number of years. The total annual yields obtained for each of the four zones are then ranked, and the probability that a given annual yield is exceeded, is also computed using the Weibull plotting position formula. The resulting cumulative frequency distribution curves for the annual yields are shown in

Figure 6.17. These curves can now be used to determine the annual reservoir operating rule curve for a specified reliability (or level of assurance), by assigning the yields at those levels of assurance to the average storage in that zone.

Figure 6.17 shows the annual yields obtained at 50% and 95%, and these are used to obtain the respective annual rule curves as shown in Figure 6.18.

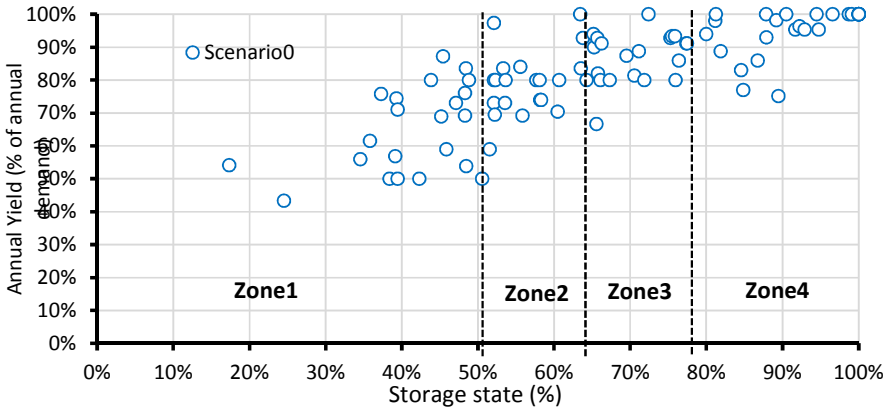
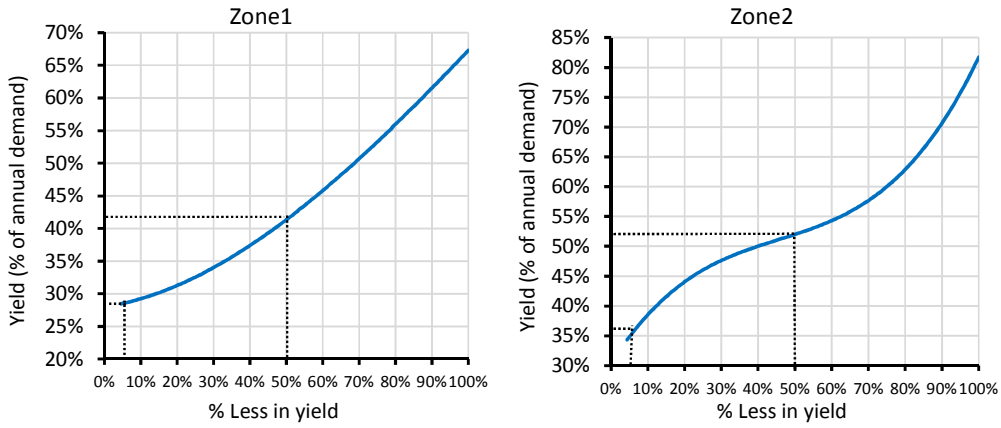


Figure 6.16: Storage-yield relationship and the four storage zones for reservoir 1



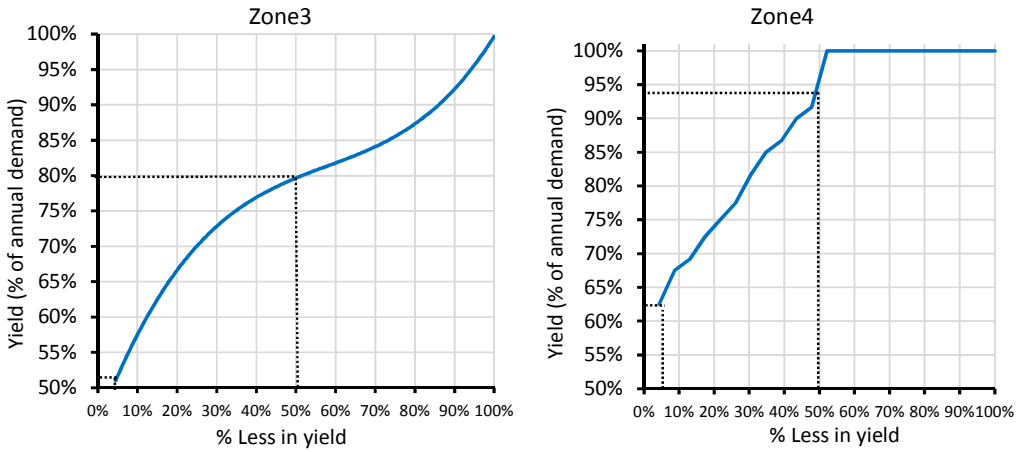


Figure 6.17: Expected annual yields to be obtained from the four storage zones

Table 6.4 and Figure 6.18 shows the yields obtained at 50% and 95% reliability of supply, and the average storage state obtained at each of the four storage zones. The yield obtained from the 95% reliability of supply curve ($Y_{95\%}$) is the safe-zone annual operating rule with which the system is not expected to fail. This is the transformed annual operating rule curve with a 95% reliability of supply, and is considered as the safe operating rule for reservoir 1.

Table 6.4: Annual yields obtained at 50% and 95% reliability of supply and the average storage for each zone

Storage zones	Zone1	Zone2	Zone3	Zone4
Annual yield (100% reliability of supply)	42	52	80	95
Annual yield 5% less (95% reliability of supply)	28	32	52	64
Average storage (%)	22	45	67	92

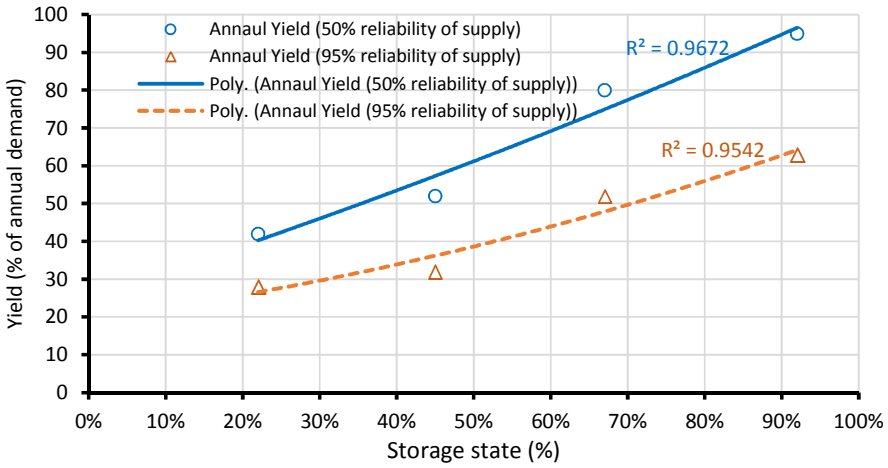


Figure 6.18: Annual yield and yield obtained at 5% less (95% reliability of supply)

The transformed annual yield ($Y_{95\%}$) was also extended to the monthly operating rules. Figure 6.19 shows the initial (Figure 6.19a) and transformed (Figure 6.19b) monthly operating rules for reservoir 1. The transformed monthly operating rule curves was computed as the product of the initial monthly rule curve value, and the ratio of the yield obtained at 50% reliability of supply to the yield, obtained at 95% reliability of supply ($Y_{50\%}/Y_{95\%}$). The transformed rule curves rises to increase the probability of imposing supply restrictions, that will conform to the 95% reliability of supply as shown in Figure 6.19b.

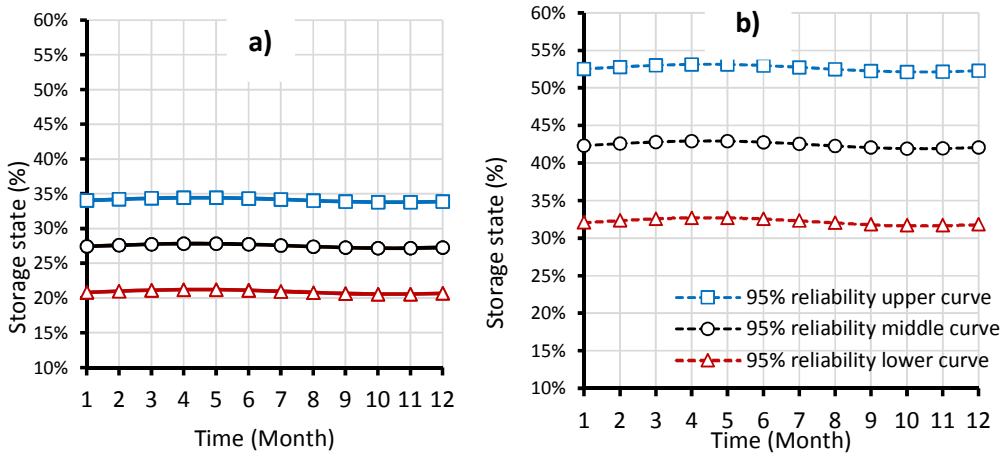


Figure 6.19: Initial and transformed (95% reliability of supply) monthly operating rule curves for reservoir 1

Figure 6.20 illustrates the annual and monthly operating rules based on the 95% reliability of supply. The monthly operating rule was extrapolated from Figure 6.19b.

The monthly operating rule found to be higher and lower than annual operating rule as storage increases and decreases respectively. This is possible since annual yield for a given water year is usually shared throughout that water year, based on the monthly demand distribution.

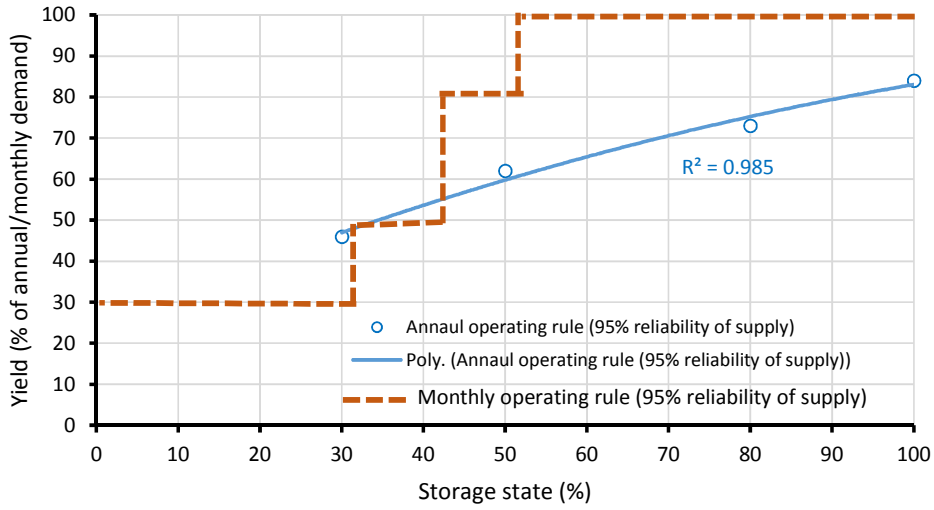


Figure 6.20: Annual and monthly operating rule at 95% reliability for reservoir 1

6.3 Summary of Chapter

The results revealed how unlawful water use can significantly impact on the reservoir storage and yield. The study therefore provide an insight into how human behaviour can impact reservoir yield quantitatively. This study presents a novel approach to yield analysis that integrates the hydrologic and human behaviour uncertainties. The study therefore emphasised the need to incorporate the impact of human behaviour in water resource systems analysis.

CHAPTER SEVEN

7.0 SUMMARY OF THESIS

This chapter presents a summary of the research and the conclusions drawn from the findings. The limitations of the study and its contributions to knowledge are also presented. Finally, recommendations for future studies are made

7.1 Development and Testing of Reservoir Operation Socio-hydrological Model

It is only recently that socio-hydrology; the study of the co-evolutionary dynamics of human-water systems that aims for more human-centred water resources planning has been formalised. Review of the literature revealed a lack of socio-hydrological studies relating to the impact of human activity on reservoir system performance although these impacts are significant and reservoirs are usually major components of water resource systems. This study, therefore, investigated the causes and impacts of human behaviour on water resource system performance and developed an approach of incorporating these impacts into reservoir system yield and operation analysis. The resulting socio-hydrological model was then used to assess the impact of human behaviour on reservoir system performance. The model simulates, couples and dynamically co-evolves four state drivers; the hydrological state, the water users' propensity to unauthorised water abstractions, the ability of management to prevent unauthorized abstractions (management competence), and the reservoir system performance. The stochastic coupling and dynamic co-evolution of the 4 state drivers is based on the notions that;

i) Reservoir hydrologic state (runoff, evaporation and storage) influences water users' propensity to unauthorised water abstractions although this tendency, termed as users' compliance also depends on socio-economic, cultural, religious and other factors.
ii) The level of users' compliance influences the frequency and extent of unauthorized water abstractions and therefore the reservoir system performance.
iii) Reservoir system performance influences the frequency and scale of corrective actions taken by management and the ability to undertake these actions is dependent on the management competence, and
iv) The actions by management influence the hydrologic state which in turn influences users' compliance.

Users' compliance and management competence are the human drivers of the model and the effect of human behaviour on reservoir performance were therefore studied by using nine scenarios with different combinations of three categories of users' compliance and management competence. The socio-hydrological model was applied to two hypothetical but realistic reservoir systems based on 90 years of monthly hydrological data and configurations of the Elands and Olifants reservoir systems. The 90-years long historical monthly hydrologic data were considered to include sufficient natural hydrologic variability to inform how the effect of human behaviour varies with hydrologic state.

A simulation-optimisation approach was adopted to maximize the yield for each scenario. As part of this, two forms of reservoir operating rule curves; one using a simple trigonometric function and varying on a monthly basis and the other linear and constant across the year, were used. The shuffled complex evolution (SCE-UA), an evolutionary optimisation technique was used for optimisation. Simulation-optimisation runs without incorporating human behaviour as typically assumed in the conventional yield and operation analysis were also carried out and they served as the references to assess the impact of human behaviour.

7.2 Conclusions

The optimisation using the SCE-UA method was found to be effective for the two systems when linear operating rule curves were used. For the optimizations involving the trigonometric rule curves, SCE-UA was effective for Elands system but got repeatedly trapped in a local optimum for the larger Olifants reservoir system. The yield of the local optimum was 35% less than that obtained using linear operating rule curves. It was therefore decided to assess the effect of human behaviour on reservoir system performance using the optimizations applying linear operating rule curves for both systems. Based on the results obtained, the two case study areas, the Elands (2 reservoirs) and Olifants (5 reservoirs) can be said to adequately represent WRS operation and analysis in South Africa as most of the reservoir systems in the country are operated in an integrated manner.

The 90-years time series' of unauthorised water abstractions, yields and storage state trajectories revealed the behaviour that would intuitively be expected and was considered realistic. These results of yield and storage state due to the co-evolution of reservoir operation and the impact of unlawful water abstractions for a long period scenario in southern African region can play a vital role in understanding and addressing the lingering water scarsity problems in the region. Storage state and yield were found to reduce as unlawful water use increased with declining users' compliance and management competence. The impacts of human behaviour were more significant for the drought years with poor hydrological state. The modelling was thus in agreement with the expectation that water users are more inclined to unlawful water abstractions when the hydrological state is poor due to a heightened perception of the threat to their farming activities and financial status.

For the 9 scenarios of varying levels of users' compliance and management competence, average losses in yield ranged from 2.7 to 9.2% and 7.1 to 11.5% for the Elands and Olifants system respectively. The overall average losses for all the nine scenarios were 5.8% and 8.9% for the Elands and Olifants system respectively. Although the incorporation of human behaviour was not based on real-life data, the average losses obtained compare realistically with the estimated annual cpmmertial water loss of 6.4% due to unlawful uses in South Africa. Commertial loss comprises losses due to unlawful use and meter inaccuracies. The losses in yield were found to be much higher in periods of poor hydrological state and for the scenarios with the least favourable human behaviour, a year with a yield reduction of 55% and 58% for the Elands and the Olifants system respectively was identified. Similarly, human behaviour was found to affect the optimised operating rules realistically with the rule curves becoming more restrictive as unauthorised water abstractions increased due to declining human behaviour. More restrictive rule curves recommend restrictions to supply at higher storage states.

The results indicate that the significant impacts of unauthorised water abstractions on reservoir yield and operation could be modelled quantitatively in a manner that incorporates human behaviour comprehensively. However, the sensitive nature of

the subject of study makes calibration and verification of the human behaviour aspects of the model on real-life water resource systems challenging.

Annual operating rules were derived from annual storage-yield relationships under different human behaviour scenarios and these were found to align satisfactorily with the optimized monthly operating rules. Declining human behaviour was found to make the annual operating rules more restrictive. Since this study did not apply stochastically generated data for incorporation of reliability into the analysis, a simple method of associating the annual and monthly operating rules with reliability was developed. This method is based on frequency analysis of the annual yields obtained within specified ranges of storage state.

Following are the major contributions to knowledge from this study:

i) This study has pioneered quantitative incorporation of human behaviour into reservoir system modelling as most socio-hydrological studies to date have focused on other aspects of human-water systems such as coupling flood risks and the associated human behaviour.
ii) The developed reservoir operation socio-hydrological model demonstrates the complex interactions and the co-evolutionary dynamics of human behaviour, the hydrologic state of the system and reservoir performance. If calibrated and verified with real-life data, the model can serve as a decision support tool for quantitative assessment of the impact of human behaviour on reservoir system yield and operation.
iii) A method of obtaining reliability-based reservoir operating rules without using stochastically generated hydrological data has been developed and applied.

7.3 Recommendations for Future Studies

Following are the recommendations for further research.

i) Although the area of this study is ethically sensitive, it is recommended that the model be calibrated and verified using real-life data on human behaviour as this would enhance the credibility of the model and the confidence with which it could be applied in practice.
ii) The study recommends an analysis that uses stochastically generated data in order to incorporate hydrologic uncertainty comprehensively while assessing the impacts of human behaviour on reservoir system performance. A comparison of

the rules derived using stochastic data with the simple approach of incorporating reliability developed in this study could, however, be worthwhile.

iii) The Shuffled Complex Evolution (SCE-UA) optimizer repeatedly got trapped in a local optimum solution in the Olifants system analysis using trigonometric rule curves. It is therefore recommended that the effectiveness of the SCE-UA for reservoir system optimization and the unique characteristics of the optimization problem that lead to the local optimum trap be investigated.

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APPENDICES

This section provides some results (Tables and Graphs) that are not presented in the results discussion chapters for readers' perusals.

Appendix A:

Appendix A1: Optimised yield for all the scenarios when the amplitude parameters was activated and deactivated for Elands River reservoir system.

	Activated Amplitude Parameters									
Run	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**
1	0.4908	0.4840	0.4682	0.4630	0.4712	0.4613	0.4576	0.4684	0.4639	0.4510
2	0.4931	0.4821	0.4695	0.4615	0.4711	0.4581	0.4601	0.4572	0.4655	0.4472
3	0.4932	0.4828	0.4776	0.4533	0.4640	0.4601	0.4555	0.4699	0.4666	0.4534
4	0.4970	0.4863	0.4714	0.4650	0.4747	0.4594	0.4639	0.4739	0.4610	0.4484
5	0.4961	0.4793	0.4671	0.4640	0.4738	0.4660	0.4536	0.4725	0.4609	0.4483
Run	**Deactivated Amplitude Parameters**									
1	0.4962	0.4799	0.4708	0.4651	0.4759	0.4673	0.4654	0.4750	0.4684	0.4502
2	0.4967	0.4855	0.4708	0.4662	0.4749	0.4672	0.4654	0.4751	0.4683	0.4532
3	0.4966	0.4856	0.4708	0.4642	0.4759	0.4674	0.4655	0.4749	0.4684	0.4493
4	0.4967	0.4816	0.4708	0.4601	0.4760	0.4674	0.4654	0.4750	0.4684	0.4521
5	0.4967	0.4846	0.4706	0.4651	0.4760	0.4673	0.4654	0.4750	0.4683	0.4502

Appendix A2: Optimised yield for all the scenarios when the amplitude parameters was activated and deactivated for Olifants River reservoir system.

	Activated Amplitude Parameters									
Run	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**
1	0.2750	0.2633	0.2640	0.2572	0.2630	0.2517	0.2622	0.2517	0.2487	0.2460
2	0.2716	0.2523	0.2548	0.2449	0.2615	0.2501	0.2588	0.2555	0.2510	0.2468
3	0.2739	0.2554	0.2530	0.2489	0.2676	0.2529	0.2488	0.2530	0.2573	0.2484
Run	**Deactivated Amplitude Parameters**									
1	0.4235	0.4002	0.3935	0.3846	0.3885	0.3839	0.3811	0.3838	0.3813	0.3745
2	0.4224	0.3884	0.3913	0.3870	0.3888	0.3829	0.3827	0.3808	0.3806	0.3731
3	0.4218	0.3928	0.3933	0.3864	0.3891	0.3874	0.3829	0.3821	0.3809	0.3743

Appendix B:

Appendix B1: Optimised parameters for Elands River system (amplitude activated).

Scenario 1	Parameter	Unit	Run1	Run2	Run3	Run4	Run5
	tp1	"	0.2660	0.3498	0.3237	0.4199	0.2976
	wp1	"	0.1607	0.1315	0.0829	0.0394	0.0931
	ap1	"	0.2239	0.3346	0.2731	0.4160	0.2644
	lp1	"	0.4019	0.3726	0.4229	0.4712	0.4136
	tp2	"	0.3885	0.4045	0.3067	0.3946	0.4386
	wp2	"	0.0428	0.0488	0.1182	0.0336	0.0862
	ap2	"	0.3714	0.3858	0.2124	0.2597	0.3863
	lp2	"	0.6251	0.4553	0.5095	0.2877	0.5457
	wg	"	0.4233	0.3719	0.4998	0.5972	0.4585
	td1	Mm3/year	14.49	14.34	14.49	14.10	14.46
	td2	Mm3/year	14.36	14.36	14.24	14.23	14.06
Scenario 2	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.3274	0.4080	0.3041	0.3899	0.3554
	wp1	"	0.1262	0.0929	0.1234	0.11954	0.1184
	ap1	"	0.2748	0.2224	0.2342	0.2367	0.2262
	lp1	"	0.5436	0.5364	0.5403	0.3136	0.4734
	tp2	"	0.3278	0.3360	0.2596	0.3826	0.3709
	wp2	"	0.0678	0.0882	0.0679	0.0864	0.039.1
	ap2	"	0.3048	0.2608	0.2548	0.3613	0.1986
	lp2	"	0.4745	0.5998	0.3645	0.4086	0.5947
	wg	"	0.5012	0.6118	0.4428	0.3719	0.4850
	td1	Mm3/year	14.37	14.43	14.42	13.75	14.46
	td2	Mm3/year	14.35	14.37	14.32	14.22	14.34
Scenario 3	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.3025	0.3558	0.3697	0.3302	0.2120
	wp1	"	0.1275	0.1690	0.0122	0.1105	0.1017
	ap1	"	0.2501	0.2860	0.3175	0.2936	0.1616
	lp1	"	0.5020	0.3946	0.5226	0.4908	0.5482
	tp2	"	0.3455	0.4190	0.3085	0.2924	0.5417
	wp2	"	0.1046	0.0815	0.1482	0.1261	0.0278
	ap2	"	0.2734	0.3991	0.2602	0.2985	0.3079
	lp2	"	0.6468	0.4303	0.2773	0.3843	0.5486
	wg	"	0.5432	0.3641	0.5510	0.6611	0.5791
	td1	Mm3/year	14.48	14.37	14.33	14.46	14.45
	td2	Mm3/year	14.32	14.36	13.71	14.33	14.30
Scenario 4	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.3585	0.4020	0.2120	0.3617	0.2620
	wp1	"	0.2248	0.0585	0.1017	0.0655	0.1258
	ap1	"	0.1593	0.3065	0.1616	0.1243	0.1617
	lp1	"	0.4915	0.5568	0.5482	0.3921	0.4830
	tp2	"	0.2824	0.4519	0.5417	0.3394	0.3437
	wp2	"	0.1325	0.0852	0.0278	0.0815	0.1018
	ap2	"	0.2308	0.2493	0.3079	0.2197	0.3155
	lp2	"	0.5928	0.6249	0.5486	0.4969	0.5320
	wg	"	0.3276	0.5687	0.5791	0.5327	0.5264
	td1	Mm3/year	14.42	14.38	14.45	14.49	14.45
	td2	Mm3/year	14.40	14.33	14.30	14.37	14.32
Scenario 5	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.2955	0.3101	0.3369	0.3568	0.2884
	wp1	"	0.1744	0.1470	0.1854	0.1342	0.0773
	ap1	"	0.2915	0.2532	0.2619	0.3329	0.2754
	lp1	"	0.3542	0.4288	0.5244	0.6318	0.4394
	tp2	"	0.4250	0.4211	0.4009	0.2541	0.2594
	wp2	"	0.0467	0.1524	0.0862	0.0951	0.1164
	ap2	"	0.3443	0.2573	0.3433	0.2077	0.2592
	lp2	"	0.5429	0.6128	0.4279	0.3932	0.5040
	wg	"	0.4836	0.6074	0.5631	0.7264	0.4735
	td1	Mm3/year	14.21	14.48	14.48	14.47	14.50
	td2	Mm3/year	14.21	13.89	14.29	14.10	14.33
Scenario 6	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.4630	0.3270	0.3827	0.3232	0.3725

	wp1	"	0.1419	0.0827	0.1348	0.1490	0.0731
	ap1	"	0.2428	0.3193	0.1166	0.2749	0.2922
	lp1	"	0.5084	0.5930	0.3986	0.5779	0.4833
	tp2	"	0.4008	0.5102	0.3705	0.3490	0.4958
	wp2	"	0.0209	0.0772	0.0706	0.0694	0.0498
	ap2	"	0.3170	0.3207	0.3184	0.3186	0.3926
	lp2	"	0.5624	0.5009	0.5248	0.4247	0.5734
	wg	"	0.4768	0.5134	0.4127	0.3692	0.5748
	td1	Mm3/year	14.23	14.36	14.25	14.47	13.98
	td2	Mm3/year	14.36	14.31	14.11	14.39	14.22
Scenario 7	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.3225	0.3816	0.3813	0.4217	0.3012
	wp1	"	0.1112	0.1420	0.1554	0.0404	0.1230
	ap1	"	0.1570	0.2593	0.2851	0.3244	0.1214
	lp1	"	0.4304	0.4326	0.6221	0.4877	0.5654
	tp2	"	0.3479	0.3640	0.3407	0.4012	0.2980
	wp2	"	0.1106	0.0518	0.0759	0.0812	0.0655
	ap2	"	0.2904	0.3415	0.3316	0.1599	0.2904
	lp2	"	0.4453	0.6193	0.5249	0.6135	0.4576
	wg	"	0.3801	0.2938	0.4448	0.4925	0.5723
	td1	Mm3/year	14.36	14.11	14.36	14.47	14.46
	td2	Mm3/year	14.15	13.72	14.30	14.40	14.29
Scenario 8	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.2503	0.3706	0.2846	0.4416	0.2274
	wp1	"	0.1722	0.0890	0.1178	0.0527	0.2499
	ap1	"	0.1643	0.2998	0.2530	0.3702	0.1403
	lp1	"	0.4422	0.4380	0.6209	0.4258	0.3754
	tp2	"	0.3553	0.3226	0.3663	0.3724	0.3012
	wp2	"	0.0639	0.1666	0.0480	0.1873	0.1113
	ap2	"	0.3401	0.2875	0.3039	0.0828	0.2245
	lp2	"	0.4896	0.5335	0.4906	0.4599	0.4221
	wg	"	0.5518	0.6240	0.6968	0.6220	0.3599
	td1	Mm3/year	14.46	14.40	14.50	14.38	14.40
	td2	Mm3/year	14.20	14.40	14.38	14.27	14.36
Scenario 9	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.3627	0.4591	0.2088	0.3643	0.3518
	wp1	"	0.1015	0.0845	0.0866	0.0442	0.0905
	ap1	"	0.3383	0.3518	0.1892	0.2473	0.0663
	lp1	"	0.3333	0.3002	0.5806	0.5378	0.8325
	tp2	"	0.4016	0.2066	0.4048	0.4446	0.4010
	wp2	"	0.0541	0.0591	0.1103	0.0382	0.0462
	ap2	"	0.3655	0.1939	0.3242	0.3875	0.3850
	lp2	"	0.4671	0.7032	0.6181	0.6306	0.3351
	wg	"	0.3145	0.1553	0.6248	0.6447	0.5385
	td1	Mm3/year	14.44	14.03	14.49	14.46	14.40
	td2	Mm3/year	14.34	14.16	14.12	14.21	14.33
Scenario 0	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.2811	0.4398	0.4883	0.4372	0.3962
	wp1	"	0.1808	0.0949	0.0096	0.1471	0.1136
	ap1	"	0.1380	0.3354	0.3944	0.2281	0.2642
	lp1	"	0.4583	0.4444	0.4918	0.3046	0.3762
	tp2	"	0.3891	0.4519	0.3539	0.4237	0.2813
	wp2	"	0.0756	0.0327	0.0344	0.1042	0.1163
	ap2	"	0.3166	0.3345	0.3138	0.2941	0.2498
	lp2	"	0.4060	0.2962	0.5474	0.5135	0.6065
	wg	"	0.5938	0.5083	0.8708	0.4479	0.4189
	td1	Mm3/year	14.26	14.41	14.30	13.29	14.48
	td2	Mm3/year	14.31	14.29	14.40	14.55	14.38

Appendix B2: Optimised parameters for Olifants River system (amplitude activated).

		Scenario 0			Scenario 5		
Parameter	**Unit**	**Run1**	**Run2**	**Run3**	**Run1**	**Run2**	**Run3**
tp1	"	0.3433	**0.2246**	0.3000	0.3312	0.2808	0.3807
wp1	"	0.2094	**0.2102**	0.2678	0.2219	0.2630	0.2080
ap1	"	0.0882	**0.1249**	0.1203	0.1773	0.1545	0.1663
lp1	"	0.3297	**0.2847**	0.3083	0.2510	0.3063	0.3395
tp2	"	0.3561	**0.2260**	0.2188	0.2478	0.1701	0.2784
wp2	"	0.0732	**0.0791**	0.1455	0.0799	0.0677	0.0637
ap2	"	0.3305	**0.1736**	0.1895	0.2404	0.1351	0.2766
lp2	"	0.3441	**0.2979**	0.3047	0.3589	0.2154	0.3659
tp3	"	0.3288	**0.3104**	0.3706	0.3136	0.3120	0.3120
wp3	"	0.1571	**0.1731**	0.1578	0.1944	0.2204	0.1753
ap3	"	0.2872	**0.2708**	0.2973	0.2558	0.2305	0.3011
lp3	"	0.4324	**0.4280**	0.3603	0.3994	0.3841	0.4855
tp4	"	0.2031	**0.2479**	0.2311	0.2064	0.1785	0.3190
wp4	"	0.2518	**0.2008**	0.3049	0.2420	0.2704	0.2643
ap4	"	0.2008	**0.1479**	0.1510	0.1668	0.1743	0.1253
lp4	"	0.4233	**0.4341**	0.4050	0.4337	0.3879	0.4079
tp5	"	0.2891	**0.2150**	0.3103	0.2979	0.2870	0.2393
wp5	"	0.2043	**0.2202**	0.1948	0.1644	0.1771	0.2128
ap5	"	0.2628	**0.1735**	0.2202	0.2438	0.2422	0.2256
lp5	"	0.2146	**0.2248**	0.3492	0.3745	0.2840	0.3134
wg1	"	0.1680	**0.1873**	0.1639	0.1375	0.1289	0.1511
wg2	"	0.1278	**0.1471**	0.1438	0.1289	0.1286	0.1294
wg3	"	0.1136	**0.1211**	0.1051	0.1017	0.1022	0.1237
wg4	"	0.0462	**0.0812**	0.0662	0.1300	0.1119	0.1344
wg5	"	0.5444	**0.4633**	0.5210	0.5019	0.5284	0.4614
td1	Mm3/year	11.4396	**12.8838**	12.5151	10.39	14.59	8.88
td2	Mm3/year	31.2896	**31.6501**	32.9086	32.74	29.12	29.78
td3	Mm3/year	7.9254	**7.5432**	7.2118	8.71	8.42	8.62
td4	Mm3/year	3.6264	**4.4924**	4.2868	4.22	3.45	4.01
td5	Mm3/year	81.2657	**87.8302**	76.2161	65.94	65.86	72.64
		Scenario 1			**Scenario 6**		
Parameter	**Unit**	**Run1**	**Run2**	**Run3**	**Run1**	**Run2**	**Run3**
tp1	"	0.3172	0.2945	**0.2790**	0.3400	0.2781	0.2597
wp1	"	0.2252	0.2067	**0.2158**	0.2299	0.2155	0.2097
ap1	"	0.1225	0.2764	**0.1363**	0.1981	0.2417	0.1789
lp1	"	0.2156	0.3072	**0.3059**	0.2479	0.2399	0.3348
tp2	"	0.2611	0.2546	**0.2335**	0.2359	0.2582	0.2610
wp2	"	0.0727	0.0604	**0.0990**	0.0981	0.0961	0.1024
ap2	"	0.2614	0.2182	**0.2336**	0.2070	0.1754	0.2506
lp2	"	0.2898	0.3337	**0.3259**	0.2435	0.4455	0.3026
tp3	"	0.3163	0.2599	**0.3262**	0.2913	0.4020	0.3007
wp3	"	0.1684	0.1948	**0.1887**	0.1844	0.1660	0.1899
ap3	"	0.3105	0.2609	**0.2614**	0.2453	0.2622	0.2923
lp3	"	0.4693	0.4462	**0.4295**	0.3665	0.3061	0.4273
tp4	"	0.1681	0.2420	**0.2467**	0.2496	0.2856	0.2269
wp4	"	0.2737	0.2514	**0.1936**	0.2228	0.2160	0.2256
ap4	"	0.1470	0.1998	**0.2077**	0.1209	0.2302	0.2243
lp4	"	0.4389	0.4839	**0.4692**	0.4560	0.4961	0.4332
tp5	"	0.3593	0.2779	**0.3000**	0.3590	0.3419	0.3597
wp5	"	0.2189	0.1809	**0.2313**	0.1595	0.1611	0.2044
ap5	"	0.1565	0.1777	**0.1723**	0.2243	0.3068	0.1890
lp5	"	0.2131	0.3367	**0.3316**	0.3547	0.3035	0.1905

wg1	"	0.1535	0.1267	**0.1576**	0.1651	0.1619	0.1543
wg2	"	0.1002	0.1317	**0.1204**	0.1665	0.1593	0.1694
wg3	"	0.1219	0.1453	**0.1327**	0.1398	0.1496	0.1443
wg4	"	0.0858	0.1031	**0.0533**	0.1018	0.1129	0.1009
wg5	"	0.5387	0.4933	**0.5360**	0.4268	0.4163	0.4311
td1	Mm3/year	12.1611	10.6953	**13.7273**	15.01	15.65	11.45
td2	Mm3/year	31.6167	33.2017	**31.7413**	30.07	26.70	30.11
td3	Mm3/year	7.4507	7.1468	**8.5061**	7.71	7.49	7.03
td4	Mm3/year	4.8042	4.2070	**4.3720**	4.46	3.65	4.70
td5	Mm3/year	64.6972	67.7329	**69.7636**	70.01	72.86	70.24
		Scenario 2			**Scenario 7**		
Parameter	**Unit**	**Run1**	**Run2**	**Run3**	**Run1**	**Run2**	**Run3**
tp1	"	0.2853	0.2713	0.3876	0.2239	0.3424	0.3981
wp1	"	0.2248	0.2131	0.1719	0.2263	0.2126	0.1843
ap1	"	0.2228	0.1241	0.1741	0.1257	0.1629	0.1270
lp1	"	0.2784	0.2656	0.2690	0.2176	0.2754	0.3071
tp2	"	0.2692	0.2929	0.2783	0.2122	0.2386	0.2689
wp2	"	0.1285	0.0976	0.1263	0.0975	0.1006	0.0836
ap2	"	0.2568	0.1851	0.2047	0.2088	0.2048	0.2725
lp2	"	0.3085	0.2203	0.2728	0.2417	0.3457	0.3807
tp3	"	0.3146	0.3066	0.2822	0.3311	0.2895	0.2651
wp3	"	0.1867	0.2077	0.2425	0.1677	0.1988	0.1468
ap3	"	0.3024	0.2634	0.2345	0.3395	0.2921	0.2469
lp3	"	0.4332	0.4120	0.2129	0.3780	0.4402	0.5031
tp4	"	0.2753	0.1909	0.2837	0.2214	0.2670	0.2418
wp4	"	0.2220	0.2836	0.1393	0.2477	0.2283	0.2125
ap4	"	0.2361	0.1897	0.1897	0.1591	0.1950	0.1795
lp4	"	0.4064	0.4341	0.4804	0.4187	0.4561	0.3716
tp5	"	0.3117	0.2835	0.3927	0.2553	0.3129	0.2792
wp5	"	0.1761	0.1896	0.2021	0.1987	0.2078	0.1755
ap5	"	0.2632	0.2470	0.2015	0.2390	0.1505	0.2795
lp5	"	0.3277	0.2742	0.4828	0.2488	0.2696	0.2614
wg1	"	0.1607	0.1543	0.1664	0.1446	0.1394	0.1460
wg2	"	0.1467	0.1189	0.1439	0.1376	0.1436	0.1382
wg3	"	0.1760	0.1623	0.1850	0.1395	0.1451	0.1386
wg4	"	0.1473	0.1034	0.1271	0.1117	0.1086	0.1145
wg5	"	0.3692	0.4611	0.3776	0.4666	0.4633	0.4627
td1	Mm3/year	13.81	13.27	10.93	14.39	11.88	11.70
td2	Mm3/year	28.18	31.18	29.51	29.48	31.91	31.94
td3	Mm3/year	8.42	6.37	10.97	7.57	8.37	8.79
td4	Mm3/year	4.30	3.94	3.74	4.34	4.97	4.33
td5	Mm3/year	71.89	67.55	65.91	64.99	65.94	68.50
		Scenario 3			**Scenario 8**		
Parameter	**Unit**	**Run1**	**Run2**	**Run3**	**Run1**	**Run2**	**Run3**
tp1	"	0.2132	0.2978	0.2957	0.3205	0.4166	0.4681
wp1	"	0.2632	0.2457	0.2510	0.2220	0.2168	0.1450
ap1	"	0.1545	0.1130	0.1416	0.1480	0.1007	0.1943
lp1	"	0.2946	0.2505	0.2704	0.2802	0.3021	0.2879
tp2	"	0.2589	0.1558	0.1634	0.2515	0.2953	0.3098
wp2	"	0.0518	0.0568	0.0772	0.1073	0.0654	0.1279
ap2	"	0.1596	0.1583	0.1630	0.2040	0.1811	0.1735
lp2	"	0.2430	0.2194	0.3277	0.3070	0.2840	0.1768
tp3	"	0.3282	0.3188	0.2546	0.2904	0.3326	0.3494
wp3	"	0.1375	0.1925	0.2273	0.2183	0.1663	0.1953
ap3	"	0.3216	0.2908	0.2439	0.2616	0.3369	0.2222
lp3	"	0.4401	0.4892	0.4492	0.4893	0.4583	0.5013
tp4	"	0.1869	0.1824	0.2247	0.2095	0.2702	0.2174

wp4	"	0.2787	0.2656	0.2537	0.2935	0.2458	0.2255
ap4	"	0.1569	0.0626	0.0887	0.1724	0.1640	0.1827
lp4	"	0.5136	0.4208	0.4481	0.4040	0.4313	0.4835
tp5	"	0.3222	0.3263	0.2395	0.2919	0.3102	0.3023
wp5	"	0.1749	0.2117	0.1645	0.1460	0.1785	0.1934
ap5	"	0.3111	0.1542	0.1362	0.1703	0.2018	0.3048
lp5	"	0.2377	0.2347	0.2952	0.2171	0.1823	0.2115
wg1	"	0.1673	0.1438	0.1592	0.1342	0.1347	0.1275
wg2	"	0.1856	0.1719	0.1801	0.1679	0.1922	0.1824
wg3	"	0.1612	0.1532	0.1521	0.1233	0.1811	0.1866
wg4	"	0.1034	0.1033	0.1182	0.1123	0.1211	0.0894
wg5	"	0.3825	0.4278	0.3904	0.4623	0.3709	0.4141
td1	Mm3/year	13.50	12.63	12.77	11.22	11.88	12.88
td2	Mm3/year	31.89	31.94	31.60	31.06	32.19	37.23
td3	Mm3/year	4.90	6.60	5.35	7.09	5.66	5.81
td4	Mm3/year	4.41	4.61	4.21	4.21	5.03	4.06
td5	Mm3/year	58.32	62.12	65.98	67.16	68.21	67.30
		Scenario 4			**Scenario 9**		
Parameter	**Unit**	**Run1**	**Run2**	**Run3**	**Run1**	**Run2**	**Run5**
tp1	"	0.3097	0.4376	0.2086	0.3146	0.3067	**0.2902**
wp1	"	0.1957	0.1764	0.2558	0.2492	0.2026	**0.2230**
ap1	"	0.2684	0.2024	0.1715	0.1852	0.2924	**0.1584**
lp1	"	0.2920	0.3684	0.2874	0.3470	0.2034	**0.3561**
tp2	"	0.2841	0.2931	0.3425	0.2747	0.3085	**0.2794**
wp2	"	0.1219	0.0535	0.2021	0.1152	0.0710	**0.0879**
ap2	"	0.2745	0.1944	0.1300	0.2328	0.2083	**0.2166**
lp2	"	0.3316	0.2834	0.0500	0.2365	0.3019	**0.2909**
tp3	"	0.3216	0.2897	0.3919	0.3365	0.4144	**0.3160**
wp3	"	0.1631	0.1733	0.0961	0.1831	0.1645	**0.1783**
ap3	"	0.3198	0.2225	0.3661	0.2225	0.2439	**0.2887**
lp3	"	0.4389	0.5385	0.5630	0.4437	0.3942	**0.4219**
tp4	"	0.2674	0.2524	0.1318	0.2575	0.2493	**0.2473**
wp4	"	0.2227	0.1911	0.1951	0.2544	0.2062	**0.2487**
ap4	"	0.2403	0.2393	0.0723	0.1449	0.2101	**0.2153**
lp4	"	0.3898	0.4196	0.8107	0.5535	0.3163	**0.3982**
tp5	"	0.3504	0.2836	0.4017	0.2997	0.3142	**0.2868**
wp5	"	0.1828	0.2341	0.0900	0.1705	0.1758	**0.2073**
ap5	"	0.2646	0.2229	0.1762	0.2337	0.3116	**0.2797**
lp5	"	0.3100	0.4214	0.4646	0.3684	0.3286	**0.2137**
wg1	"	0.1446	0.1437	0.1543	0.1366	0.1455	**0.1679**
wg2	"	0.1319	0.1411	0.1344	0.1286	0.1489	**0.1346**
wg3	"	0.1522	0.1621	0.1518	0.2179	0.1796	**0.2023**
wg4	"	0.1121	0.0954	0.1009	0.0486	0.0863	**0.0549**
wg5	"	0.4592	0.4577	0.4586	0.4683	0.4398	**0.4404**
td1	Mm3/year	12.00	13.47	5.95	13.48	12.40	**12.76**
td2	Mm3/year	32.22	29.82	42.42	32.18	31.55	**30.42**
td3	Mm3/year	9.58	7.69	2.61	9.24	9.12	**8.35**
td4	Mm3/year	3.52	3.40	2.86	4.27	4.00	**3.86**
td5	Mm3/year	68.29	70.23	94.97	63.06	67.00	**69.10**

Appendix C:

Appendix C1: Optimised parameters for Elands River system (amplitude deactivated).

Scenario 1	Parameter	Unit	Run1	Run2	Run3	Run4	Run5
	tp1	"	0.4233	0.5811	0.5578	0.4560	0.4718
	wp1	"	0.0926	0.0194	0.1386	0.0707	0.1095
	tp2	"	0.1129	0.0930	0.1109	0.0354	0.0925
	wp2	"	0.0348	0.0538	0.0512	0.0364	0.0338
	wg	"	0.2436	0.2632	0.2823	0.2743	0.1212
	td1	Mm3/year	14.44	14.34	14.30	14.42	14.42
	td2	Mm3/year	14.40	14.21	14.20	14.23	14.05
Scenario 2	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.1085	0.499592	0.6019	0.5538	0.2569
	wp1	"	0.0452	0.055409	0.0901	0.0440	0.0955
	tp2	"	0.0282	0.073967	0.0339	0.0660	0.0374
	wp2	"	0.0929	0.026398	0.0060	0.0623	0.0337
	wg	"	0.4068	0.064672	0.0764	0.0623	0.2866
	td1	Mm3/year	14.49638	14.49741	14.4965	14.4978	14.4934
	td2	Mm3/year	14.39732	14.3977	14.3995	14.3994	14.3904
Scenario 3	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.313818	0.313502	0.438333	0.343613	0.35725
	wp1	"	0.071512	0.023958	0.071528	0.085551	0.061293
	tp2	"	0.06389	0.04282	0.020425	0.025605	0.053178
	wp2	"	0.022921	0.082044	0.041146	0.07308	0.056262
	wg	"	0.135746	0.106687	0.156702	0.144571	0.216847
	td1	Mm3/year	14.49	14.49	14.49	14.49	14.49
	td2	Mm3/year	14.39	14.39	14.39	14.39	14.39
Scenario 4	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.663484	0.536428	0.340838	0.500407	0.619678
	wp1	"	0.03484	0.09924	0.099276	0.059683	0.034115
	tp2	"	0.133618	0.141135	0.148398	0.103163	0.048311
	wp2	"	0.062771	0.030916	0.057936	0.026541	0.042333
	wg	"	0.092299	0.141289	0.217434	0.14895	0.1643
	td1	Mm3/year	14.49988	14.45934	14.49464	14.49828	14.49
	td2	Mm3/year	14.39615	14.37265	14.39741	14.39865	14.39
Scenario 5	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.6882	0.3692	0.3444	0.3772	0.5141
	wp1	"	0.0567	0.0533	0.0427	0.1008	0.0604
	tp2	"	0.1239	0.0151	0.0604	0.0449	0.0626
	wp2	"	0.0225	0.0220	0.0326	0.0138	0.0117
	wg	"	0.0821	0.2788	0.0920	0.2591	0.0495
	td1	Mm3/year	14.4984	14.4872	14.4986	14.4986	14.49
	td2	Mm3/year	14.3953	14.3964	14.3998	14.3972	14.39
Scenario 6	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.380513	0.286986	0.220733	0.449291	0.565872
	wp1	"	0.075739	0.036759	0.101637	0.100543	0.066078
	tp2	"	0.084183	0.095833	0.026302	0.029991	0.036669
	wp2	"	0.084183	0.0201	0.019261	0.029991	0.031019
	wg	"	0.083675	0.46895	0.366358	0.068849	0.07494
	td1	Mm3/year	14.49912	14.49704	14.49912	14.49604	14.4992
	td2	Mm3/year	14.39421	14.3997	14.39996	14.39892	14.39918
Scenario 7	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.6347	0.3413	0.3533	0.5867	0.2675
	wp1	"	0.0422	0.1234	0.0333	0.0012	0.0981
	tp2	"	0.0864	0.1160	0.1700	0.0563	0.0438
	wp2	"	0.0420	0.0589	0.0407	0.0386	0.0987
	wg	"	0.1221	0.1180	0.3959	0.0681	0.1937
	td1	Mm3/year	14.4992	14.4997	14.4920	14.4967	14.4962
	td2	Mm3/year	14.3995	14.4000	14.3993	14.3972	14.3984
Scenario 8	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.544407	0.50189	0.412843	0.312198	0.435514
	wp1	"	0.041383	0.056062	0.143723	0.086611	0.055925
	tp2	"	0.079677	0.093624	0.090868	0.094276	0.096073
	wp2	"	0.014972	0.038495	0.029843	0.04404	0.048745
	wg	"	0.180296	0.096072	0.119495	0.157057	0.204451

	td1	Mm3/year	14.4982	14.49831	14.49943	14.49614	14.495
	td2	Mm3/year	14.39976	14.39535	14.39862	14.39967	14.39663
Scenario 9	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.582448	0.486795	0.522608	0.451378	0.513085
	wp1	"	0.079259	0.050235	0.063588	0.102958	0.058753
	tp2	"	0.036142	0.104008	0.01928	0.06042	0.11387
	wp2	"	0.023721	0.036133	0.041187	0.037318	0.033522
	wg	"	0.21798	0.245168	0.235826	0.211198	0.222008
	td1	Mm3/year	14.29563	14.49577	14.29971	14.39862	14.19976
	td2	Mm3/year	14.09697	14.39931	14.1996	14.19928	14.09857
Scenario 0	**Parameter**	**Unit**	**Run1**	**Run2**	**Run3**	**Run4**	**Run5**
	tp1	"	0.567727	0.539906	0.532817	0.52503	0.476677
	wp1	"	0.098189	0.08956	0.110384	0.067708	0.139837
	tp2	"	0.114295	0.153309	0.091454	0.186961	0.044459
	wp2	"	0.049459	0.035522	0.088011	0.045688	0.080877
	wg	"	0.228387	0.235139	0.289894	0.240574	0.132957
	td1	Mm3/year	14.46881	14.49944	14.49893	14.49781	14.49676
	td2	Mm3/year	14.39547	14.39421	14.39724	14.3988	14.39991

Appendix C2: Optimised parameters for Olifants River (amplitude deactivated).

		Scenario 0			**Scenario 5**		
Parameter	Unit	Run1	Run2	Run3	**Run1**	**Run2**	**Run3**
tp1	"	0.192558	0.241375	**0.043952**	0.2510	0.1809	0.0114
wp1	"	0.157427	0.146096	**0.111205**	0.1181	0.0909	0.1589
tp2	"	0.04075	0.07531	**0.009643**	0.1123	0.0751	0.2042
wp2	"	0.104043	0.056457	**0.067598**	0.0782	0.1019	0.0610
tp3	"	0.10947	0.08351	**0.208945**	0.1100	0.2094	0.0364
wp3	"	0.145325	0.17851	**0.06614**	0.0316	0.1197	0.0817
tp4	"	0.132984	0.297695	**0.109495**	0.2658	0.3636	0.1313
wp4	"	0.048768	0.114921	**0.067681**	0.0316	0.1172	0.0691
tp5	"	0.004738	0.005596	**0.010867**	0.0078	0.0093	0.0133
wp5	"	0.000112	0.010755	**0.001712**	0.0173	0.0015	0.0053
wg1	"	0.150783	0.067954	**0.178992**	0.1287	0.1642	0.1436
wg2	"	0.182337	0.127789	**0.217471**	0.1279	0.1978	0.1288
wg3	"	0.117469	0.113609	**0.138395**	0.1083	0.2195	0.1580
wg4	"	0.110519	0.04621	**0.07075**	0.1306	0.0619	0.0492
wg5	"	0.438891	0.644437	**0.394391**	0.5046	0.3565	0.5204
td1	Mm3/year	23.85502	23.91923	**23.91923**	23.6682	23.9291	23.8284
td2	Mm3/year	46.94532	46.86645	**46.86645**	46.6988	46.8410	46.9041
td3	Mm3/year	21.8858	21.94276	**21.94276**	21.8476	21.9423	21.8456
td4	Mm3/year	8.720109	8.888507	**8.888507**	8.0781	8.0743	8.8392
td5	Mm3/year	94.99732	94.82439	**94.82439**	94.9484	94.9620	94.9746
		Scenario 1			**Scenario 6**		
Parameter	**Unit**	**Run1**	**Run2**	**Run3**	**Run1**	**Run2**	**Run3**
tp1	"	**0.2227**	0.2282	0.0916	0.0274	0.0265	0.0047
wp1	"	**0.1072**	0.0981	0.1202	0.0810	0.1039	0.1450
tp2	"	**0.1898**	0.0750	0.0633	0.0085	0.0987	0.0057
wp2	"	**0.0499**	0.0991	0.0567	0.1349	0.0288	0.0666
tp3	"	**0.1805**	0.1151	0.1233	0.1248	0.0106	0.0061
wp3	"	**0.1525**	0.0927	0.0836	0.0298	0.0644	0.0607
tp4	"	**0.1663**	0.1163	0.2435	0.0556	0.0476	0.1949
wp4	"	**0.0950**	0.1306	0.0688	0.1216	0.1069	0.0966
tp5	"	**0.0056**	0.0048	0.0137	0.0064	0.0100	0.0069
wp5	"	**0.0108**	0.0575	0.0017	0.0277	0.0080	0.0034
wg1	"	**0.1458**	0.1742	0.1288	0.1691	0.1479	0.1484
wg2	"	**0.1198**	0.1181	0.1164	0.1677	0.1567	0.1921
wg3	"	**0.1445**	0.1374	0.1306	0.1497	0.1972	0.1070
wg4	"	**0.0640**	0.0789	0.0885	0.1051	0.0966	0.0606
wg5	"	**0.5260**	0.4913	0.5357	0.4084	0.4015	0.4920
td1	Mm3/year	**23.89**	23.90	23.85	23.8503	23.7677	23.9590
td2	Mm3/year	**46.95**	46.93	46.85	46.8758	46.9657	46.9639
td3	Mm3/year	**21.84**	21.97	21.88	21.8435	21.9781	21.9610
td4	Mm3/year	**8.98**	7.22	8.98	8.9891	8.9747	8.7502
td5	Mm3/year	**94.87**	94.94	94.95	93.5380	91.4958	90.3006

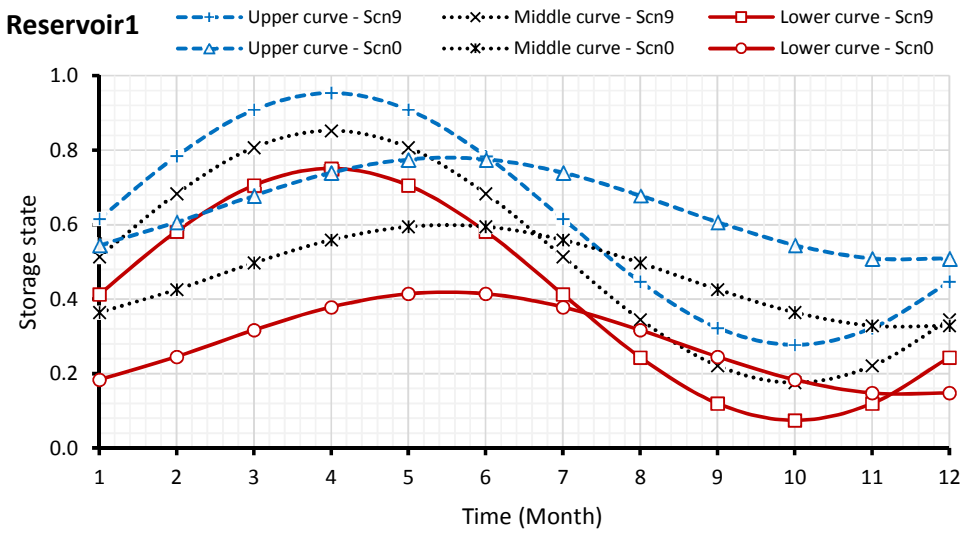
Parameter	Unit	Scenario 2			Scenario 7		
		Run1	Run2	Run3	Run1	Run2	Run3
tp1	"	0.0465	0.0973	0.2129	0.1877	0.0903	0.0225
wp1	"	0.1064	0.1151	0.1003	0.0815	0.0659	0.1199
tp2	"	0.0101	0.0058	0.0094	0.1362	0.0763	0.1210
wp2	"	0.0994	0.0636	0.1187	0.0977	0.1318	0.0809
tp3	"	0.0162	0.1649	0.1682	0.0928	0.2434	0.0363
wp3	"	0.0036	0.0859	0.0792	0.0605	0.0395	0.1738
tp4	"	0.0875	0.0350	0.1955	0.1608	0.0917	0.1929
wp4	"	0.1368	0.1051	0.1330	0.1179	0.1920	0.0794
tp5	"	0.0141	0.0069	0.0081	0.0143	0.0159	0.0146
wp5	"	0.0241	0.0030	0.0043	0.0384	0.0189	0.0059
wg1	"	0.1607	0.2442	0.0572	0.1283	0.0955	0.1060
wg2	"	0.1467	0.2154	0.1930	0.1343	0.1243	0.2092
wg3	"	0.1760	0.1020	0.0512	0.1343	0.1052	0.1054
wg4	"	0.1473	0.1012	0.0438	0.1198	0.1125	0.0960
wg5	"	0.3692	0.3373	0.6548	0.4833	0.5437	0.4834
td1	Mm3/year	23.83	23.98	23.95	23.9612	23.9436	23.9977
td2	Mm3/year	46.95	46.93	46.93	46.8841	46.7372	46.9407
td3	Mm3/year	21.93	21.95	21.91	21.9953	21.9372	21.7988
td4	Mm3/year	8.97	8.14	8.51	8.9436	7.3172	7.8704
td5	Mm3/year	94.91	94.90	94.90	93.3674	93.6152	93.9378
Parameter	Unit	Scenario 3			Scenario 8		
		Run1	Run2	Run3	Run1	Run2	Run3
tp1	"	0.1485	0.0206	0.0743	0.1225	0.1083	0.2317
wp1	"	0.0979	0.0321	0.0368	0.1110	0.0741	0.1680
tp2	"	0.0517	0.1053	0.0180	0.0108	0.1159	0.0165
wp2	"	0.1191	0.0576	0.0669	0.0607	0.1139	0.1623
tp3	"	0.1650	0.1829	0.1481	0.1095	0.2925	0.0128
wp3	"	0.1219	0.0789	0.0903	0.0547	0.0937	0.1051
tp4	"	0.3260	0.0345	0.2363	0.2755	0.0942	0.1351
wp4	"	0.0729	0.0961	0.0944	0.1217	0.1907	0.0951
tp5	"	0.0066	0.0078	0.0093	0.0103	0.0105	0.0047
wp5	"	0.0030	0.0048	0.0076	0.0113	0.0137	0.0046
wg1	"	0.1698	0.1272	0.1065	0.1266	0.1275	0.1032
wg2	"	0.1996	0.1606	0.1867	0.1844	0.1287	0.1430
wg3	"	0.1367	0.0834	0.1037	0.1822	0.0582	0.0924
wg4	"	0.0985	0.0625	0.0847	0.0530	0.0822	0.1137
wg5	"	0.3955	0.5664	0.5184	0.4538	0.6034	0.5477
td1	Mm3/year	23.9635	23.9565	23.9600	23.9956	23.9713	23.9631
td2	Mm3/year	46.8749	46.9475	4.6900	46.8324	46.9024	46.9643
td3	Mm3/year	21.9230	21.9461	21.8800	21.9487	21.9286	21.9407
td4	Mm3/year	8.9317	8.9809	8.9900	8.9825	8.9136	8.9934
td5	Mm3/year	91.7262	92.0460	90.2300	92.6974	92.4832	92.9411
Parameter	Unit	Scenario 4			Scenario 9		
		Run1	Run2	Run3	Run1	Run2	Run3
tp1	"	0.1673	0.0057	0.0231	**0.1363**	0.0548	0.0193
wp1	"	0.0379	0.0317	0.2024	**0.1472**	0.1596	0.0999
tp2	"	0.2813	0.1111	0.2069	**0.1705**	0.0584	0.1239
wp2	"	0.1553	0.0022	0.0016	**0.1113**	0.0396	0.0457
tp3	"	0.0183	0.0806	0.1973	**0.2555**	0.1369	0.1077
wp3	"	0.1727	0.1076	0.1051	**0.0995**	0.0755	0.1018
tp4	"	0.1434	0.1465	0.1089	**0.1349**	0.1326	0.1408
wp4	"	0.1009	0.1471	0.0564	**0.0467**	0.1229	0.0973
tp5	"	0.0109	0.0091	0.0127	**0.0056**	0.0054	0.0067
wp5	"	0.0046	0.0118	0.0029	**0.0132**	0.0147	0.0305
wg1	"	0.1354	0.2240	0.0790	**0.1366**	0.1654	0.1201
wg2	"	0.1374	0.1438	0.1550	**0.1286**	0.1147	0.1633
wg3	"	0.1509	0.1754	0.1019	**0.2179**	0.1380	0.0966
wg4	"	0.0969	0.0786	0.0669	**0.0486**	0.1227	0.0451
wg5	"	0.4794	0.3780	0.5972	**0.4683**	0.4592	0.5749
td1	Mm3/year	23.99	23.72	23.95	**23.90**	23.88	23.93
td2	Mm3/year	46.92	46.99	46.96	**46.86**	46.91	46.91
td3	Mm3/year	21.98	21.96	21.82	**21.89**	21.89	22.00
td4	Mm3/year	9.00	8.95	8.98	**9.00**	9.00	8.98
td5	Mm3/year	94.10	93.93	94.40	**94.26**	93.96	94.20

Appendix D

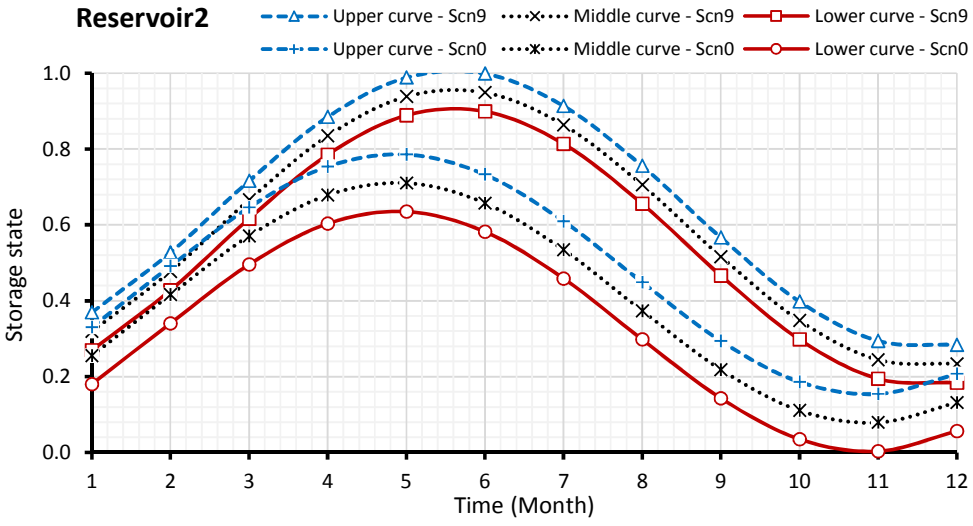
Appendix D shows the change in rule curves due to changing human behaviour (scenario 0 and 9). For each reservoir, all the three curves (upper, middle and lower) are shown in the same plot.

Appendix D1:

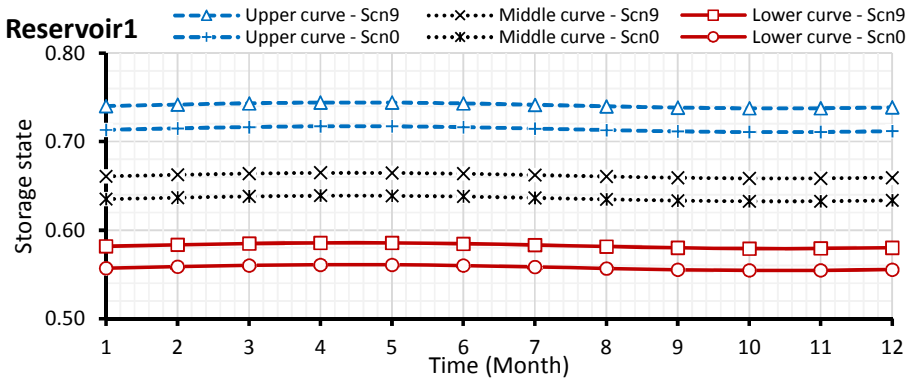
Appendix D1-1: Reservoir1 optimised rule curves for scenarios 0 and 9 with activated amplitude (Elands River reservoir system).



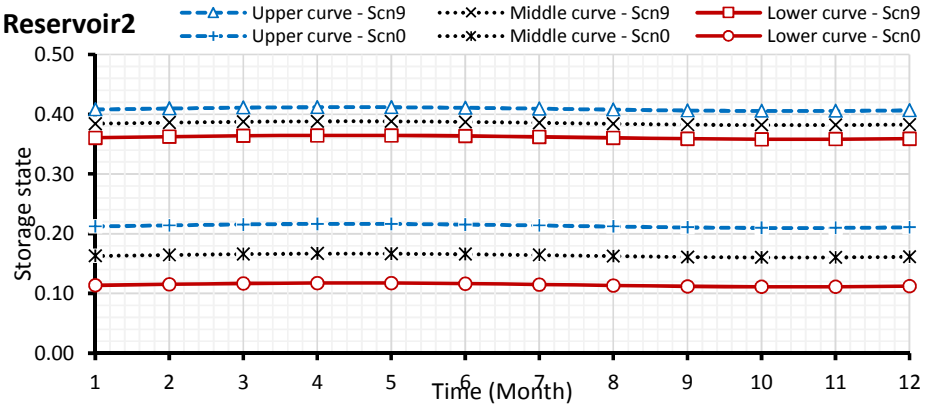
Appendix D1-2: Reservoir2 optimised rule curves for scenarios 0 and 9 with activated amplitude (Elands River reservoir system).



Appendix D1-3: Reservoir1 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Elands River reservoir system).

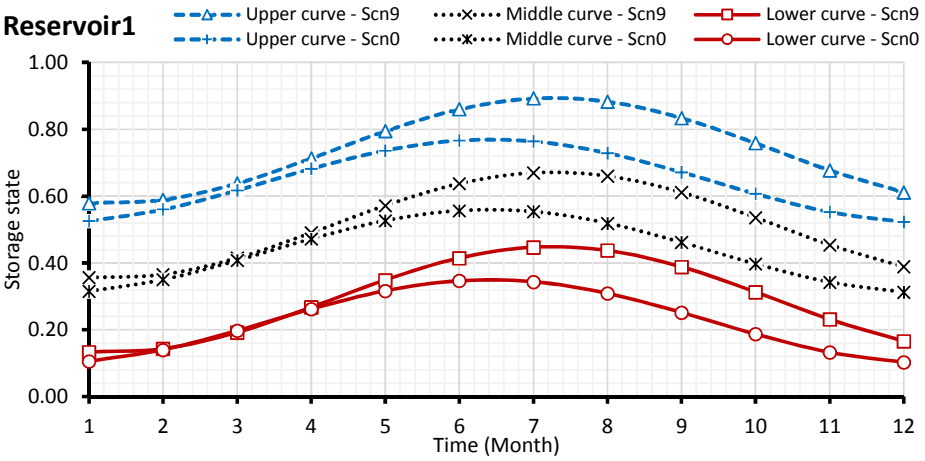


Appendix D1-4: Reservoir2 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Elands River reservoir system).

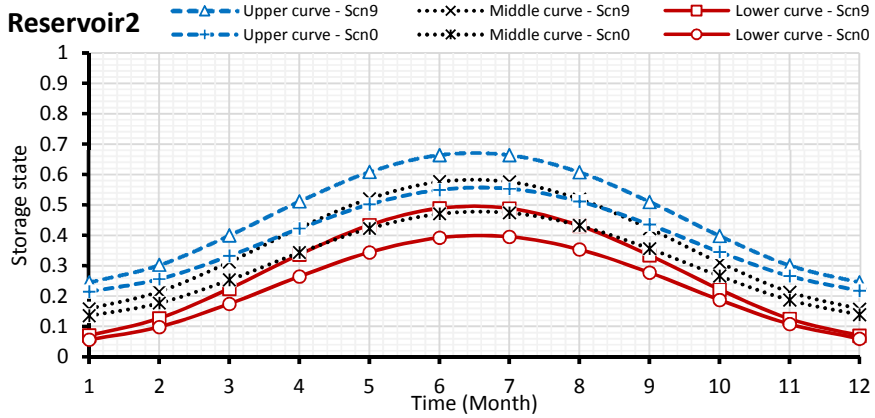


Appendix D2

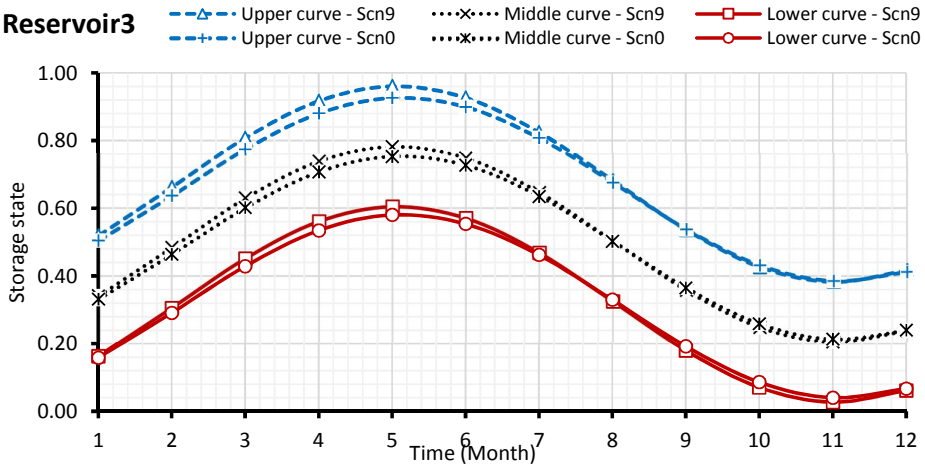
Appendix D2-1: Reservoir1 optimised rule curves for scenarios 0 and 9with activated amplitude (Olifants River reservoir system).



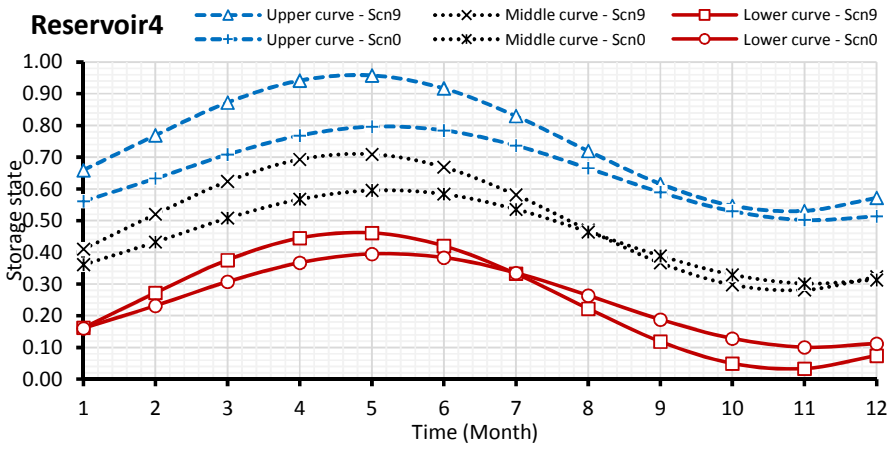
Appendix D2-2: Reservoir2 optimised rule curves for scenarios 0 and 9 with activated amplitude (Olifants River reservoir system).



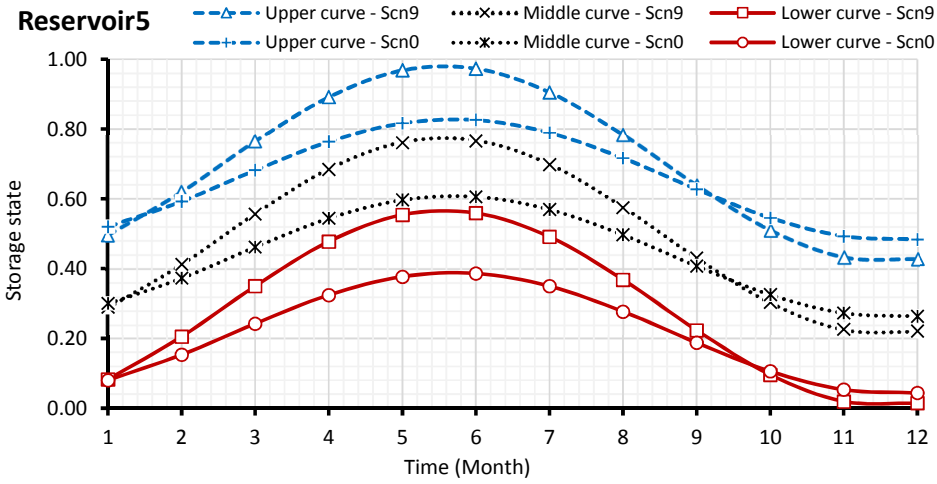
Appendix D2-3: Reservoir3 optimised rule curves for scenarios 0 and 9 with activated amplitude (Olifants River reservoir system).



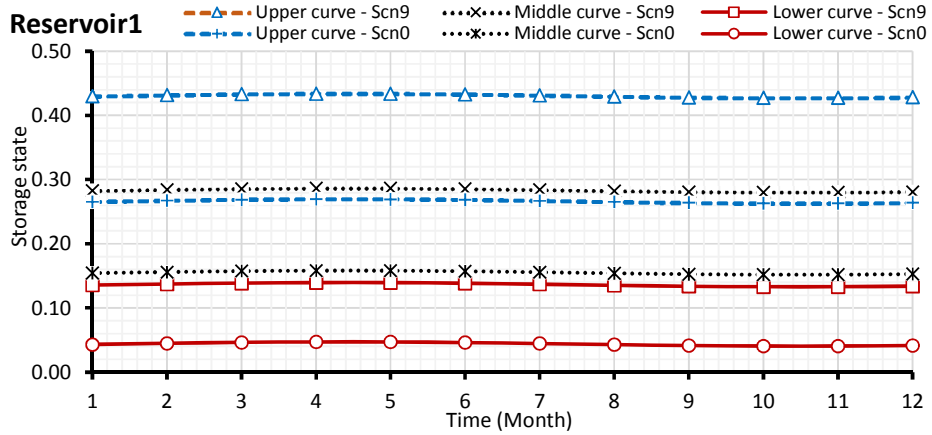
Appendix D2-4: Reservoir4 optimised rule curves for scenarios 0 and 9 with activated amplitude (Olifants River reservoir system).



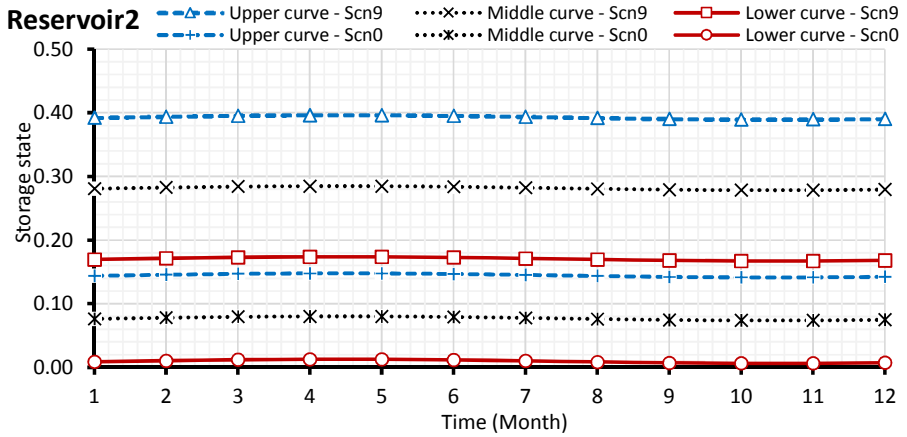
Appendix D2-5: Reservoir5 optimised rule curves for scenarios 0 and 9 with activated amplitude (Olifants River reservoir system).



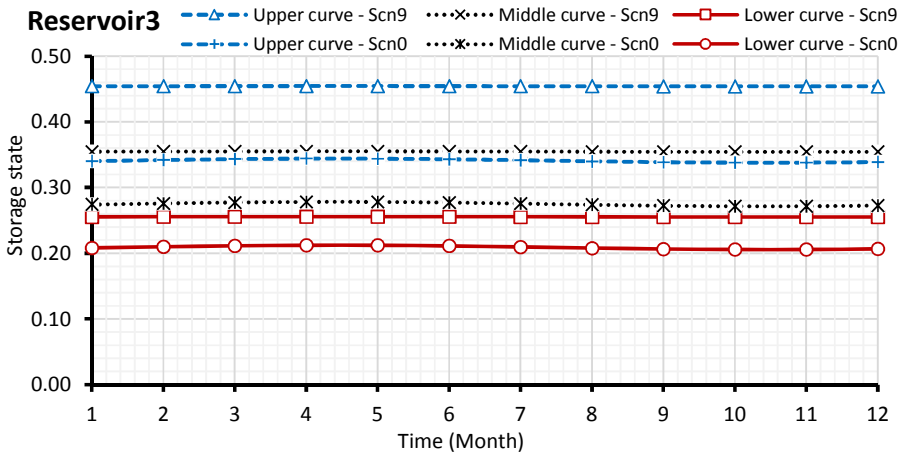
Appendix D2-6: Reservoir1 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Olifants River reservoir system).



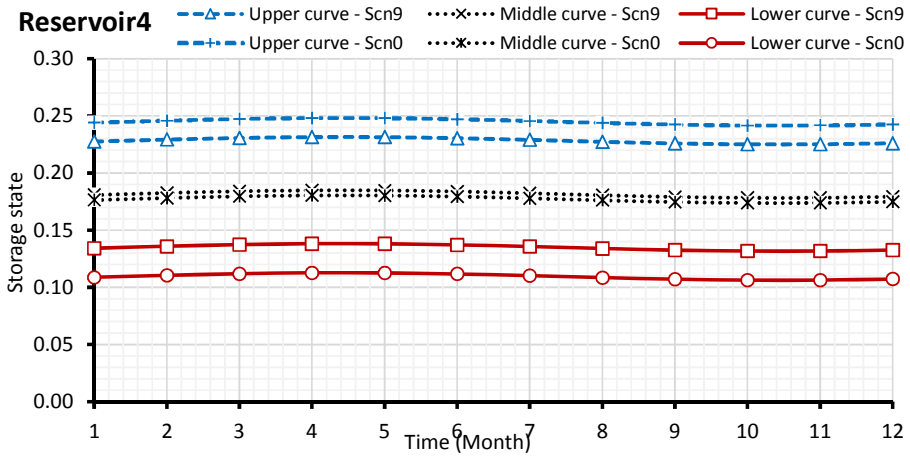
Appendix D2-7: Reservoir2 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Olifants River reservoir system).



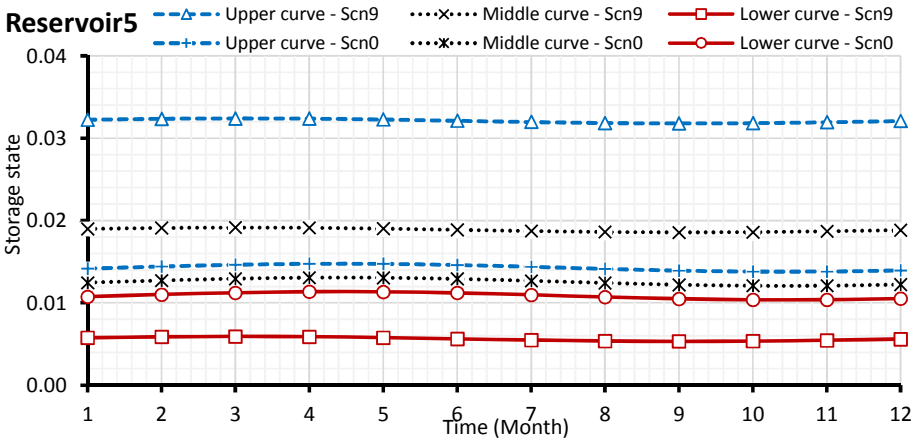
Appendix D2-8: Reservoir3 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Olifants River reservoir system).



Appendix D2-9: Reservoir4 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Olifants River reservoir system).

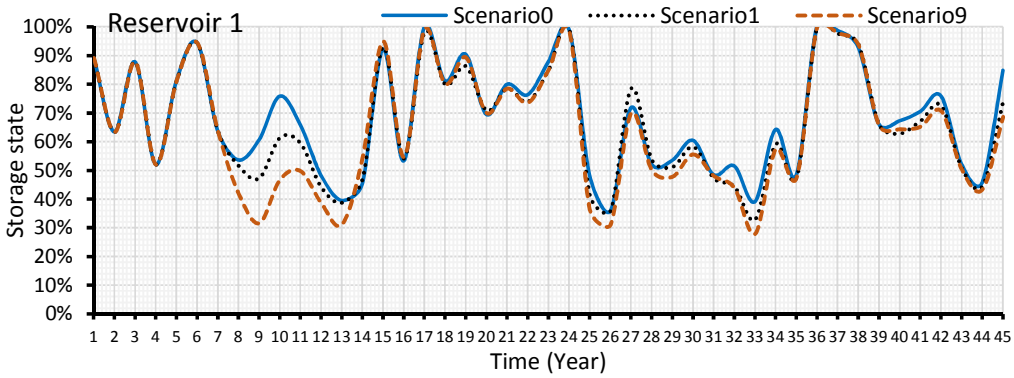


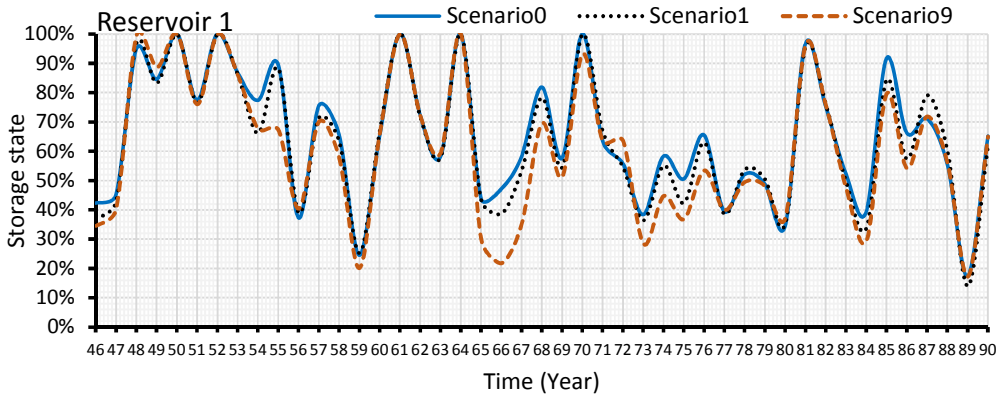
Appendix D2-10: Reservoir5 optimised rule curves for scenarios 0 and 9 with deactivated amplitude (Olifants River reservoir system).

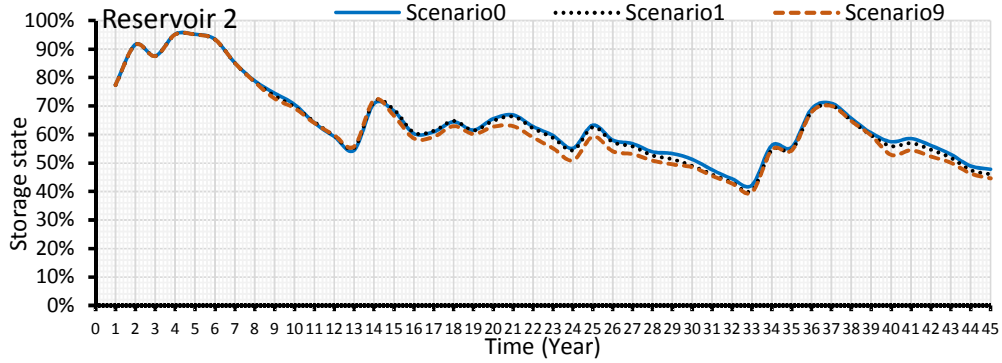


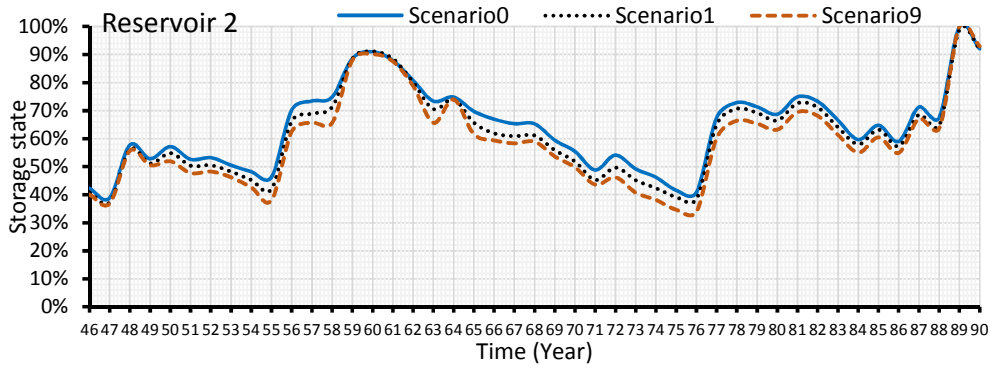
Appendix E:

Appendix E1: Annual storage state trajectory for the individual reservoir as affected by human behaviour (Elands River reservoir system)

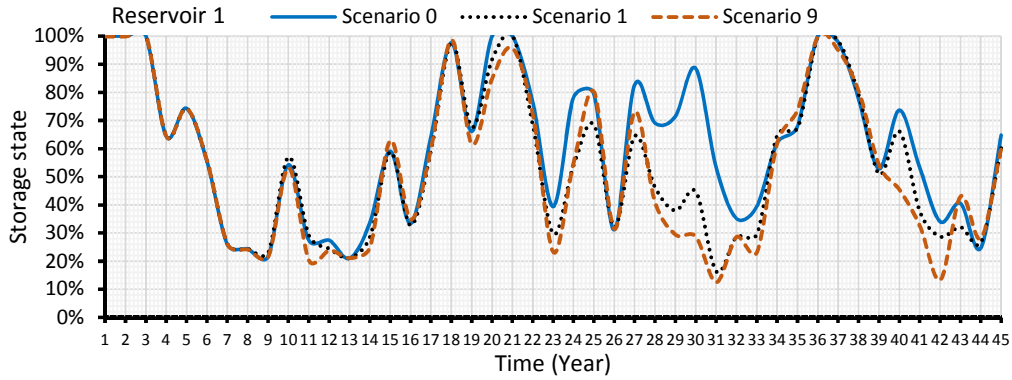


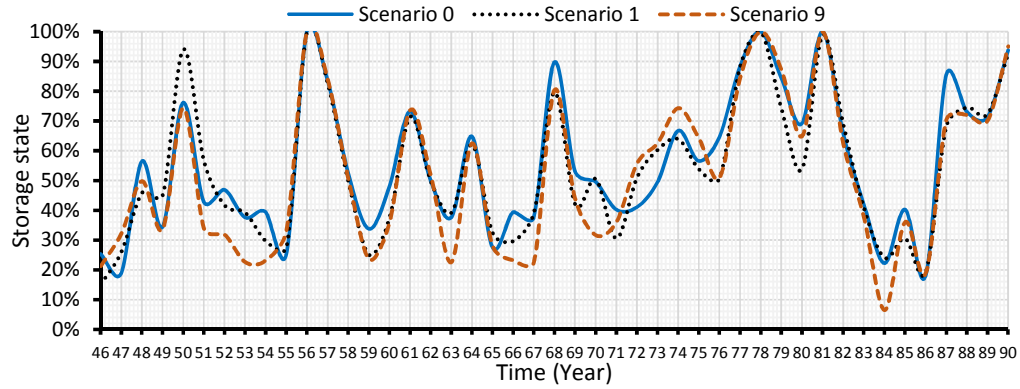


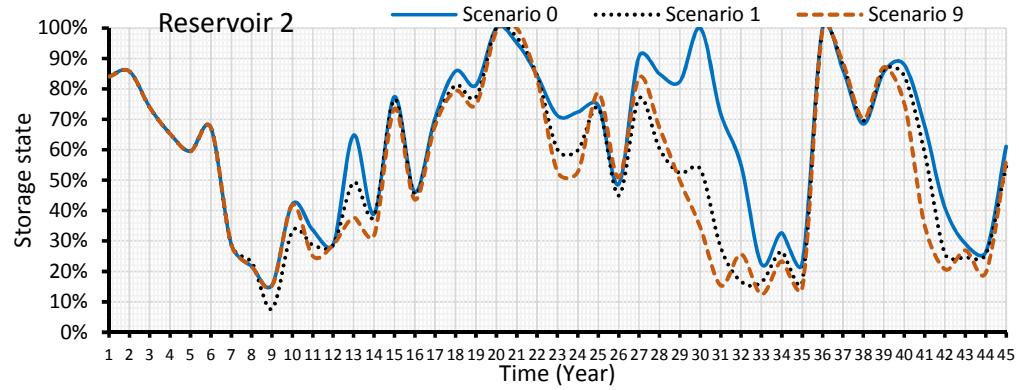


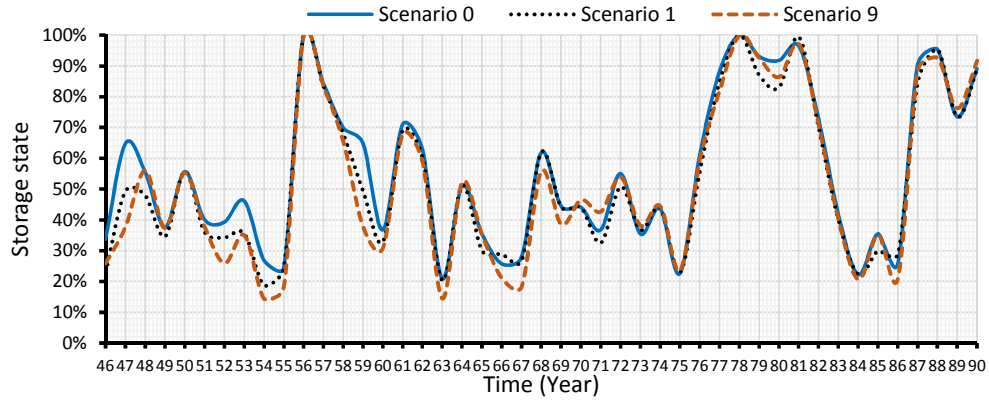


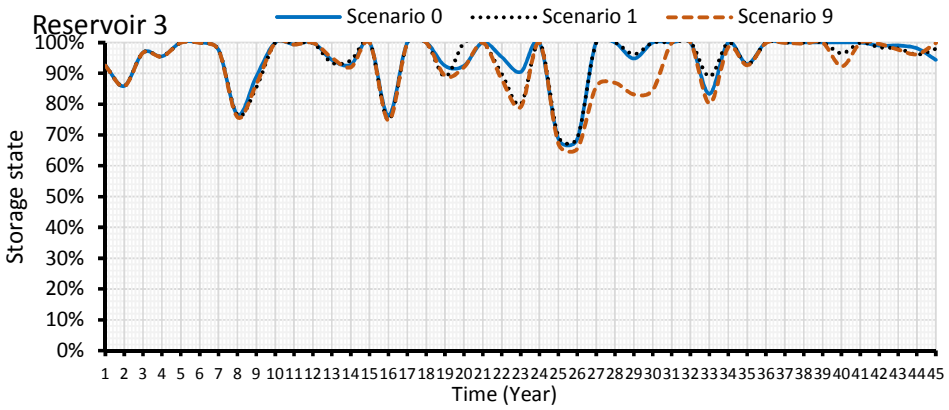
Appendix E2: Annual storage state trajectory for the individual reservoir as affected by human behaviour (Olifants River reservoir system)

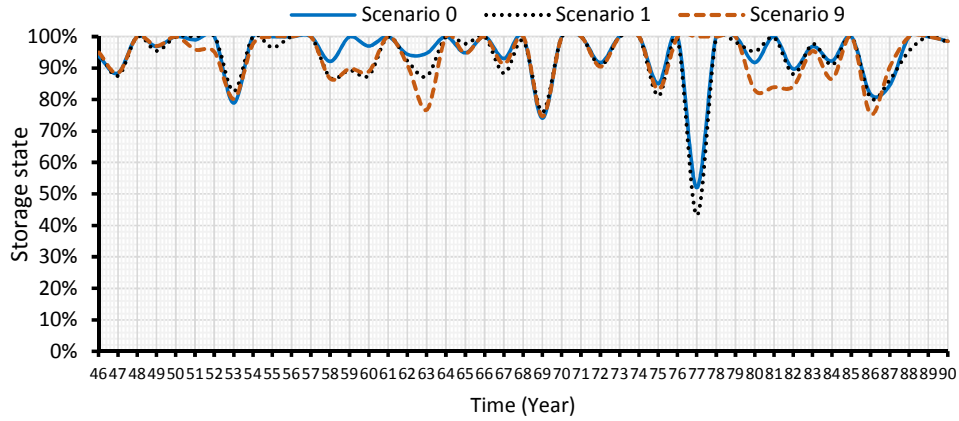


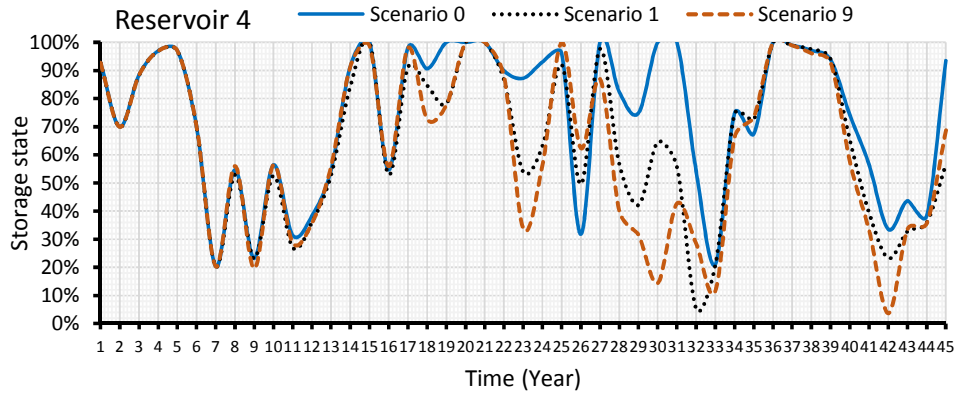


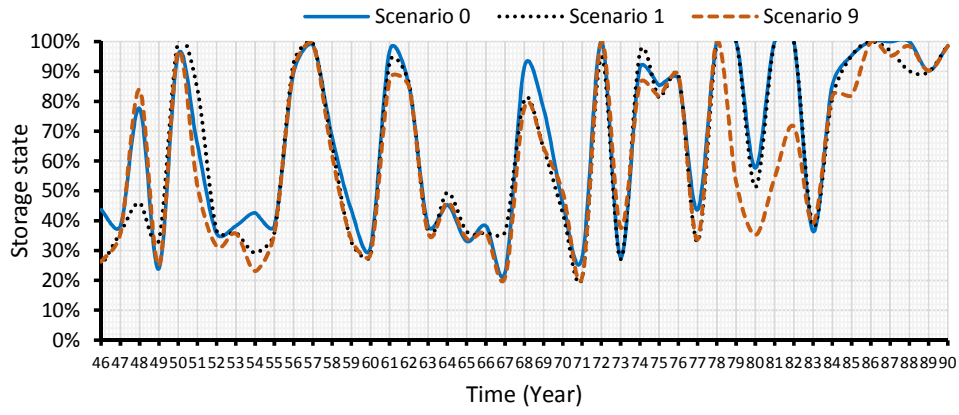


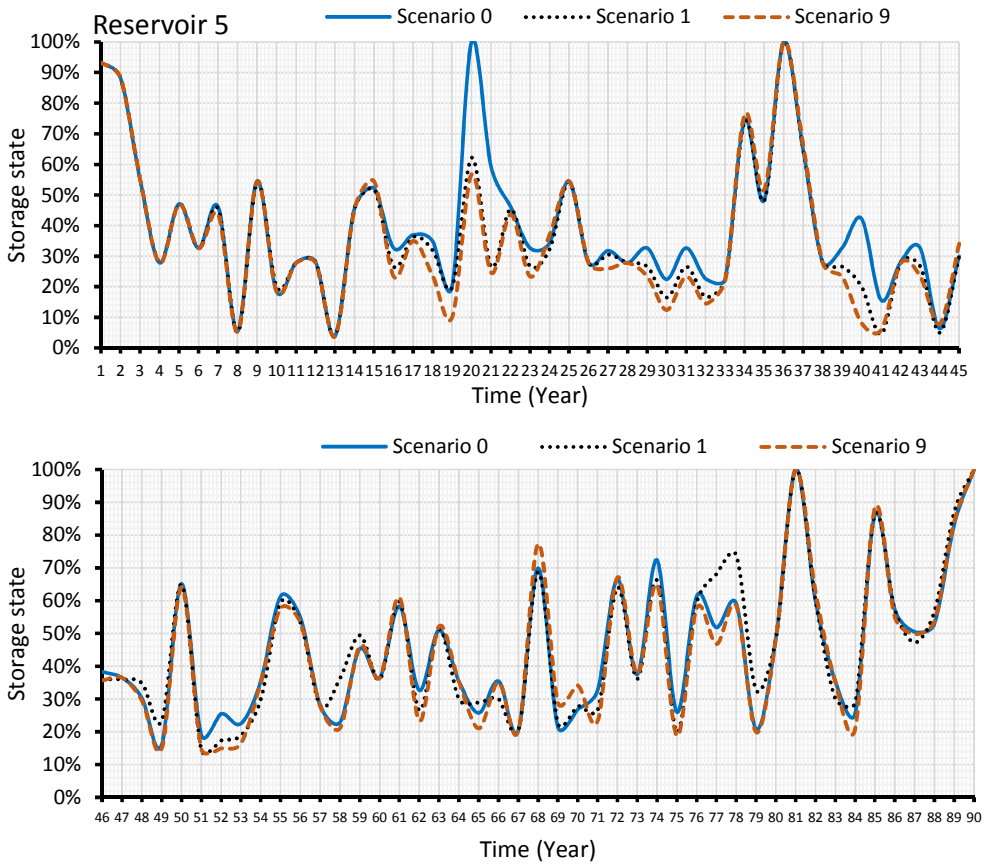



Reservoir 3
Scenario 0
Scenario 1
Scenario 9
Storage state
Time (Year)


Scenario 0
Scenario 1
Scenario 9
Storage state
Time (Year)

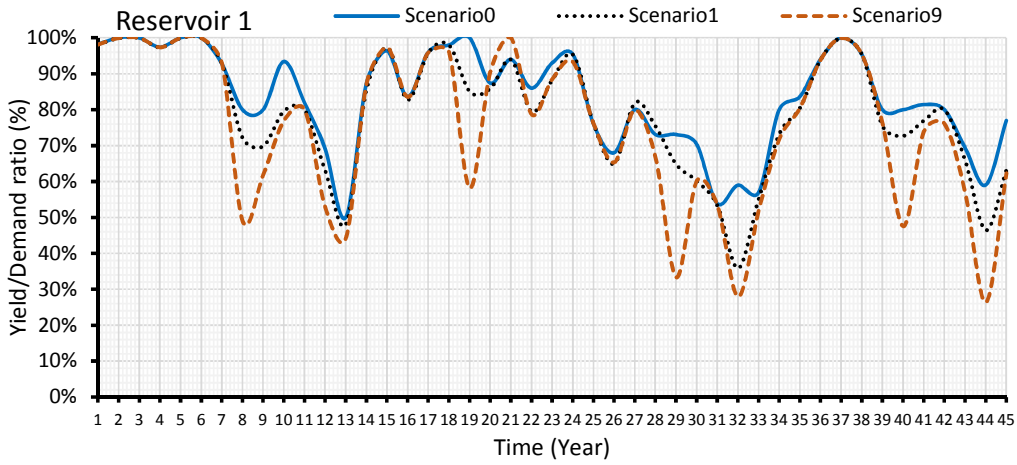

Reservoir 4
Scenario 0
Scenario 1
Scenario 9
Storage state
Time (Year)

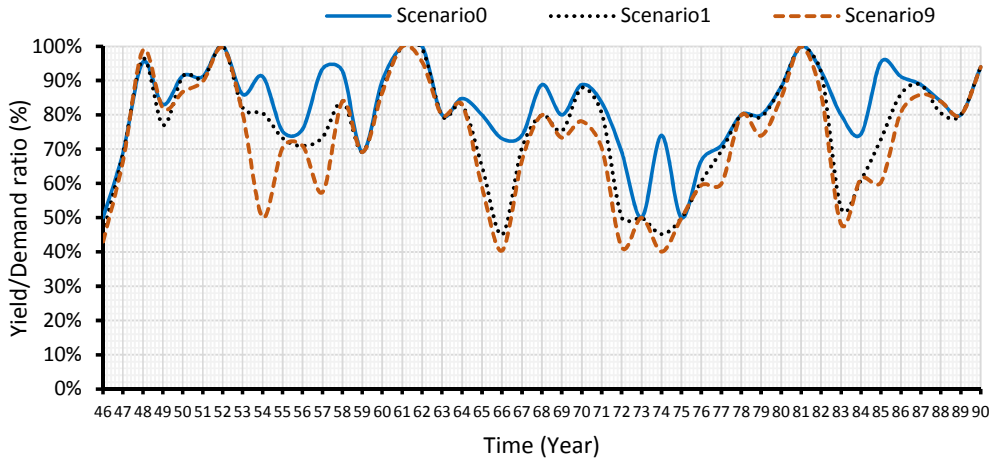

Scenario 0
Scenario 1
Scenario 9
Storage state
Time (Year)

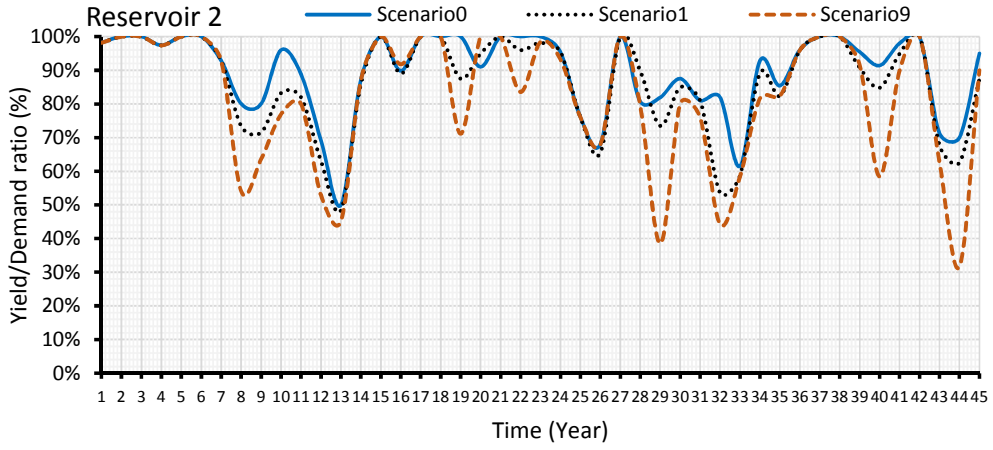

Reservoir 5
Scenario 0
Scenario 1
Scenario 9
Storage state
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Time (Year)
Scenario 0
Scenario 1
Scenario 9
Storage state
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
Time (Year)

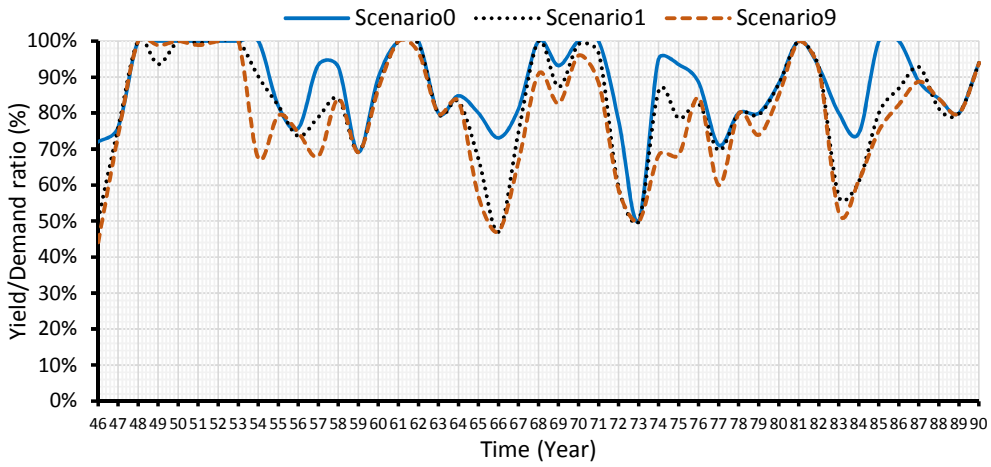
Appendix F:

Appendix F1: Yield/demand trajectories for individual reservoirs as affected by human behaviour (Elands River reservoir system)

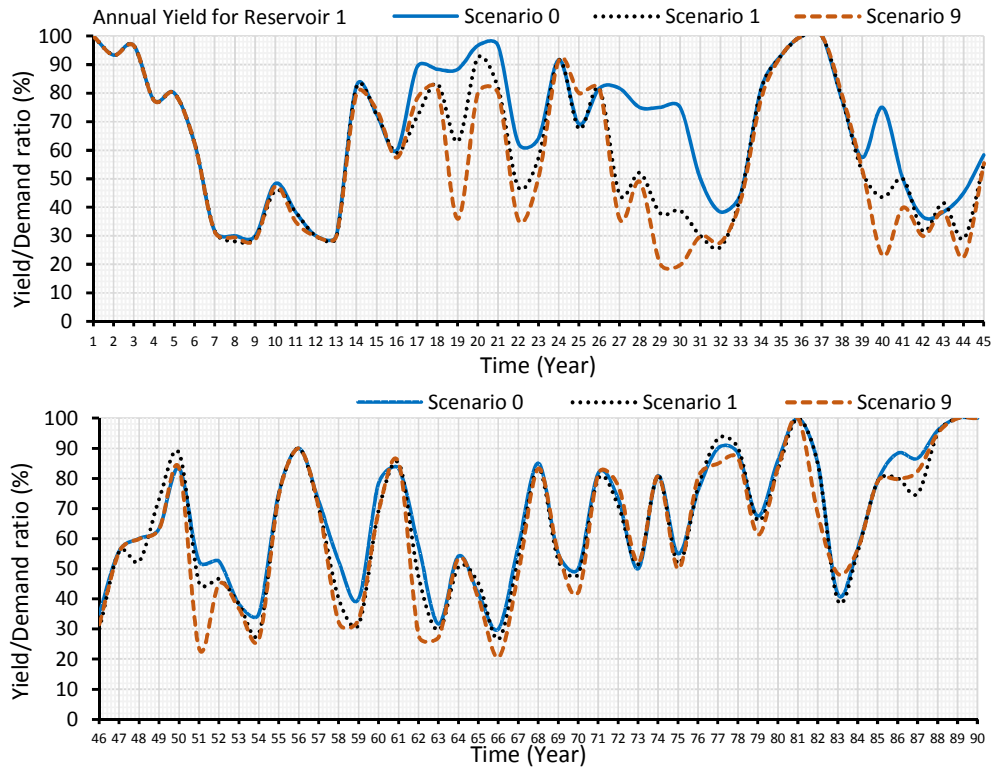


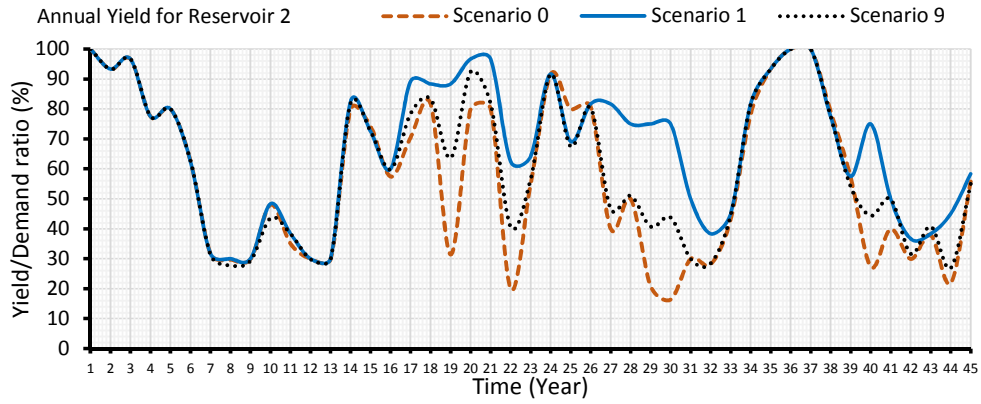


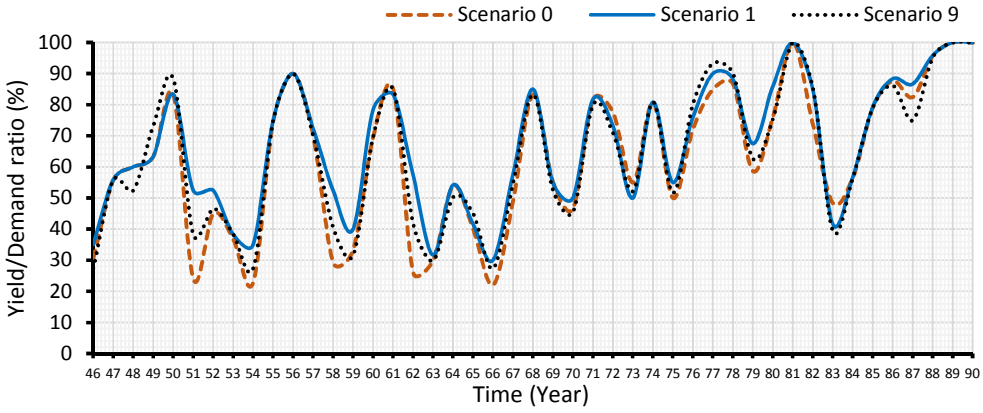


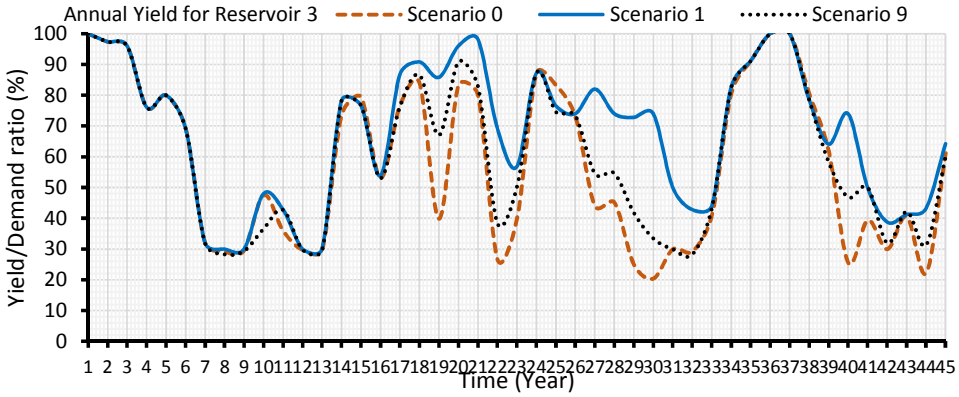


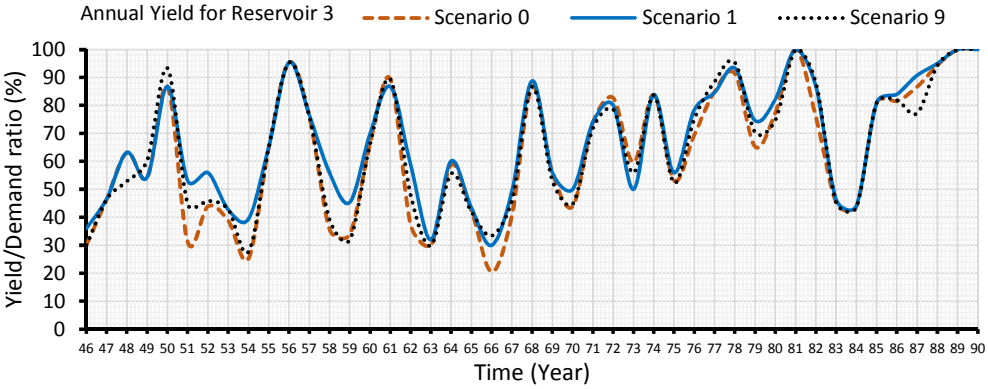
Appendix F2: Yield/demand trajectories for individual reservoirs as affected by human behaviour (Olifants River reservoir system).

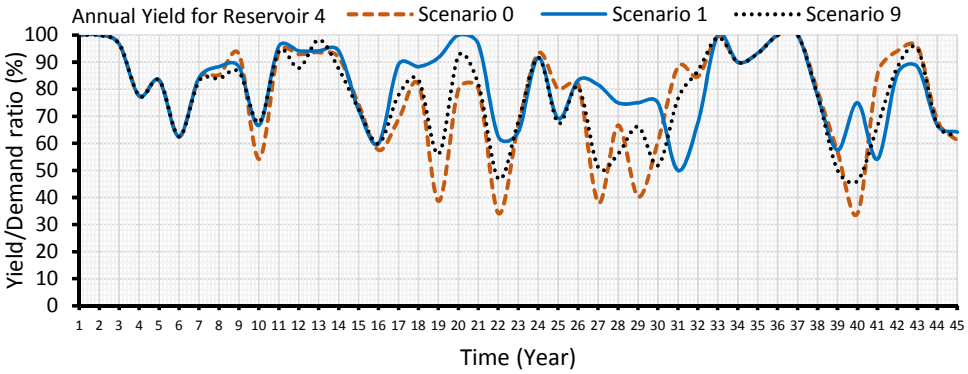


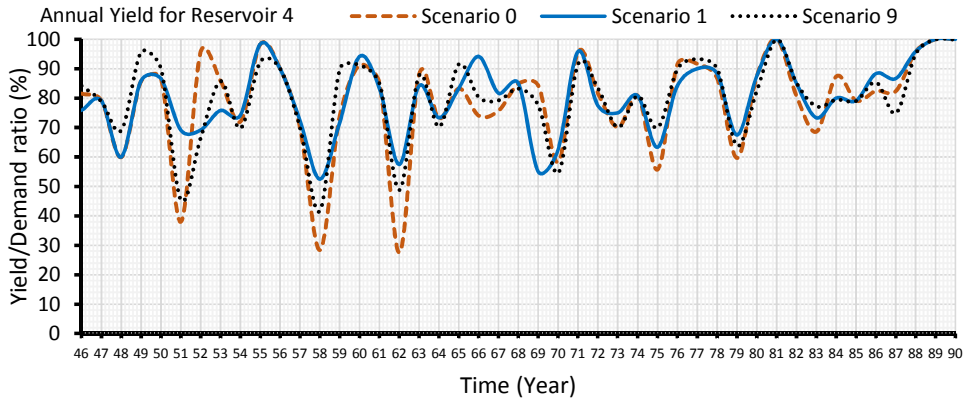

Annual Yield for Reservoir 2
Scenario 0
Scenario 1
Scenario 9
Yield/Demand ratio (%)
Time (Year)

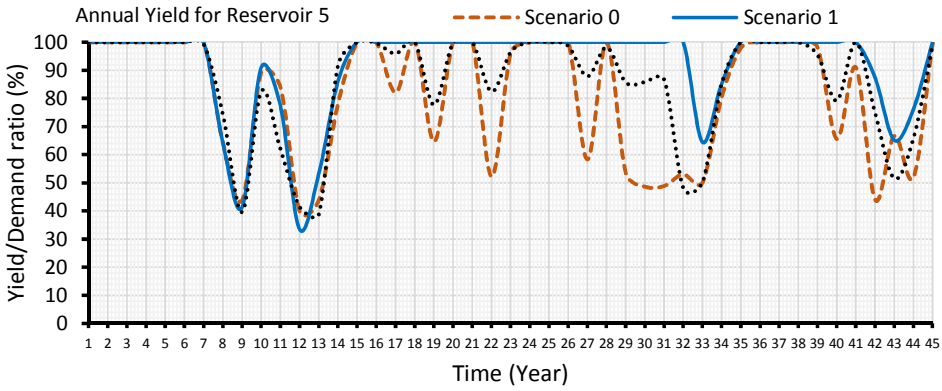

Scenario 0
Scenario 1
Scenario 9
Yield/Demand ratio (%)
Time (Year)

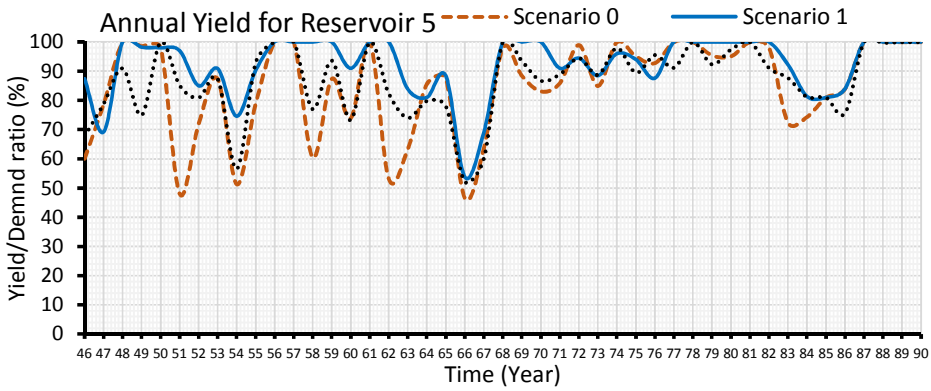

Annual Yield for Reservoir 3
Scenario 0
Scenario 1
Scenario 9
Yield/Demand ratio (%)
Time (Year)


Annual Yield for Reservoir 3
Scenario 0
Scenario 1
Scenario 9
Yield/Demand ratio (%)
Time (Year)


Annual Yield for Reservoir 4
Scenario 0
Scenario 1
Scenario 9
Yield/Demand ratio (%)
Time (Year)


Annual Yield for Reservoir 4
Scenario 0
Scenario 1
Scenario 9
Yield/Demand ratio (%)
Time (Year)


Annual Yield for Reservoir 5
Scenario 0
Scenario 1
Yield/Demand ratio (%)
Time (Year)


Annual Yield for Reservoir 5
Scenario 0
Scenario 1
Yield/Demnd ratio (%)
Time (Year)