

ECONOMIC OPTIMIZATION OF ASSURANCE IN STOCHASTIC YIELD ANALYSIS  
OF WATER RESOURCE SYSTEMS

BY

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## DECLARATION

I Chris Ndubi Nyadawa declare that '**Economic optimization of assurance in stochastic yield analysis of water resource systems**' is my own study, and covers no section copied in whole or in part from any source unless it is clearly acknowledged with detailed, complete, and precise referencing. Further, the study has not been submitted before for any degree or examination at any university.



..... (Signature)

...07/09/2023..... (Date)

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I wish to thank the Department of Water and Sanitation (DWS) for assistance in obtaining the Water Resources Yield Model (WRYM) and its required files. I wish to also extend my great thanks to all my friends and colleagues for the contribution they made in executing my work, and out mostly to Mr. Nkuna T.R, and Ndaedzo Nthulani.

## ABSTRACT

Allocation of water from South Africa's already straining water resources systems is a complex task given the ever-increasing water demand. The situation is made worse because of diminishing suitable sites for water resources infrastructure development, limited financial resources, and effects of climate change. To mitigate failure of water supply and ensure progressive water allocation, South Africa adopted a risk-based water allocation system in which it allocates water at different assurances of supply. Since assurance of supply is inversely proportional to yield, some water authorities tend to allocate water at relatively excessive high assurances of supply to mitigate total failure of water resources. This practice of allocating water at excessively high assurances of supply in turn reduces the amount of allocable water from the water resource. Consequently, the practice in turn results in either emerging users being denied access to water and/or lowly prioritised users being curtailed more early/frequently to satisfy the highly prioritised users. This study, therefore, examined prospects of optimizing existing water resources by specifically investigating the prospects of increasing the economic benefits from a water resource through reduction of its assurance of supply.

The study therefore conducted a comparative analysis on the Western Cape Water Supply System (WCWSS) to assess if the yield of the system could be increased for more economic benefits by either reducing the assurance of supply only or by adopting an infrastructural development. To achieve this objective, the study compared the net benefits derived from the Berg River Voelvlei Augmentation Scheme (BRVAS) infrastructural development project that would increase the yield of the WCWSS by  $23 \times 10^6 \text{ m}^3/\text{a}$ , and the net benefits that could be derived from an increase in yield due to reduction of assurance of supply by a margin that would result in a yield similar to that of the intended BRVAS infrastructural project. The second section determined incremental yields from Tzaneen Dam and their corresponding net economic benefits due to reduction of assurance of supply. The third section tested if the optimum assurance of supply of Tzaneen Dam was sensitive to other water resources systems characterized by different hydrological regimes. To conduct this sensitivity analysis, incremental yields and corresponding net benefits due reduction of assurance of supply from, Midmar, Goedertrouw, Mokolo and Boegeberg dams were determined.

The comparative analysis demonstrated that the yield of the WCWSS could also be increased by reducing the assurance of supply from the existing 1 in 50 years (1:50) to 1 in 30 years (1:30). It also demonstrated that adoption of reduction of assurance of supply as a method of increasing assurance of supply more economic benefits when compared to yield augmentation through infrastructural interventions as reduction of assurance of supply had a net benefit of R 96.2 x10<sup>6</sup> while the BRVAS infrastructural intervention had a net benefit of R 15.5 x10<sup>6</sup>. Results established that Tzaneen Dam could be optimised at 1:18 assurance of supply. It was therefore concluded that not all reductions of the assurance of supply result in an incremental increase of the net benefits. Results from the sensitivity analysis revealed that each water resources system is unique as different water resources used in the sensitivity analysis, Midmar, Goedertrouw, Mokolo and Boegeberg Dams had their optimum assurances of supply at 1:12, 1:12, 1:8 and 1:10 levels, respectively.

Both the comparative analysis and the sensitivity analyses acknowledge the role played by water availability in socio-economic development, however, for ease of analysis due to challenges of quantifying contribution due to sufficient or insufficient water, the socio-economic aspect was not included in the analysis. Overall, the study highlighted that the economic benefits of a water resource may be optimized by reducing the assurance of supply up to a certain level. The study therefore recommended that this practice should also be considered as an alternative method of increasing water availability from a system.

**Keywords:** Assurance of supply, risk-based water allocation, risk of failure, water allocation, water resources, yield, economic optimization.

## DEDICATION

This thesis is dedicated to:

- My beloved parents for their continued prayers and encouragement during the study.
- My Uncle Wycliffe Muaka who had always insisted on the importance of education but passed on before completion of this study.

## ABBREVIATIONS

BCR:	Benefits Cost Ratio
BRC:	Berg River Catchment
BRVAS:	Berg River Voelvlei Augmentation scheme
CCT:	City of Cape Town
DM:	Demand Management
DWAF:	Department of Water Affairs and Forestry
DWS:	Department of Water and Sanitation
GDP:	Gross Domestic Product
GVA:	Gross Value Added
IRR:	Internal Rate of Return
LCCA:	Life Cycle Cost Analysis
LYRC:	Long-term yield reliability curve
MAP:	Mean Annual Precipitation
MAR:	Mean Annual Run-off
NPV:	Net Present Value
ORASECOM:	Orange-Senqu River Commission
SANCOLD:	South African National Committee on Large Dams
SAWIS:	South African Wine Industry Information and Systems
TCTA:	Trans-Caledon Tunnel Authority
TIPS:	Trade and Industrial Policy Strategies
WC:	Water Conservation
WCWSS:	Western Cape Water Supply System
WMA:	Water Management Area
WRYM:	Water Resources Yield Model
YRC:	Yield reliability curves

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## CHAPTER 1: INTRODUCTION

### 1.1 Background

Sustainable supply of water is important for South Africa to achieve assured social and economic development as water is a basic requirement for life. Globally, South Africa is ranked as the 30<sup>th</sup> driest country, with a mean annual rainfall of about 480 mm when compared to the global mean of 860 mm. In South Africa, rainfall variability is significant both spatially and temporarily, generally decreasing westwards from the east. Hence, although countrywide precipitation averages may serve some purpose, it has very little meaning in instances where the local rainfall amounts are significantly different from the national average. Furthermore, water security itself is a function of drought recurrences and whether water use, regulation and management are done properly or not (Martinez-Ibarra, 2015). Despite being a water-scarce country, South Africa's consumption is around 233 l/c/d, compared to the international benchmark of around 180 l/c/d (DWS 2017).

With South Africa being a developing country and therefore characterized by rapid population and socio-economic development, its water resources cannot match up with its ever-growing water demand. Therefore, to mitigate the catastrophic failure of its strategic water demands, South Africa adopted a risk-based water allocation plan in which it allocates its water resources at a 98% or higher assurance of supply for some water demands. However, even with the existing water resources management and allocation measures, the task of reconciling South Africa's water requirement with its water availability remains a daunting task that cannot be addressed by infrastructural interventions only as will be elaborated in the succeeding chapter.

From the aforementioned, it can therefore be seen that South Africa has a notable water scarcity problem that is compounded by the limited resource being also highly variable. Hence, besides its volumetric availability, its measure of assurance of supply is equally significant for consideration in its management requirements. Generally, water resource systems have definite relationships between their yield amounts and assurances of supply. The relationships show that a reduction in the assurances of supply will result in a corresponding increase in the yield of the system. In view of

South Africa's water scarcity problem as outlined above, it is hoped that instead of considering the volumetric measure of water resources alone, consideration of the other dimension of reliability can bring some prospects of increasing their water availability. This study will therefore explore this prospect, together with appropriate water resources engineering economics, with the aim of presenting an alternative option of increasing water availability for progressive and efficient water resource allocation from a given system.

## 1.2 Problem statement

In 2007, the Department of Water Affairs and Forestry (DWAF) observed that water demands of the Western Cape Water Supply System (WCWSS) would surpass its water availability at the required assurance of supply by the year 2019. The DWAF, therefore, came up with several development interventions that would augment the yield of the system to ensure water availability for the growing demand. However, it is important to note that although the water demand of the system started surpassing its yield in 2018, the first intervention, the construction of the Berg River Voelplei augmentation scheme (BRVAS) project to correct the imbalance problem was not yet in place by 2022. It may therefore be hypothesised that the 2016 to 2018 drought and the probability of a "Day Zero" can be attributed to failure of correcting the imbalance. It is also worthwhile to note that this problem of negative water imbalance is not unique to WCWSS alone, but widespread across the country. This is why it is necessary to explore the possibility of other ways of sharing water resources in existing systems without jeopardizing the overall economic benefits of the system.

In addition to numerous challenges of equitable and sustainable water allocation, reliable water supply at an acceptable quality and quantity that is not detrimental to the health of people and their livelihoods, social and economic development is essential for the future of South Africa. Stressed water resources are increasing because of erratic rainfall patterns and the ever-increasing demand for water. Taking the Luvuvhu River Catchment in northern South Africa, for example, the catchment is experiencing growth in population, urbanization, irrigation, and negative effects of climate change. The growth comes with an escalated need for more water, and hence its state of water availability continues to deteriorate (Maré *et al.*, 2007).

To mitigate catastrophic failure of water resources, South Africa uses a risk-based water allocation strategy whereby water is allocated at an assurance of supply (reliability). Additionally, to ensure that the demands of certain sectors (high priority sectors) are met almost all the time, water is normally supplied to different sectors at different assurances of supply. For example, the agricultural sector is generally allocated water at a lower assurance of supply as compared to the industrial sector. This means that in the process of imposing restrictions, the industrial sector will only experience restrictions after severe restrictions have been imposed on the agricultural sector. Given the inverse relationship between volume and assurance of supply/reliability of a water resource system, some water resource managers and relevant water authorities resort to allocating water resources at very high assurances of supply, the resultant effect is a limited volume of water for allocation from the system. It is because of such strategies that some water resource systems are “artificially strained” without the capacity to accommodate new emerging users.

Although this practice may seem to be a biased and unfair way of allocating water because the industrial sector is more guaranteed of its water allocation while the agricultural sector is experiencing frequent curtailments, at a national level this can be justified. Considering the variability of water availability from season to season, curtailments based on proper operating rules have been tested and proven to be necessary practices for managing water resources to facilitate equitable and sustainable allocation of water during drought periods.

Sharing of water resources is complex and dynamic as it involves both technological and socio-economic considerations like, among others, the yield of the resource, its reliability, usage scheduling or operating rules and infrastructural configuration, which keep changing with time. There are strategies that have been devised for progressive water allocation, however, they have been mostly focused on development of more infrastructural capacities to ensure that sufficient amounts of water with associated ample assurances of supply are maintained for the already allocated users. In this approach, when development of more resource capacity has been found to be lagging behind the growing demand, stressed resources (also referred to as closed or fully allocated systems) have been exclusively preserved for the privileged existing allotted

users only. In this situation, it is only during dry periods with extended intensity (drought), when water shortage is experienced that operating restriction rules are applied to curtail some usage to ensure sustainable and equitable water sharing among the existing allottees. However, the limitation of operating systems at such a relatively high assurance of supply is that during relatively good rainfall years, water losses are experienced from the systems through spillage. This spillage represents water that could have been used to accommodate emerging users into the system or even existing users who had been denied access because the system seemed “strained”.

Besides, such ample assurance of supply allocation is not consistent with the consensus that South Africa has a water scarcity problem. It also does not promote the policy of water use efficiency or the principle of “*some water for all*”. It instead seems to be promoting water hoarding for those that already have access to the resource. For instance, Eskom, the national power generation utility of South Africa, and therefore a significant water user in the country, gets its water allocation at a 1:200 assurance of supply (DWS, 2018). But by comparing, this significantly high reliability is not consistent with observed reliability levels of Eskom’s own assets like facilities’ lifespans and maintenance schedules.

The tendency to allocate water at relatively high assurance of supply is not only seen as a form of water hoarding but also as a practice that is insensitive to equitable water allocation among its people. Unlike water resources of a country, which are relatively finite, demand for water especially in developing countries, continues to grow relatively much faster than the development of the country’s water resource capacity. In South Africa, the challenge is compounded by the legacy of past policies not having been focused on equitable water allocation sharing. In the past, water was still relatively plentiful and therefore other considerations were more important than water resources availability analysis and sharing. Then, there was no need for a formal water allocation license to access water resources. In present circumstances that is not the case as water is now physically limited such that prior water availability analysis is now a prerequisite for proper management of water resources allocation licensing.

### **1.3 Research questions**

Considering the inter-dependence of water availability, assurance of supply, growing demand, and associated economics of a water resource system, some research questions that emerged include:

- i. Other than conventional infrastructural development interventions to increase the availability of water in a given system, can its yield be increased by reducing its assurance of supply without jeopardising the resultant economic productivity of the water resource system?
- ii. Other than the opportunity cost, capital costs and operation and maintenance costs, are there other costs associated with allocating water at a specific assurance of supply? How does economic productivity relate to decreasing assurance of supply of a given water resource system?
- iii. Is the relationship between the economic productivity and assurance of supply sensitive to the hydrologic regime of the given water resource system?

Related to these research questions a hypothesis was conceived for further analysis in search of improved water resource allocation especially, for a developing country with high growth in water demand relative to its fresh-water resources.

### **1.4 Hypothesis**

It is hypothesized that through well-calculated reductions of assurance of supply of a given water resource system its yield can be increased to some optimal level for progressive and more efficient water allocation that would improve its economic productivity.

### **1.5 Objectives of the study**

The overall objective of this study is to develop an alternative framework for availing additional water on a given resource system with growing demand for progressive water allocation.

### **1.5.1 Specific objectives**

The specific objectives include:

- (i) To undertake water resources engineering economic analysis to compare and contrast economic benefits due to additional water emanating from increased system yields of two interventions with the first one based on conventional infrastructural development, and another based on reduced assurance of supply of the same water resource system.
- (ii) To determine incremental yield amounts due to decreasing assurance of supply and the corresponding change in economic benefits of a given water resource system in to test the hypothesis in section 1.4.
- (iii) To test if the optimal assurance of supply in (ii) above is sensitive to hydrological regimes of other water resource systems.

### **1.6 Motivation of the study**

Over the years, South Africa has been endeavoring to increase its water availability through various interventions to meet its ever-increasing water demands. The conventional intervention used to increase water availability is increasing the country's water storage infrastructures. In line with this, the Department of Water and Sanitation (DWS) has annually set aside a budget to facilitate augmentation of the country's water availability. However, its efforts have not always met the desired targets of reconciling water requirements with availability in its water resources. Failure to achieve these targets can be attributed to budgetary limitations and the fact that capital projects take long to be completed while water demand keeps growing on a continuous basis.

Notwithstanding these challenges, numerous studies have shown that water demand will keep increasing over time. For instance, a DWAF (2007), water reconciliation study observed that the WCWSS's water requirement would exceed its water availability, at the required reliability, in the year 2019. A study conducted by Pengelly et al. (2017) also observed that despite grape farms in the Berg River catchment already consuming 79% of the catchment's irrigation water, regional climate changes will

increase the farms' water requirements by an additional 34% of its present use by the year 2040. It is because of such challenges that there is a need to devise other ways of increasing water availability to cater to ever-emerging water requirements in the country.

Water as a resource has also been realized to have properties whereby its volume can be expanded to some degree when its assurance of supply is reduced by some margin (Maré *et al.*, 2007). It can therefore be expected that by careful manipulation of the assurance of supply of a water resource system, more water can be made available albeit at a reduced assurance of supply. In line with this, it is hypothesized here that by considering both the volumetric and reliability features of water resources systems, a more progressive alternative for equitable and efficient water allocation strategy can be achieved.

The strategy to “expand” water availability through carefully reduced reliability of a given water resource system to accommodate additional demands for emerging users, together with appropriate operating rules will also inevitably promote better water use efficiency. This is because the system will be operating at a relatively lower assurance supply and therefore adherence to operating rules will have to be a prerequisite to avoid total system failures.

## **1.7 Overview of the Dissertation**

The dissertation is comprised of six chapters. The first chapter is the introduction. It provides the background of the study, problem statements, research questions, hypothesis and the objective of the study. This chapter also highlights the motivation behind the study and a general overview of the dissertation. In the second chapter, an extensive literature review is provided, with the aim of highlighting water resources management and allocation in South Africa and also showing the dire need of coming up with new ways of increasing water availability other than the conventional infrastructural approach.

Chapter 3 presents a water resources engineering methodology that aims to assess the prospects of increasing water availability of a water resource through reduction of

its assurance of supply. It additionally assessed the prospects of optimising existing water resources by assessing the cost associated with allocation of water at a specific assurance of supply. Chapter 4 provides a detailed analysis of the results. Chapter 5 presents the discussions emanating from the results and is structured to answer the research questions in chapter 1. Chapter 5 also provides the conclusions deduced from the study. Lastly, a list of references and appendices are provided at the end of the dissertation.

## CHAPTER 2: LITERATURE REVIEW

### 2.1 Water scarcity in South Africa

Water scarcity could be viewed in two ways. The first one being physical water scarcity, in which the actual problem is the lack of water because of climatic and other environmental issues. The second scarcity is economic water scarcity, which relates to the fact that there is water, but economic factors hinder access to water or further good quality water (Rocha *et al.*, 2015). Gude (2017), stated that whereas a large part of southern Africa faces physical water scarcity, it was also facing economic water scarcity stemming from inadequate financial and human capital needed to counter water scarcity. Unlike many developing countries in the world, South Africa's physical and economic water scarcity can be attributed to its unique hydrological patterns that are characterized by low average annual precipitation and the unevenness of its distribution. Its geographical and climatic attributes lead to only 8.6% of rainfall being converted to run-off, the lowest proportion in the world (Molobela *et al.*, 2011).

Based on population and economic growth projections, annual water demand in South Africa is estimated to reach 17.7 billion m<sup>3</sup> by 2030. This means that South Africa could have a 17% gap between supply and demand by 2030 (Young *et al.*, 2015). Young *et al.* (2015) also noted that depending on South Africa's investment in new water supply systems, if the development trends, business expansion, and population growth continue at the present rate, a 1 to 3 billion cubic meters deficit or a 7 to 22% of water deficit per year would be experienced by 2030. From the two studies, it can be acknowledged that in every development initiative, consideration of water scarcity as a major cross-cutting vulnerability is a reality.

By around 2017 it had been estimated that South Africa was required to invest R90 billion annually to facilitate water and sanitation infrastructure development over a period of ten years (DWS, 2017). This budget estimate included the construction of new infrastructure while refurbishing and upgrading the existing ones to support population and economic growth. However, with an accounted funding of only R56.6 billion in 2017, there are significant deficits in the funds budgeted for infrastructure development within the public sector as shown in Figure 2.1 (DWS, 2017).

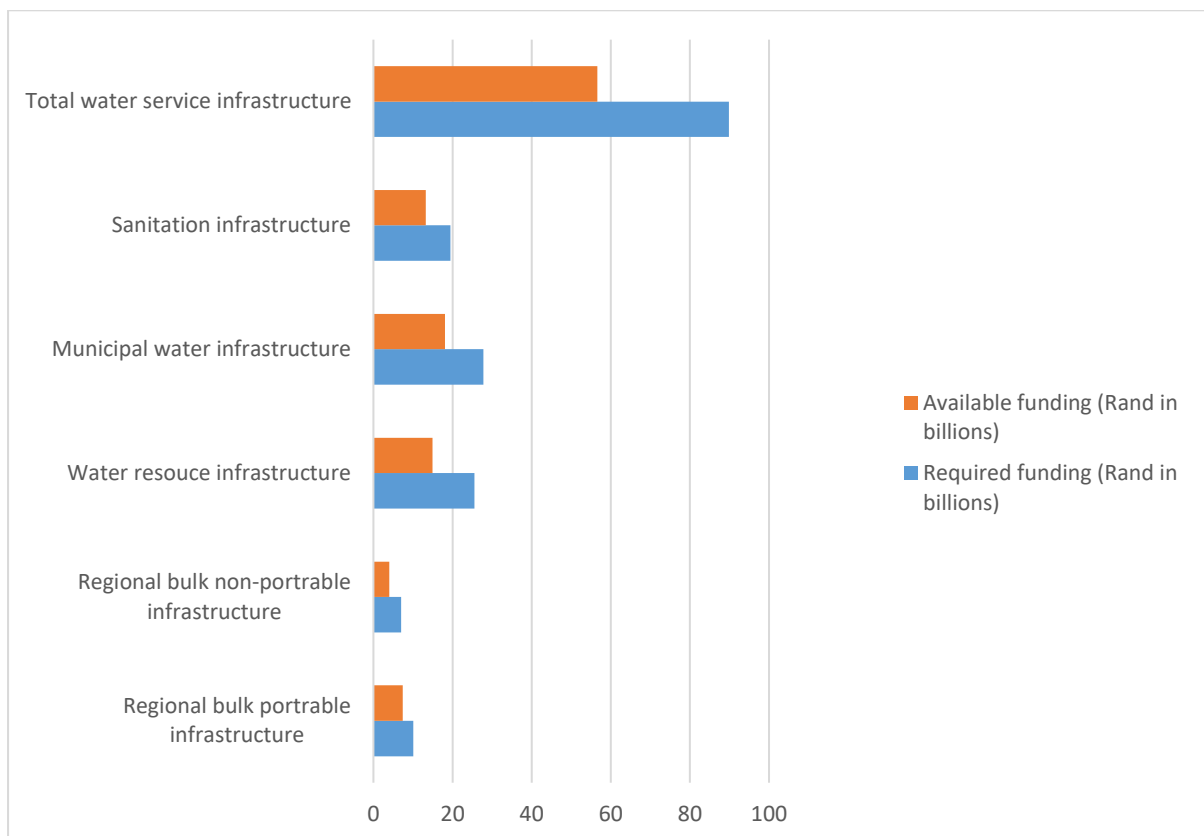


Figure 2.1: Required and available public sector funding for water services infrastructure in 2017 (Source: DWS, 2017).

South Africa is already dependent on large-scale inter-regional water transfers and seems set to become more so. With the possibility that regions will become more autonomous in the future, there is a dire need to come up with better and more efficient measures and policies for managing the limited water resources and thus ensure water security.

## 2.2 Evolution of water resources management

South Africa has a notable water scarcity problem, which is compounded by the high variability of the limited resource (DWS, 2017). Hence, besides its volumetric availability, its measure of assurance of supply is equally of significance when the various challenges encountered at different phases of water resources management and allocations are considered. Generally, water resource management can be categorized into three phases judging from the main challenges faced (See Table 2.1).

The first one is the "natural phase" (Table 2.1), when water resources, relative to demand, were still plentiful such that there was no need for legislation. Here, there was no limit on the amount of abstraction. The second one was the "development phase" when demand became higher than the natural yield. Therefore, the development of infrastructures like dams, pumps, and pipelines amongst others, to increase system yield to meet the growing demand, and legislation to regulate the constructions, operations, and maintenance of the schemes characterised the management of water resources systems. Here, water features as an economic good, policies are necessary for raising funds, and regulating water supply is prioritized according to users' funding capacities and contributions.

Table 2.1: A summary of the three generic phases of evolution of water resources management and some of their associated main management challenges (DWS, 2019)

<b>Natural phase</b>	<b>Development phase</b>	<b>Allocation phase</b>
Water is not limited.	Water is limited only economically.	Water is totally limited physically.
Water management institutions are not necessary	Organizations dominated by technical management to serve largely the infrastructural water schemes from the top.	Institutional arrangement requiring stakeholder participation.
Data is not important.	Data is necessary mostly for sizing infrastructure development.	Data needed mostly for equitable allocation of water as well as for sizing infrastructure developments.
No water scheme to be managed.	Infrastructure scheme development to be managed	The whole river system including catchment and scheme's infrastructure to be managed
Not much linkage to groundwater and/or other resources.	Groundwater is employed to supplement surface water.	Water resources are used conjunctively, including other water source mixes.

In South Africa, the Water Act of 1956 was developed during the development phase, when development in terms of reservoir storage capacity was still increasing notably

towards the current capacity of about 32 billion m<sup>3</sup> (Figure 2.2). In the third phase of “water allocation”, the growth in water demand has greatly and is still increasing whilst the potential for development to increase system yield is significantly limited. Here, water is now physically limited and the water resource systems are now characterized by challenges of equitable allocation and inter-sectoral conflicts. Policies seeking to promote water allocation, even to the environment, are now dominant in the present National Water Act, unlike in previous legislations.

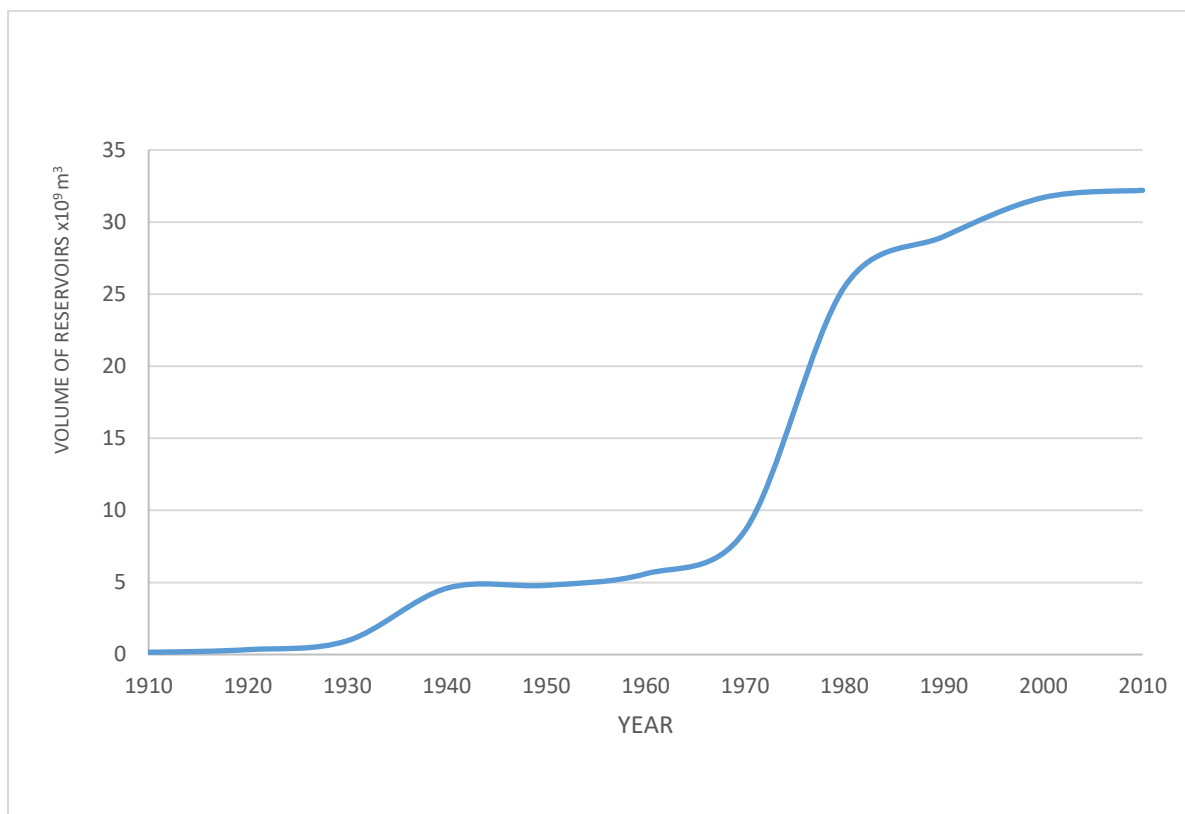


Figure 2.2: Trends of water resources development in terms of storage capacity in South Africa (Source: SANCOLD, 2020).

From Figure 2.2, it can be noticed that the main challenge of advancing water resources management in South Africa has now passed the first two phases of natural and infrastructure development and has now reached the ultimate third phase of water resources allocation. Consequently, more elaborate systems and operating policies to manage water reconciliation of increasing water demand competitiveness, and expanded system configuration complexity is required (Makungo *et al.*, 2009).

### 2.3 Applying yield analysis in water resources allocation

Yield analysis is typically applied to calculate the water volume (target draft) that can be stored for allocation to a specific demand at a desired assurance of supply (or reliability). Basson *et al.* (1994) stated that yield analysis is the process of evaluating the ability of a water resource system to supply water for a given period when subjected to a certain set of circumstances. The yield of a system can therefore be defined as the volume of water that can be allocated over a certain period (normally a year) at a specified assurance of supply. Reliability offers a measure of certainty that a given yield can be met without failure. In this context, failure is regarded as being when the full target amount of water cannot be abstracted from the system.

Reliability uses the concept of recurrence interval to quantify the risk of failure. A 2% risk of failure in any one year corresponds to a recurrence interval of one failure in every 50 years (Basson *et al.*, 1994). The risk of failure is calculated using Equation 2.1.

$$R = \frac{1}{RI} \quad (2.1)$$

Where  $R$  = Annual risk of failure

$RI$  = Recurrence interval of failure

The annual risk is also expressed as 1:  $RI$ , read as one in  $RI$  years.

The annual reliability is then calculated by subtracting the annual risk of failure from the probability of meeting all the demands, which in prospect is equivalent to one. Therefore, the annual reliability is calculated using Equation 2.2.

$$r = 1 - \frac{1}{RI} \quad (2.2)$$

Where  $r$  = Annual reliability of supply

With equations 2.1 and 2.2, the long-term risk of failure which is closely related to the annual risk of failure can be computed using equation 2.3.

$$R_n = 1 - (1 - 1/RI)^n \quad 2.3$$

Where  $R_n$  = long-term risk of failure  
 $n$  = planning time in years

In the process of allocating water, the typical reliabilities associated with systems/reservoirs in South Africa are 90%, 95%, 98%, 99%, 99.5% or, risks of 1 in 10, 1 in 20, 1 in 50, 1 in 100, and 1 in 200, respectively. Assessment of reliability is done by mimicking historically observed sequences by generated artificial sets of operational hydrology. Thereafter, yield reliability relationships are demonstrated by yield-reliability curves, which are basically flow duration curves of the system. The curves tend to show the exceedance probability (reliability or assurance of supply) of base yields against target drafts of the system (Figure 2.3). Base yield is the lowest yield recorded from a water resource system that is attempting to satisfy a target draft with a specified temporal demand pattern, and under a specific operating policy. Firm yield is the maximum base yield that can be abstracted from a water resource.

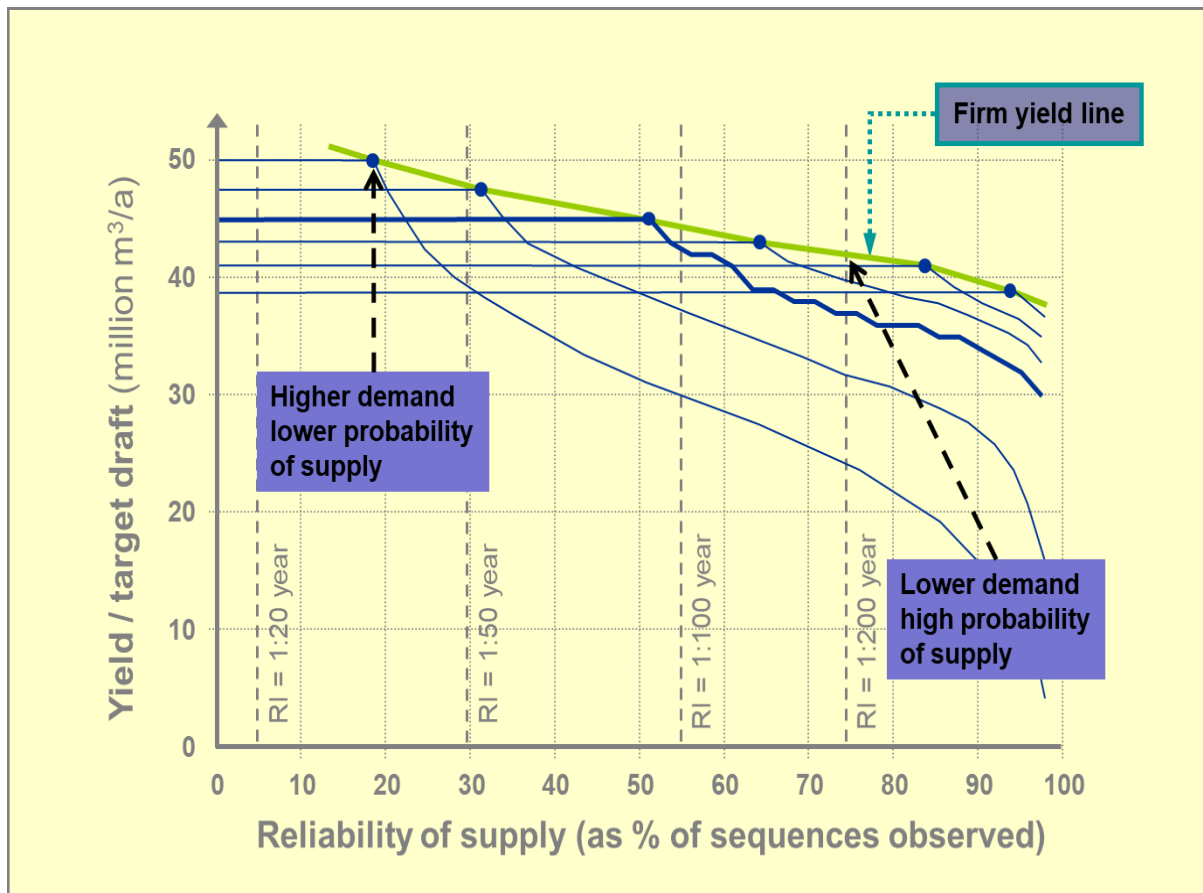


Figure 2.3: Typical yield-reliability characteristics curves (DWS, 2019)

From typical yield-reliability characteristics curves (Figure 2.3), allocable water availability at various required levels of assurance of supply can be derived based on the firm yield curve as exemplified in Table 2.2. As shown in the table the yield keeps decreasing as the reliability of supply increases, implying that the yield is inversely proportional to the reliability of supply.

Table 2.2: Water availability at various assurances of supply – based on Figure 2.3

Assurance of Supply	1:20	1:50	1:100	1:200
Yield ( $\times 10^6 \text{ m}^3/\text{a}$ )	60	48	46	43

## 2.4 Water allocation in South Africa

It is only through critical analysis of the system behavior in the short and long terms with storage draft rules using many inflow sequences that an assessment of inherent variability of the system's yield performance can be ascertained (Quibell *et al.*, 2012).

Regarding long-term and short-term yield analysis, water allocation can be viewed in two stages. The first one, long-term or licensed water allocation, is achieved through licensing processes which are based on long-term average yield based on many years (Basson *et al.*, 1994). In South Africa, it is applied to give the upper limit of water availability that can be allocated/licensed to users' dependent on the system. The second one, short-term or operational allocation, is achieved by undertaking annual operating analyses which are based on the understanding that water is an annually renewable resource, whose hydrology or water availability also varies annually (Basson *et al.*, 1994; Maré *et al.*, 2007). However, consideration of the two allocations should be aligned to ensure that the water resource system is utilized to maximize economic benefits.

Even though water allocation has always been a globally challenging task since the start of the "allocation phase" (Table 2.1), South Africa's water allocation process is even more complex due to its unique past non-inclusive policies, compounded by its highly variable hydrological systems. Spatially, almost two-thirds of the country is semi-arid. More precisely, apart from the eastern part of the country, the rest receives an annual rainfall of below 500 mm/annum compared to a world average of 860 mm/annum (Dennis *et al.*, 2012). Temporally, most parts of South Africa have the rainy season only in summer (November to March). Additionally, South Africa is heavily reliant on its surface water for its allocations. This is because of its short duration, torrential rains that are accompanied by high evaporation rates and hence resulting in poor groundwater recharge (Konikow and Kendy, 2005).

The twentieth century has been characterised by numerous circumstances that have resulted in a further complication of water allocation processes. These circumstances include:

- Increasing water demands due to emergence of transformative constitutionalism that allow all its people to participate equitably in economic activities of the country.
- Social and economic growths whose patterns keep changing.
- Changing socio-economic and environmental rules and hence water use patterns

- Diminishing/Lack of suitable sites for water infrastructure developments.
- Climate change.

With the increasing water shortage globally, water allocation plans and agreements have taken a significant role in resolving inter-regional and inter-sectoral conflicts over access to water (Quibell *et al.*, 2012). Although water allocation approaches and objectives have evolved over time, the core objectives of water resources allocation process have fundamentally remained to be:

- Balancing supply and demand: Such practises entail ensuring that there is an equilibrium between water availability and water demand as the excessiveness of either demand or supply has detrimental impacts.
- Equity: This involves allocating water in a manner that is impartial amongst different individuals as well as different sectors of the economy. It can also include equity between upstream and downstream users or different catchments/basins.
- Protection of the environment: water allocation in a manner that recognizes the existence of freshwater-dependent ecosystems and allows for the protection of significant freshwater services such as groundwater recharge, waste-water assimilation, estuarine functioning, and sediment transportation.
- Development priorities: water should be allocated in a manner that promotes and supports economic development. This can include supporting strategic priorities and protecting existing dependencies.
- Promoting efficient use of water in a manner that upholds the most efficient use of available water.

Generally, reservoirs are meant to increase the reliability of water supply systems. This in turn leads to a reduction in vulnerability to drought, resulting in increased industrial and agricultural productivity, and better livelihoods. South Africa has a yield (supply from existing infrastructure) of approximately 15 billion m<sup>3</sup>/year at a 98% reliability – or 2% annual risk of supply failure. A large volume of this yield, 68% is from surface water, though groundwater and return flows are also used to support surface water as shown in Figure 2.4 (DWS 2017a).

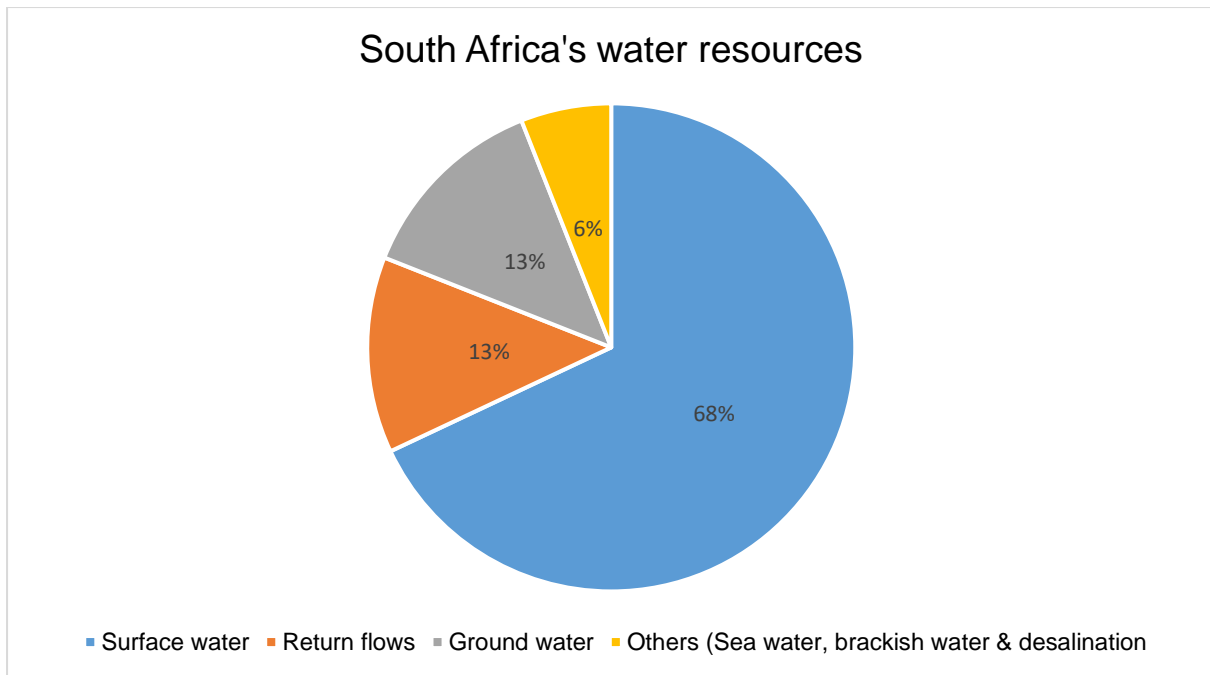


Figure 2.4: Types of South Africa's water resources (Source: DWS, 2017).

Despite South Africa's current water use of around 15-16 billion m<sup>3</sup>/a, water demand still surpasses the reliable yield (DWS 2017a). This essentially implies that for water supply sources to meet these increasing demands, the reliability of supply systems will have to drop to below 98% assurance of supply, meaning that the annual risk of failure will increase to over 2%. Approximately one-third of South Africa's water allocation is meant for urban use (industrial, commercial, and residential use), while the remainder is allocated to the agriculture sector, which is mostly used in the summer months, as demonstrated in Figure 2.5 (DWS 2015).

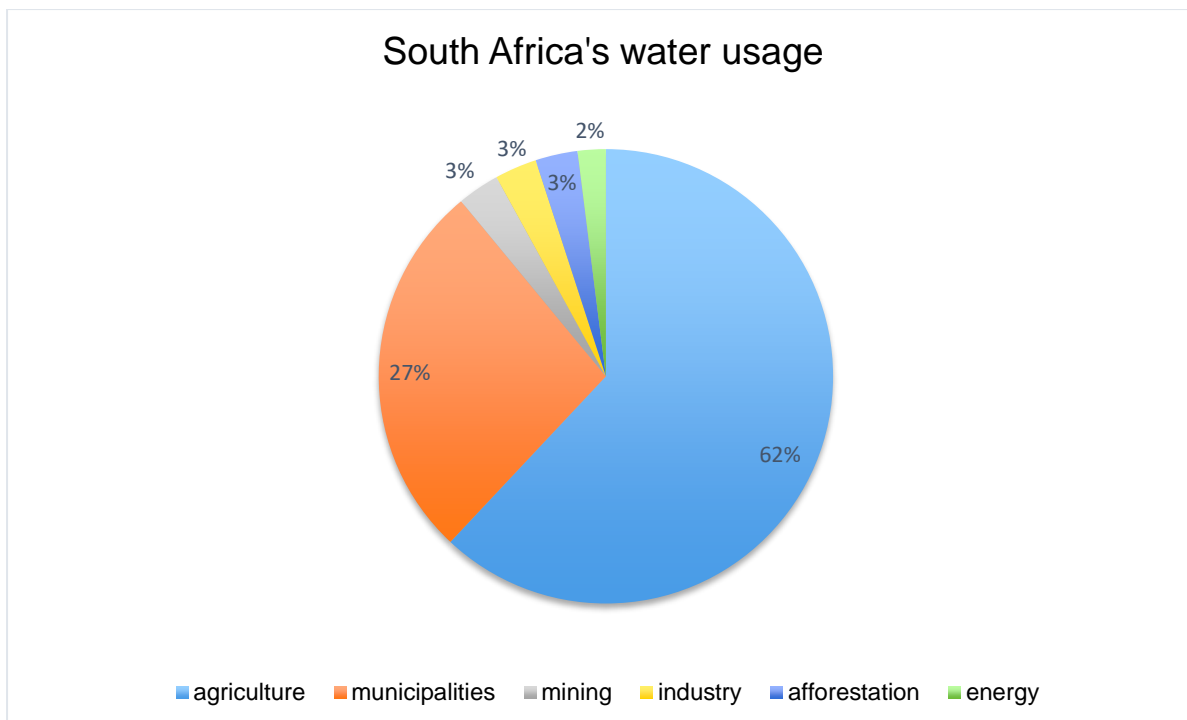


Figure 2.5: Water use sectors of South Africa (Source: DWS, 2015).

Unless otherwise, licensed water allocation is once-off. However, the allocation of water amidst South Africa's seasonal and inter-annual variations in rainfall, which are amplified by high run-off production and evaporation rates, is always a big challenge. Hence, this is the reason for the country's heavy dependency on water resources operating rules/policies to ensure it meets its water demands without failing its water resources systems.

Johnson (1993) noted that operating policies were statements that help water resource managers and operators schedule water abstraction from a given water resource at a given period, with the element of equity and sustainability being the main objective. Operating rules/policies are, simply, policy instruments that may be applied to define operating procedures that need to be implemented in cases where conditions are conflicted or complex. Ideally, during planning stages, the modest but hierarchical operating policies are preferred (Maré *et al.*, 2007). An operating rule can also be defined as a governing procedure for regulating a water resource system to reconcile water requirements with availability. It is therefore based on the prevailing hydrology, infrastructural setup, and user requirement patterns, among others.

With the stochastic nature of hydrological events, it is not possible to come up with a water resource system that can satisfy all demands of various sectors at all times (Basson *et al.*, 1994). This means that the users cannot be supplied 100% of their water demand 100% of the time. Occasionally, there will be shortfalls as a result of various factors such as drought and high temperatures. If shortfalls are regular, then the supply is said to have a high risk of failure (low assurance of supply) whereas if the shortfalls are rare the supply indicates a low risk of failure and therefore a high assurance of supply.

#### **2.4.1 Water restrictions as a water management strategy**

Supply restrictions are considered to be among the ideal management methods that are available for use by operators given the stochastic nature of river flow conditions in South Africa (Quibell *et al.*, 2012; Haque *et al.*, 2013). Since water is an annually renewable resource, its operating policies are essential for use on an annual basis, and with water being a scant resource, the operating policies have to be scientifically verifiable but simple for stress-free use by operators of water resources systems (Maré *et al.*, 2007). The restriction rule is necessary to allow operators to easily ascertain the required curtailment volumes and quickly impose the necessary priority restrictions on the various water sectors during drought. Operating rules involve monitoring of the systems as a way of aiding the assessment of performance of the reservoirs in terms of storage levels of water in the reservoirs and trigger the commencement of restrictions (Basson *et al.*, 1994).

During drought periods, demand for water exceeds the supplying resource availability. This can lead to an abstraction regime in which the reservoir is at risk of total failure (Ndiritu *et al.*, 2011). This results in the need to impose appropriate restrictions/curtailments. Water restrictions policies achieve their goals relatively well in developed countries because of their already established infrastructures and steady population situations. However, this is not necessarily the case for developing countries. Developing countries like South Africa exhibit growing socio-economic capacities, increasing populations, and improving standards of living that are relatively higher when compared against a limited scope of development of water resources capacities.

Therefore, water shortages in developed countries occur mostly as temporary incidences, coming only during dry or drought periods. Under these circumstances water restriction rules, though inconveniencing, are welcomed and complied with by users as instruments for managing the temporarily limited resource. But in developing countries, however, besides the temporary shortages due to drought, water shortage also comes as a permanent feature, relatively, because of developments in system yield capacity lagging behind growth in the demand imposed on the resource system as demonstrated by the water reconciliation situation on the Western Cape Water Supply System (WCWSS) that supplies the City of Cape Town in Figure 2.6. The figure shows water demand projections until 2030 – without water conservation and demand management (WC&DM) for the upper curve and with successful WC&DM for the lower curve. Without WC&DM, water demand surpassed availability in 2012, while with successful WC&DM, the demand was surpassed in 2020 (DWAF, 2007). However, implementation of the next intervention to increase water availability (the Voelvlei Phase1) is yet to commence as of 2022. Under these conditions, water shortages in the WCWSS are not likely to happen during drought situations alone but are expected to happen regularly as demand is on average more than the system's yield capacity.

Hence, under such conditions, water resources management authorities are faced with the challenge of deciding whether to:

1. Continue allocation of water to new/emerging demands and in the process lower the assurance of supply of the system with associated more frequent restrictions.
2. Cap any further water allocation from the system to preserve the assurance of supply of existing water users.

To make this decision, some economic considerations may have to be undertaken to justify the choice.

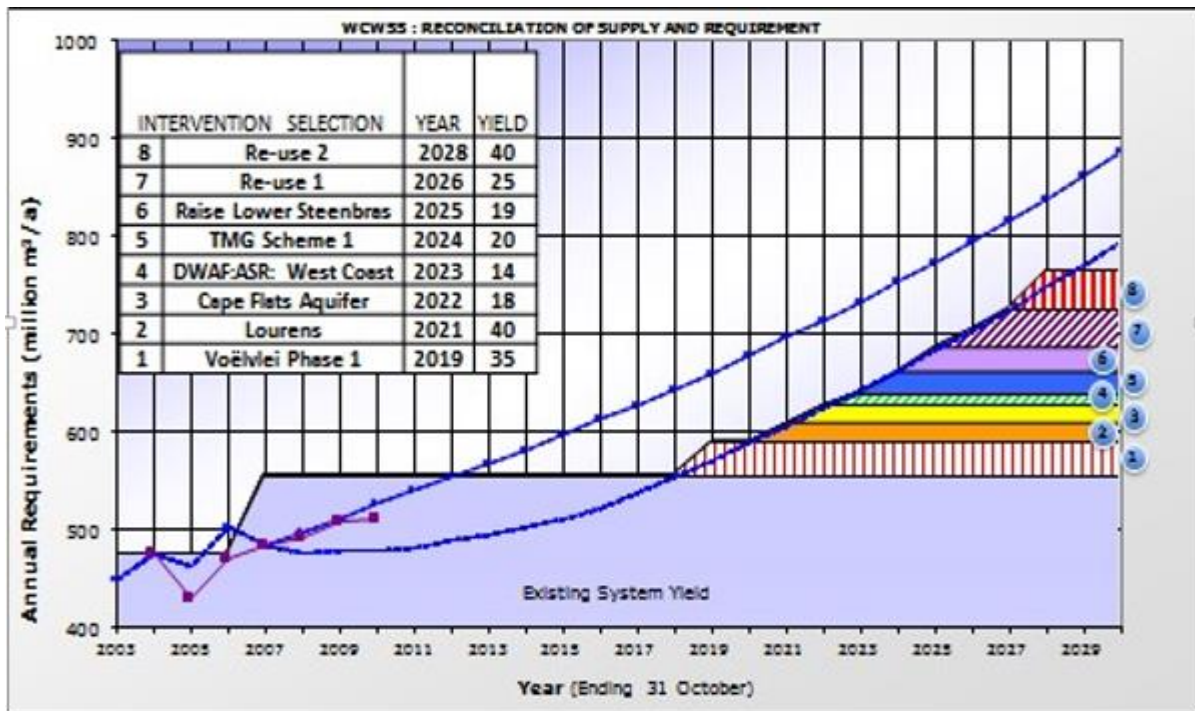


Figure 2.6: A planned development schedule of water resources systems required to meet the growing water demand for WCWSS (Source: DWAF, 2007).

Generally, different sectors are supplied with water at different assurance of supply levels. For example, irrigation demands are usually supplied at a lesser assurance of supply as compared to water for industrial, hydropower, or even domestic purposes. Maré et al. (2007) suggested that it was also rational to further divide the sectoral supply into different levels of assurance of supply. The reasoning behind this is, for example, for irrigation, seasonal crops like horticultural crops may require a lesser assurance as compared to permanent crops like grapes. The high assurance of supply to permanent crops is necessary to ensure that rarely should the crops wither to death since they then cannot be salvaged thereafter. If not, it will take a very long time (years) for the permanent crops to be re-established. The assurance at which various demands are supplied differs with each set proportion of demand being assigned a specific reliability level. Annual or operational water allocation resolutions prioritize supply based on specific assurances of the demands (Campos, 2010).

In South Africa, the Department of Water and Sanitation (DWS) is responsible for coming up with reliabilities of different sector demands, which is done in consultation with relevant stakeholders. Decisions made with regards to licensed and operational allocations of water are not only meant for prevailing conditions but also seek to

safeguard future supplies (Liuzzo *et al.*, 2016). Demands for water for each sector are normally divided into different specified priority classes. Priority classes define the volumes of water demands that ought to be supplied to different sectors and at the required reliability. Typically, low prioritized sectors experience water curtailments/restrictions before highly prioritized sectors/users.

Though the risk-based water allocation principle has over time ensured that water resource systems in South Africa do not fail, it has however sometimes resulted in underutilization of the water resources. With the core elements (volume and reliability) of water allocation having an inverse relationship, some water managers and operators have resorted to maintaining high assurance of supply in a bid to ensure that their water resource systems do not fail. In other words, some stakeholders and water managers tend to be more concerned with water demands being met at all costs, rather than maximizing the economic utilization of the water resource.

Armer (1998) observed that economically, South Africa's unviable farming could be attributed to the level of risk at which irrigators were allocated water by DWS. With this assumption, Armer (1998) conducted a study focused on addressing the degree of risk of water allocation in agricultural economic modelling. The study also highlighted lack of efficient techniques and risk programming tools for water allocation, therefore hydrological and agricultural economic modelling had always been processed independently. The study concluded that these findings were the reason behind uneconomical farming and therefore, failure to optimize the available water resources. Armer (1998), therefore recommended the need for further research that would link hydrological modelling with agricultural economic modelling. According to Armer (1998), proper risk assessment in decision-making processes would facilitate better economic gains from available water resource systems.

In line with findings from Armer (1998), numerous studies have been conducted to assess implications of allocating water at high assurance of supply. Quibell *et al.* (2012) acknowledged that allocation of water at high reliability in the Inkomati basin had addressed the problem of managing inter-annual variability and in turn ensured water security for most water users within the basin. However, Quibell *et al.* (2012) also noted that by allocating water at reduced reliability of 90%, a 25% increase in the

volume of allocable water would have been achieved and a further 46% more would have been made available at a reduced reliability of 86%.

Barnard *et al.* (2019) conducted a sensitivity analysis to determine whether the allocation of water at a lower assurance of supply would result in more economic benefits from a given water resource system. In the study, it was acknowledged that although the reliability of water resources was already being considered in water resources management, its implications were seldom incorporated in economic analyses of water resources allocations. Their sensitivity analysis entailed the reduction of the assurance of supply for irrigation water users, and thereafter assessed the economic impacts that resulted from the alterations. The study used Gross domestic product (GDP), employment, and household income as the economic indicators of the economic analysis.

Findings from the study showed that when the demand imposed on the Orange River Project was maintained, and the water supplied to the farmers at a relatively lower reliability, there was an increase in the reduction in gross domestic product (GDP) of the area. The increase of the GDP can be attributed to the surplus yield available at lower assurance. Increase in irrigation agriculture ensured that more employment opportunities were created and consequently more household income. Given that all the three economic indicators returned positive results at the reduced assurance of supply, it was concluded that irrigation within the Orange River Project was being supplied at a very high assurance of supply.

According to Browning *et al.* (2006), an allocation strategy is more efficient if there are no other feasible allocation options that would make any other sector better off without compromising other sectors. However, it should also be noted that an amendment to the assurance of supply of one sector is likely to affect the assurance of supply of another sector. But generally, by reducing the assurance of supply of a system, the possibility of having some more sectors/users benefiting from the system is presented. It is evident that allocation of water at high assurances of supply overtime has been used to mitigate failure of water resources. However, although this practice has managed to achieve this narrow goal, it has also hindered optimisation of existing water resources.

Simon (1956) conducted a study on the rational choices and structure of the environment advocated for this practice, which he termed “satisficing”. The study by Simon (1956) stated that “satisficing” promotes robust water management decisions that maximize the probability of achieving satisfactory outcomes rather than optimizing the overall performance. Almost similar to arguments by Simon (1956), Ben-haim (2006) highlighted the need for decision-makers to only use robust satisficing when severe uncertainties are often. Therefore, considering the stochastic nature of hydrological events and with the operations of water resource systems progressively changing with time to counteract the ever-increasing water demands, it is ideal to not only focus on ensuring a progressive water allocation through allocating water at high reliability but also ensure equitable allocation which would in turn ensure optimisation of the existing water resources.

While the study by Barnard *et al.* (2019) assessed prospects of increasing benefits of a water resource system by comparing economic impacts due to allocation of water at lower assurances of supply, this study is seeking to advance the analysis further to assess prospects of achieving an optimal assurance of supply for a water resource system. It is conjectured that although different reductions in the assurance of supply may result in different net economic benefits, only one of them will have the ultimate maximum net benefits.

#### **2.4.2 Need for an efficient water resource allocation strategy.**

Common features of water resource management challenges in the allocation phase include increased user interdependency and increased marginal costs for the provision of water. In this phase, scarcity of water and external cost is intensified. External costs come up when one user interferes with the supply of another user. For example, when an upstream user pollutes the river and therefore raises the water treatment cost for users downstream (Briscoe, 1996). In the context of water allocation, external costs are incurred when a user like the municipality sector is allocated water at a higher reliability as compared to another user like the agriculture sector. In this case, during drought, the agricultural sector will have to face restrictions first before restrictions are imposed on the municipal sector (Quibell *et al.*, 2012).

To resolve these complex conflicts amongst different users and economic sectors, better elaborate management systems need to be devised. Developing efficient water strategies is difficult because water possesses distinctive physical characteristics, complex economic features, and significant social characteristics that distinguish it from other resources. The ever-increasing array of goods and services provided by water produces a challenge for efficient water allocation. Additionally, because of its excludability and rivalry characteristics, water resources are always prone to market failures if not properly managed (Briscoe, 1996).

In the period 2015 - 2017, South Africa recorded its worst drought since 1904 and its impact was felt nationwide. The agriculture sector contracted by almost 15% from R78 billion in the fourth quarter of 2014 to R66 billion in the second quarter of 2016. Most of this decline is attributed to the drought (GreenCape, 2018; TIPS, 2016). In the Western Cape Province, water demand from the commercial and industrial sectors was largely affected by the drought, such that, by 2018, industrial and commercial businesses in Cape Town had reduced their consumption by around 30% and 10% respectively (CoCT, 2018a).

During water restrictions, water allocation to municipality users is prioritised compared to that destined for agriculture. A case in point is during the 2017 drought. To reduce WCWSS's water supply in line with its reduced water availability, agricultural water supply was restricted by 60% of its usual consumption (DWS, 2018a). Due to the restrictions, there was a production drop in the agriculture sector, which corresponded to a loss of R 5.9 billion of Gross Value Added (GVA) and more than 30,000 job losses (Pienaar and Bonzaaier, 2018). Where this was most felt was in the wine grape industry, which plays an important role in the region's economy, creating almost 200,000 jobs (SAWIS, 2014).

Although different operational policies have been developed to help in the allocation of water (Ansink *et al.*, 2008) however, some do not incorporate a holistic economic analysis. Rather than focusing only on the cost and benefits achieved because of implementing the operating policies, an economic analysis of the effect of failure of the system will also play an important role in ensuring optimization of the water resource system.

## 2.5 Reasons for considering non-infrastructureal interventions in water resources augmentation

It can be argued that economic growth will always cause an increase in water demand and water availability will cause an increase in economic growth. The symbiotic relationship has crucial policy implications due to South Africa's notable gap between its water demand and water availability. For example, South Africa's Berg water management area is expected to have a water supply deficit of 300 million cubic meters per year by 2040. The deficit is projected to cost the region more than R146 billion and almost 650 000 jobs if no new water resources are developed (Bronkhorst, *et al.*, 2017). Therefore, to spur progressive economic growth, it is important to incorporate aspects of economics in the planning and allocation of water resources.

There have always been calls for incorporation of social economic analyses in the process of water resource planning. In 1970, the commission of inquiry into water matters strongly advocated for thorough integration of overall planning of South Africa's limited water resources with economic planning of the country. These sentiments were further reiterated in 1986 by the Department of Water Affairs and Forestry in its publication "The management of water resources of the Republic of South Africa" where it stated:

*"The national management strategy aims at optimising national benefits from all uses of water according to a scarce resource allocation strategy implemented in harmony with the prudent development of water infrastructure and the application of appropriate controls."*

Water availability is an important catalyst for economic development and growth of a region. Conversely, with water having a fundamental role in driving economic system functions, lack of water can act as a constraint to economic growth of a country. Where water is scarce, allocation decisions involve trade-offs between alternative demands for water from different regions or economic sectors. Water allocation planning, therefore, needs to align with future development and economic objectives.

However, it is impossible to establish and operate water resources systems in South Africa that meet all economic demands at all times. This statement is grounded on the fact that South Africa is a developing semi-arid country whose water demands cannot always be fully met by existing water resources. In this regard and acknowledging that each water resource has its unique characteristics, each water resource allocation needs to be addressed with its specific analysis. Ideally, three basic strategies are used in analysing water resources planning and development. These are yield analysis, developmental analysis, and operational analysis (Basson *et al.*, 1994). Whereas each strategy has its unique problem definition, the three analyses must align amongst themselves to ensure that the water resource system does not fail but ultimately allow for better water allocation.

With the current challenges of limited resources, there has been a global decline in the construction of large dams. In South Africa, most of the suitable dam construction sites have already been exhausted (Ndiritu, 2005), while in Australia, the decline was attributed to the limited availability of funds (Cui *et al.*, 2003). Labadie (2004) noted that there was a virtual standstill in the USA and other developed countries. He further pointed out an increased mobilisation in opposition to large dam storage projects in developing countries. Initially, more focus had been put on infrastructural development to increase water reliability in South Africa. Even though this strategy worked, the combination of depleted suitable sites and lack of resources have made it difficult to augment South Africa's water supply resources at the required rate of development to meet that of growth in demand. The situation is further worsened by the effects of climate change.

In response to these challenges, it is now imperative to put more emphasis on more efficient operations and management of existing water resource systems that would easily allow for the optimisation of water resources. Ideally, the reliability of a water resource system is increased by development of a storage reservoir. Chang and Chang (2001) noted that to mitigate the challenge of insufficient water supply during low flow periods, improvement of water resource management through optimal reservoir operation should be seen as a critical intervention. In water resources systems analysis, a variety of mechanisms are used to optimize the performance of a system, as each system possesses unique characteristics. Hence, this is the reason

why the behaviour of a water resource system depends on the functions of the system, and ultimate governing operating rules (Basson *et al.*, 1994).

However, most water resources optimization problems involve conflicting objectives (Chang and Chang, 2001). Oliveira and Loucks (1997) stated that defining efficient operating rules for a particular water supply system is a challenging decision, especially those that apply to multiple reservoirs that serve multiple purposes and objectives. Hence, optimization models play a critical role in identifying possible management systems operating rules. Management of water resources may be regarded as a multi-objective optimization problem. It poses a considerable challenge in the determination of operating policies that would lead to maximizing benefits while minimizing adverse effects (Adeyemo, 2011). To optimise existing water resource systems in the short term, more focus is put on yield and operational analyses. Given that efficient short-term water resource allocation is governed by operating policies, which take many forms depending on the water resource problem being analysed, maximisation of economic utilisation of the available water resource stands out as one of the operating policies that need more focus for economic development in South Africa.

For long-term water allocation, it is acknowledged that there are other options to increase the availability of water to cater to the growing water demand. For example, the Department of Water and Sanitation (DWS) has developed other strategies like desalination, groundwater, and wastewater reuse, among others. However, reconsiderations to reduce the chosen reliability of 98% for South Africa's water resources systems and optimise the assurance of supply to increase the availability of water have so far not featured much. This is despite Barnard *et al.* (2019) having acknowledged the need to incorporate risk of water supply in economic analyses of water allocation. Other factors that motivate the need to relook into the yield–reliability interrelationship as an option for maximising the economic gains of existing water resources systems rather than constructing new ones include:

### **2.5.1 Avoidance of capital costs for new infrastructural developments**

Capital projects take in a lot of money and time for their development. South Africa in its efforts to ensure it is water secure, has invested heavily in many water infrastructure

projects. Other than dam construction, other infrastructural interventions that DWS has developed to increase its water reliability include the raising of dam heights, desalination, groundwater, and recycling of wastewater. Putting up these projects is expensive. For example, raising the Tzaneen Dam to increase its yield by  $4 \times 10^6 \text{ m}^3/\text{a}$  was estimated to cost R42 million (DWAF, 2010), while the BRVAS project of the WCWSS that is meant to increase the yield of the system by  $23 \times 10^6 \text{ m}^3/\text{a}$  was estimated to cost R 933 million. Even with the capital costs already so high, a study by Flyvjerb *et al.* (2013) on large dams that compared 245 dams from 65 countries, noted that 90% of the infrastructural water projects cost higher than the initial budgets by the time of their commissioning. Here in South Africa, the statement by Flyvjerb *et al.* (2013) is substantiated by the BRVAS project cost, which had as of 2020 increased to R 933 million from the initial cost of R 728 million at the inception stage in 2010.

### **2.5.2 Social Disruptions**

Water resources infrastructural developments like dams are always characterized by displacement or resettlement of people. Huang *et al.* (2018) in their study on the social impacts of dam induced displacement and resettlement, estimated that approximately 40-80 million inhabitants have been displaced due to dam construction from the year 1950 – 2000. The construction of the Three Gorges Dam in China resulted in the displacement of 1.3 million people (Bhargava *et al.*, 2015), whereas the Baihetan dam was estimated to displace 65 million people. With South Africa's suitable sites for dam construction being almost depleted, any future dam construction will require even more displacement or resettlement of people. Apart from displacement and resettlement interfering with people's livelihoods, it also comes at a huge cost, as the displaced people have to be compensated for lost amenities like grazing riparian plains, evergreen medicinal plants, recreation facilities, and ritual/spiritual sites, among others.

### **2.5.3 Environmental impacts**

Even though it is difficult to quantify impacts caused by dam construction, many studies have illustrated that dam construction has significant negative impacts on flora and fauna. Ekierman *et al.* (2015) noted that the construction of Baihetan dam had negative impacts on the fishing industry that resulted in a net present value of R10 billion. Earthquakes have also been associated with the rapid filling of large dams (Tahmiscioğlu *et al.*, 2007).

## **2.6 Water resources engineering economics in risk-based water allocation processes**

Water resource allocation and planning will always be characterized by conflicting operational goals. Among these goals are ensuring engineering feasibility and utilizing the flexibility of supply, maximizing yield, minimizing cost of operations, and minimizing negative environmental and social impacts. Given that there may be many feasible alternatives that can achieve a specific goal, there is always a need to seek better ways that would help in sound decision making during the selection process. Hence, for better comparison each alternative should be based on a common denominator, usually its economic value (costs and benefits). If an alternative cannot be expressed in monetary units, it is considered incommensurable, and therefore, cannot be appropriately compared with other alternatives.

The need to use monetary value of a project in decision-making process of water resource allocation and planning, is also supported by the fact that apart from water resources projects being expensive, most water resources interventions are long-term, and therefore, once adopted, it will take a lot of resources and time to change or remove. Therefore, as water demand continues to grow, it is important to put emphasis on efficient operations and management of existing water resources that will allow for economic optimization of existing water resources.

One might therefore argue that although engineers recognize the importance of sound economic analysis, sometimes they neglect or disregard social costs that arise from unsound decisions in what are perceived as minor matters. But such “minor” matters may occur frequently such that their aggregated importance becomes relatively

significant. For example, allocation of water at high assurances of supply results in less target draft, which can lead to only a section of the demand/society being allocated the water resource. This can lead to social unrests, besides the injustice of inequitable access to the limited resource.

With risk-based water allocation, capital cost and operation and maintenance costs alone do not suffice to conduct a comprehensive economic analysis that can ensure optimisation of a water resource. This is because, increase in water demand will always call for development of more water resources capacities and therefore more capital and operation and maintenance costs. Allocation of water at different assurances of supply/risk of failure results in different volumes of allocable water and economic benefits. Therefore, to ensure optimisation of a water resource, there is also need to assess the economic value/cost associated with the assurance of supply/risk of failure and incorporate them in economic analysis of water resources.

### **2.6.1 Associating costs with risk of water supply**

The economic objective in any development design/intervention is to minimize costs while maximizing its benefits. However, when conducting economic analyses for a water resource project or intervention, it is important to consider that failure of most water resource interventions is normally related to extreme hydrological events such as floods or droughts. However, during the design period, dates of the extreme hydrological events are unpredictable. Hence, the need to compute the extreme values from a probabilistic approach. It is obvious that the greater the extreme event, the more catastrophic the impact on human life and property. As a result, the more serious the adverse effect of the hydrological event, the greater the justifiable economic intervention to reduce the probability of occurrence of the extreme event. Consequently, it becomes economically sound to design a water resource structure/intervention against extreme events that are not likely to occur during the structure's life, that is, reducing the probability of failure of a water resource to almost zero (Linsey *et al.*, 1964).

In water resources management and water allocation in particular, the reliability (probability) of a water resource not failing to meet its target demand is assessed by undertaking yield analysis. Failure in water resources is the inability of a resource to

meet its demand. Given the unpredictable nature of hydrological events, water resource engineers tend to use a probabilistic approach that allows for a progressive water allocation over a certain duration. In South Africa, yield analysis is mostly undertaken using the Water Resource Yield Model (WRYM). Through yield analysis, water resource managers and operators assess the probability of a system meeting its water demands against a certain set of circumstances (Basson *et al.*, 1994). For instance, water can be allocated from a resource in a manner designed to withstand a failure of the resource that is equalled or exceeded only once in a certain number of years. This probability is called the assurance of supply. Water is therefore allocated at a specific assurance of supply.

Given the inverse relationship between target draft and assurance of supply of a water resource system, water managers and operators, to ensure progressive allocation of water, tend to allocate water at relatively a higher assurance of supply to reduce the risk of failure to supply by the system. However, water allocation at high assurances of supply results in low system yields of water and most likely low economic benefits. Therefore, though this strategy to mitigate failure of the water resource is desirable, on the other hand many water managers and operators fail to optimise water allocation of the resource, which should be the main goal of any water resource system.

But although reducing the assurance of supply may result in increased yield of water and economic benefits from the water resource, a reduction in the assurance of supply also results in an increase in the risk of failure of the water resource. Therefore, since the assurance of supply is inversely proportional to the yield of water of a resources system, and yield of water is directly proportional to net economic benefits of the water resource systems, it is therefore obvious that assurance of supply and its inverse, risk of failure, is also associated with cost of supply. In other words, for every allocation at a specific assurance of supply, a certain cost is incurred.

However, this cost cannot be expressed as an absolute annual damage cost and hence is expressed as an annual cost due to a risk of failure. The annual cost due to risk of failure is computed as the product of the expected damage cost and the estimated probability that the event will be equalled or exceeded in any one year

(Linsey *et al.*, 1964). The annual cost due to risk of failure is therefore computed using Equation 2.4.

$$\text{Annual cost due to risk of failure} = \text{Expected damage} \times \text{Risk of failure} \quad (2.4)$$

The expected damage is the estimated cost of the adverse consequence if an event occurs. With regard to irrigation projects, the expected damage is the income a farmer would lose if their irrigation water demands are not met. Hypothetically, if the water resource experienced total failure, then a farmer who is 100% reliant on irrigation would not get any produce. To reduce this damage while still ensuring a continuous water supply from the water resource, the total failure to supply water by a resource is usually mitigated through curtailments/restrictions. If water was the only limiting factor for an irrigation venture, it can be hypothesised that a reduction in the assurance of supply will result in more water, and therefore more land for irrigation and ultimately more production. However, it is obvious that a reduction in the assurance of supply will also result in an increase in the risk of failure of the water resource and therefore an increase in the annual cost due to the risk of failure. It can therefore be concluded that there is an increment in the annual cost due to risk of failure whenever one reduces the assurance of water supply.

### **2.6.2 Economic analysis in water resources allocation**

Unlike other water engineering projects such as flood prevention, irrigation and wastewater recycling, water allocation and planning projects are unique as they not only focus on cost effectiveness of the water resource but also equity, water scheduling and efficiency in the sharing of the scarce resource. As a result, time becomes a very significant aspect for consideration in economic assessment of water resources. In any case, poor water resource decision-making, on very costly investments with far-fetching effects, is normally due to the absence of an economic analysis that spans throughout the life of the project (Pearce, 1998). Normally, a comparative analysis involves comparing project alternatives with different costs and/or different benefits, therefore, to achieve this while still putting time to consideration life cycle cost analysis (LCCA) are conducted.

Life cycle cost analysis (LCCA) is a systematic method for computing the economic efficiency of projects by translating negative and positive effects on a mutual measure, usually money, while still incorporating the aspect of time. A Rand spent today is worth more than a Rand spent in the future (Jawad *et al.*, 2006). Therefore, the life cycle cost analysis process uses an economic method called “discounting” to convert different benefits and costs of a project incurred at different periods to a common period. For comparison of projects, LCCA uses the following capital budgeting methods: net present value (NPV), internal rate of return (IRR), and the benefit-cost ratio (BCR).

- Net present value (NPV)

The NPV is the difference between discounted benefits and discounted costs. This computation is based on a specific period and uses a specific discount rate. Equation 2.5, Economists (2014) is used to compute the NPV.

$$NPV = \left\{ \frac{B_1}{(1+r)^1} + \frac{B_2}{(1+r)^2} + \dots + \frac{B_n}{(1+r)^n} \right\} - \left\{ \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \dots + \frac{C_n}{(1+r)^n} \right\} \quad (2.5)$$

Where B = benefits

C= costs

r = discount rate

n = time (in years)

The discount rate is an interest rate applied to benefits and costs that are expected to occur in the future to convert them into a present value. Normally, a project is only accepted when the NPV has a positive value. Generally, a project is considered best if its NPV is a minimum of 10% less than the other competing projects. If the difference is less than 10%, the projects are considered similar or equivalent (Ozbay *et al.*, 2003).

- Internal rate of return (IRR)

IRR is the discount rate that equates the sum of the difference between the costs and benefits to the initial investment. According to Economists (2014), IRR is the value of the discount rate that satisfies Equation 2.6. When using the IRR, only projects with a higher IRR value than the discount rate are acceptable.

$$\left\{ \frac{B_1 - C_1}{(1+r)^1} + \frac{B_2 - C_2}{(1+r)^2} + \dots + \frac{B_n - C_n}{(1+r)^n} \right\} = 0 \quad (2.6)$$

- Benefit-cost ratio (BCR)

A BCR is a ratio of the discounted benefits to the discounted costs. The BCR is computed using Equation 2.7 (Economists, 2014).

$$\frac{\left\{ \frac{B_1}{(1+r)^1} + \frac{B_2}{(1+r)^2} + \dots + \frac{B_n}{(1+r)^n} \right\}}{\left\{ \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \dots + \frac{C_n}{(1+r)^n} \right\}} \quad (2.7)$$

Generally, a project is worth undertaking if the BCR is greater than one. A project with a BCR value above one implies that the discounted benefits exceed the discounted costs. If all project alternatives have a BCR value of greater than one, then the one with the highest BCR is selected. However, it is not recommended for the BCR to be adopted as the prime capital budgeting method, more so, if the alternatives are mutually exclusive. Therefore, when dealing with mutually exclusive projects, the NPV should be used as the prime method (Economists, 2014).

### ***2.6.3 Significance of economic analysis in water resources allocation considerations***

With South Africa's National Water Act (No. 36 of 1998) putting emphasis on equitable and sustainable water usage, an economic analysis of its water resources under conditions of resource scarcity will play an important role in sustainable water resources allocation. Water allocation among competing users is one of the critical challenges facing water resource managers. The complexity of water allocation is further worsened, by virtue of different sectors having different marginal benefits and costs. However, viewing water as an economic good and in turn, valuing it in monetary terms provides a common metric for evaluating inter-sectoral allocations and hence give insights into equitable water resource allocation with necessary trade-off and ultimately, synergies among competing sectors (Griffin 2006; Loomis, 2000).

Furthermore, knowledge of the value of water is vital in the process of water allocation for purposes of designing a fair, informed, and rational allocation system as it

highlights and informs users on the need of using water sparingly and efficiently (Perret *et al.*,2007; Lange 2007). Economic assessment of water resources allocation additionally plays a vital role in the optimization of water resources as it provides information needed for rational decision-making about evaluating investments on both infrastructural approaches and non-structural or policy-based options (Hussain *et al.*,2007; Young *et al.*, 2005a).

## 2.7 Summary

Reviewed literature established that the complexity of water allocation in South Africa can be attributed to its past policies and unique hydrological patterns that vary both spatially and temporally. Reviewed literature established that to increase its water reliability, South Africa had adopted numerous infrastructural and non-infrastructural interventions. However, like most developing countries, these efforts have always faced setbacks due to budget cuts and the effects of climate change. Furthermore, the growth rate in population, socioeconomic and agricultural developments in such countries occur at a relatively faster rate when compared to the rate of augmenting water resources capacities, consequently, the task of reconciling water requirements with the available water becomes a very complex process.

To mitigate failure of its water resources and therefore, ensure progressive water allocation South Africa adopted a risk-based water allocation strategy in which it allocates its water at a specific assurance of supply. However, the literature reviewed also established that although risk-based water allocation strategy has over time mitigated failure of water resources, it has at times resulted in underutilization of existing water resources. For example, Armer (1998) attributed South Africa's unviable farming to the level of risk at which irrigators are allocated water by DWS. Studies by Quibell (2012) and Barnard *et al.* (2019), highlight the prospects of increasing water availability by only reducing the assurance of supply.

From the literature reviewed, it was established that though South Africa has adopted numerous infrastructural and non-infrastructural interventions to increase its water availability, reduction of assurance of supply has not featured, notwithstanding that it is not associated with capital costs, compensation costs, or environmental costs.

## CHAPTER 3: METHODOLOGY

### 3.1 Preamble

It is evident from the literature review that water allocation in an already water-stressed country is a complex task. South Africa's water scarcity situation is further worsened by the continuous increase in water demand against its already straining water resources and effects of climate change. Since water availability is a key driver towards South Africa achieving a sustainable economy, there is a dire need to not only use existing water resources effectively but also efficiently before resorting to engineering infrastructural augmentation as a method of increasing water availability.

Although the hypothesis that decreasing the assurance of supply would increase the yield of water resource systems in the country, which in turn would increase the economic benefits from the system is expected to apply for all water use sectors, as was applied in the ORASECOM (2020) and Barnard *et al.* (2019) studies, only the irrigation sector was used here for ease of analysis. Among other reasons why only irrigation was used is because the focus of this study was not necessarily to determine the absolute economic benefits due to increased system yield, but rather focus on comparative analyses of economic benefits emanating from increased system yield due to reduced assurance of supply when compared with other options. Besides, irrigation water accounts for about two thirds of the country's water resource usage.

For the other main water use sector, domestic, its revenue and hence economics, on many occasions, does not necessarily correspond to its water allocation from a resource system. For example, non-revenue water in different municipalities of the WCWSS was found to vary both spatially and temporally. This consideration is better envisioned by noting that the cumulative water use by South African municipalities is approximately  $4 \times 10^6 \text{ m}^3/\text{a}$ , of which 41% is estimated to be non-revenue water (DWS, 2017b). Therefore, it would not be quite realistic to include domestic water use sector's allocations to reflect its true revenue or economics. The sum of water allocation to the two sectors of irrigation and domestic usage account for more than 90% of the water resource of the country.

Furthermore, water tariffs of different municipalities are adjusted differently by corresponding local water service providers – meaning the tariffs vary both temporally and spatially. It would therefore be a daunting task to realistically project revenues for domestic water allocation - for a proper assessment of its economic impact due to increased yield of the water resource system. But to pursue this task of correlating domestic water use allocation with revenue collection would fall outside the scope of this study. Unlike tariff for domestic water usage, tariff for irrigation usage is relatively stable and/or predictable. This chapter, therefore, describes the systematic approach that was used in achieving the objectives of the study.

### 3.2 Case studies

The study used six water resources supply systems to meet its main objective. These were the Western Cape Water Supply System (WCWSS). Tzaneen Dam, Midmar Dam, Goedertrouw Dam, Mokolo Dam, and Boegeberg Dam. However, it is important to note that different water resources systems were used to address each of the three specific objectives.

To achieve the first specific objective, the WCWSS was used. The WCWSS is a complex interlinked system of dams, pipelines, and distribution networks supplying water to the urban centres of Cape Town, Drakenstein, Stellenbosch, Witzenberg, Bergrivier, Saldanha bay, and Swartland local municipality (Figure 3.1). The WCWSS falls within the Berg River Catchment (BRC) of the Berg-Olifants Water Management Area. The BRC covers 9 000 km<sup>2</sup>, while the Berg River itself stretches 285 km from Franschoek in a western direction towards the West Coast where it drains near Laaiplek into the Atlantic Ocean. The catchment receives most of its precipitation during the winter season. However, the rainfall is highly variable, with the eastern side receiving approximately above 1500 mm per annum while the western side averages between 400-500mm per annum (DWS, 2016; Bailey *et al.*, 2016). The mean annual run-off of the catchment averages at 931 Mm<sup>3</sup>/a (DWAF, 2007).

The WCWSS is comprised of six major dams with a total capacity of 900 x10<sup>6</sup> m<sup>3</sup>. These are Theewaterskloof Dam, Berg River Dam, Wemmershoek Dam, Upper Steenbras Dam, Lower Steenbras Dam, and the Voelvlei Dam (DWS, 2018). The

Dams are operated in an integrated manner to supply both urban and agricultural sectors. The current yield from the WCWSS is  $545 \times 10^6 \text{ m}^3/\text{a}$  at an assurance of supply of 98%. The total allocable water from the system is  $590 \times 10^6 \text{ m}^3/\text{a}$ , as per the DWS's reconciliation strategy. Approximately, two-thirds of the total allocation is shared by urban (industrial, domestic, and commercial) sectors, while the agriculture sector takes the remainder (DWS, 2019b). Therefore, even without reserving some allocation for the ecological reserve as mandated by law, the systems' total allocations had already exceeded the system's yield of  $545 \times 10^6 \text{ m}^3/\text{a}$  (DWS, 2018).

Based on the reconciliation strategy study conducted by DWAF in 2007, looking on the range of bulk water schemes that would serve towards meeting the growing water demands of the WCWSS over a 25-year planning horizon, it was observed that water demand for the WCWSS would exceed water availability at the required reliability by the year 2019 (Figure 2.6). As a result, there was need for augmentation of the yield for the WCWSS. Hence, the first development intervention to increase the yield of the system was the Volvolei phase 1, also called the Berg River Voelvolei Augmentation scheme (BRVAS) project (Figure 2.6). The BRVAS project entails abstraction of high winter (April-September) run-off from the Berg River via:

- A low-level weir, abstraction works, and pump station on the Berg River
- A 6.3 km long pipeline, to deliver water from the weir into the Voelvolei Dam.

Figure 3.1 shows the location of Voelvolei Dam within the WCWSS.

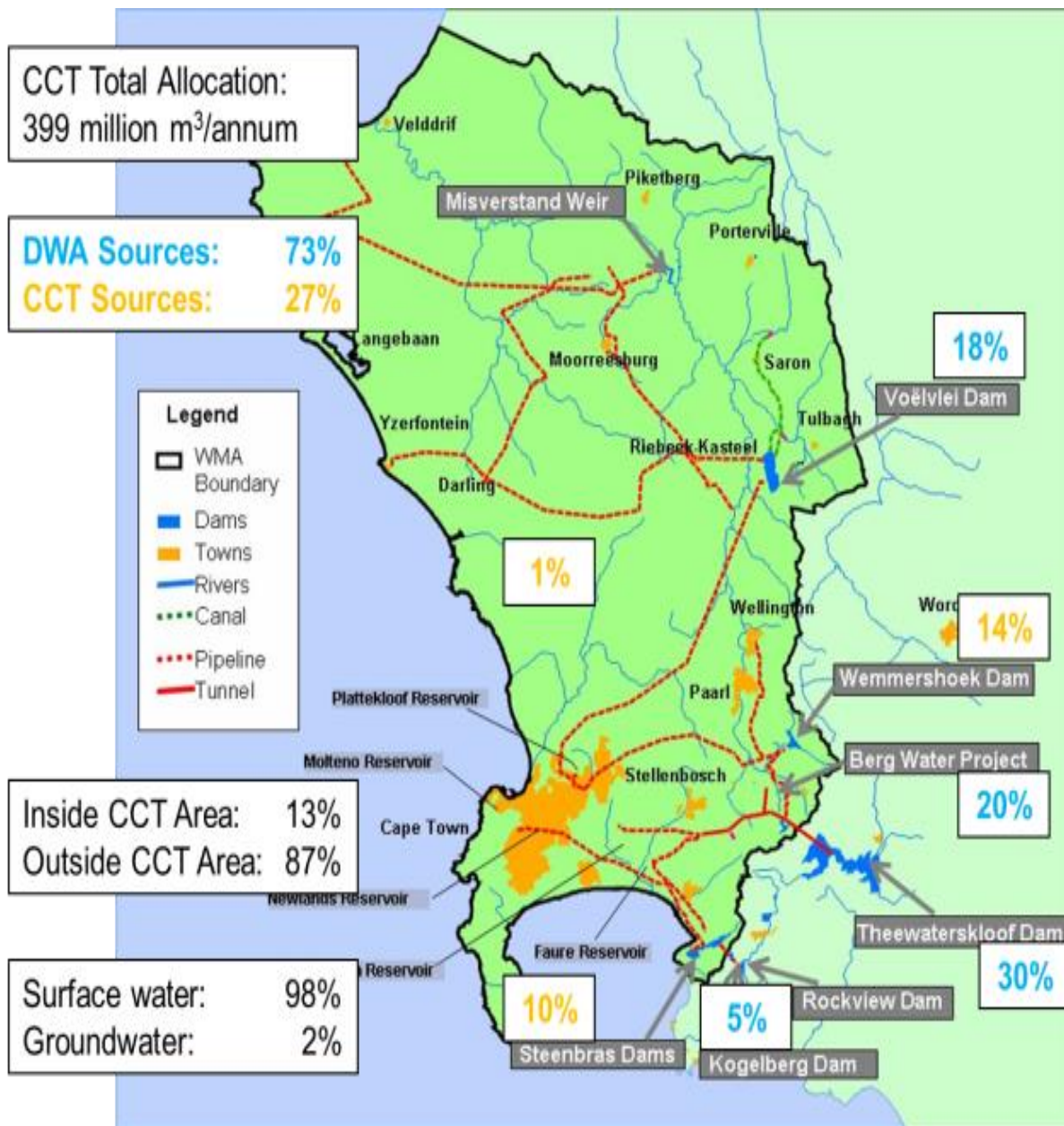


Figure 3.1: Overview of the Western Cape Water Supply System and the City of Cape Town water supply (Faiqa *et al.*, 2021)

But from the literature review, the yield from a water resource is inversely proportional to its assurance of supply, which implies that water availability from a water resource can also be increased by reducing its assurance of supply (Figure 2.3 and Table 2.2). Therefore, considering that the BRVAS project on the Western Cape Water Supply System (WCWSS) was chosen to study the additional economic benefits due to its development, the yield-reliability relationship of the system (Figure 3.2) was accordingly chosen to also analyse the corresponding economic benefits, if any, when the assurance of supply of the WCWSS is reduced.

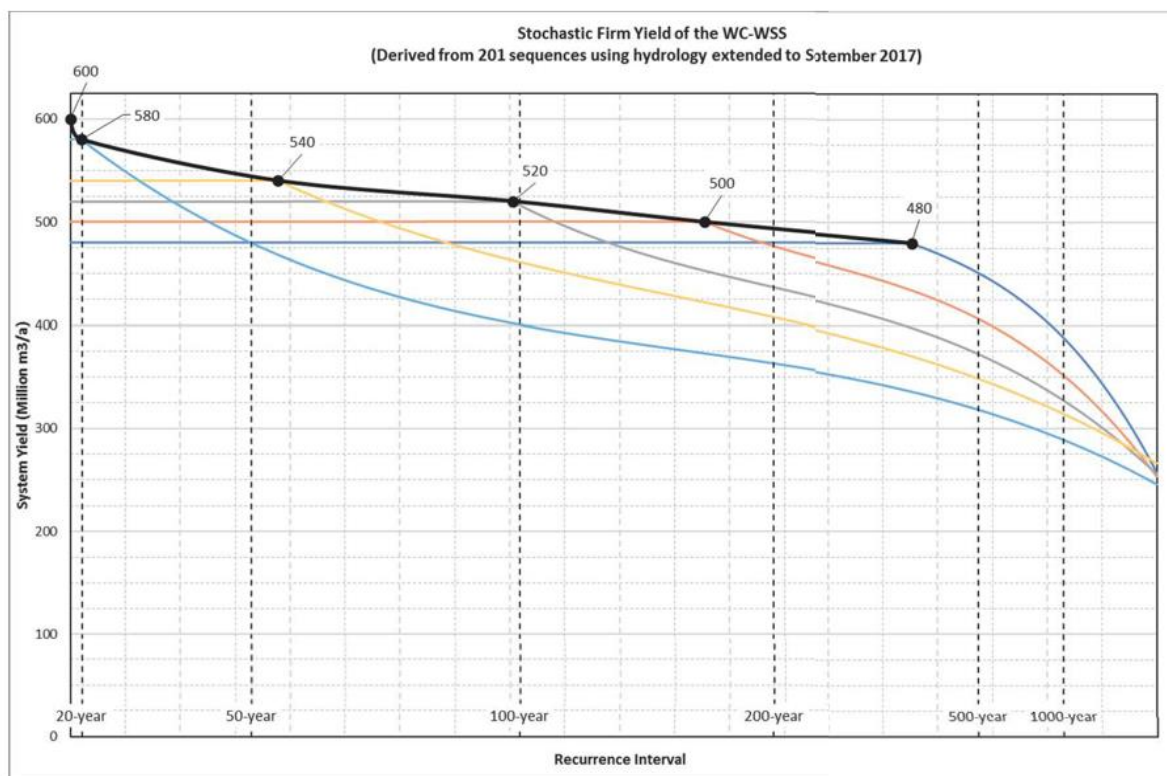


Figure 3.2: Long- term yield-reliability curves of Western Cape Water Supply System (Source: DWS, 2019)

Based on the WCWSS’s yield-reliability curves (Figure 3.2), its allocable water with corresponding assurances of supply are as presented in Table 3.1. Although, the yield of the system reduces with each reduction of the assurance of supply, in this study’s comparative analysis, the assurance of supply was steadily reduced to a level that would achieve the same yield as that achieved by the BRVAS infrastructural development project.

Table 3.1: Water availability at the various assurance of supply of the WCWSS.

Assurance of Supply	1:20	1:50	1:100	1:200
Yield (x10 <sup>6</sup> m <sup>3</sup> /a)	580	545	520	495

The WCWSS was chosen for this study as it offers a practical on-going infrastructural development (BRVAS), with readily available information/data (see Table 3.2) for computing the additional yield of water and associated economic benefits for

computing and making comparative analysis against the other option of increasing yield by reduction of assurance of supply.

With respect to the second specific objective, Tzaneen Dam was used to determine the incremental yield and corresponding benefits due to reduction of its assurance of supply to test the extent of the study's hypothesis. Tzaneen Dam is an earth-fill type of dam which impounds the Great Letaba River in the Groot Letaba River Catchment (B81B), within Luvuvhu/Letaba Water Management Area. The catchment has a mean annual precipitation (MAP) ranging from 1000mm to 1600mm and a unit mean annual run-off (MAR) of 200mm – 500mm (Bailey *et al.*, 2016). The gross storage capacity of the dam is 157.3 Mm<sup>3</sup> (DWAF, 1999). Tzaneen Dam is significant to this study, because, similar to the WCWSS, the dam also underwent infrastructural augmentation through a 3m raising of its full supply level (FSL) to increase its yield from 60 to 64 Mm<sup>3</sup>/a. This infrastructural development was to cost more than R 42 million (DWAF, 2010).

To achieve the third specific objective, assessing if the optimal assurance of supply of a water resource was sensitive to different hydrological regimes, Midmar Dam, Goedertrouw Dam, Mokolo Dam, and Boegeberg Dam were used. Midmar Dam is in the upper uMgeni catchment (U20A), in the Pongola Mtamvuna water management area. The catchment has a mean annual rainfall (MAR) ranging from 900mm to 1200 mm and a unit mean annual run-off of more than 500mm (Bailey *et al.*, 2016). The gross storage capacity of the dam is 235.4 Mm<sup>3</sup>.

Goedertrouw Dam is Mhlatuze Catchment (W12B), of the Pongola Mtamvuna water management area. The dam has a gross storage capacity of 301.3Mm<sup>3</sup>. The catchment has a mean annual rainfall (MAR) ranging from 800 – 1000mm and a unit mean annual run-off higher than 500mm (Bailey *et al.*, 2016).

Mokolo Dam is located in the Mokolo River Catchment (A42), which forms part of the Limpopo water management area. Mokolo River Catchment covers an area of 8387km<sup>2</sup>. Rainfall in Mokolo catchment ranges from approximately 400mm in the west to 600mm in the east (Bailey *et al.*, 2016). The dam's main purpose was to supply water to Lephalale Municipality, Grootegeluk mine, Matimba power station and for

irrigation downstream of the dam. The catchment has a unit mean annual run-off (MAR) of 20mm to 50mm. The dam has a gross storage capacity of 145.9 Mm<sup>3</sup> (DWS, 2021).

The Boegoeberg Dam is a gravity dam, located in the Orange Catchment (D72C). The catchment has a mean annual precipitation (MAP) ranging from 50mm to 200mm, and a unit mean annual run-off (MAR) of 2.5mm – 5.0mm (Bailey *et al.*, 2016). Boegoeberg Dam has a gross storage capacity of 19.8 Mm<sup>3</sup>.

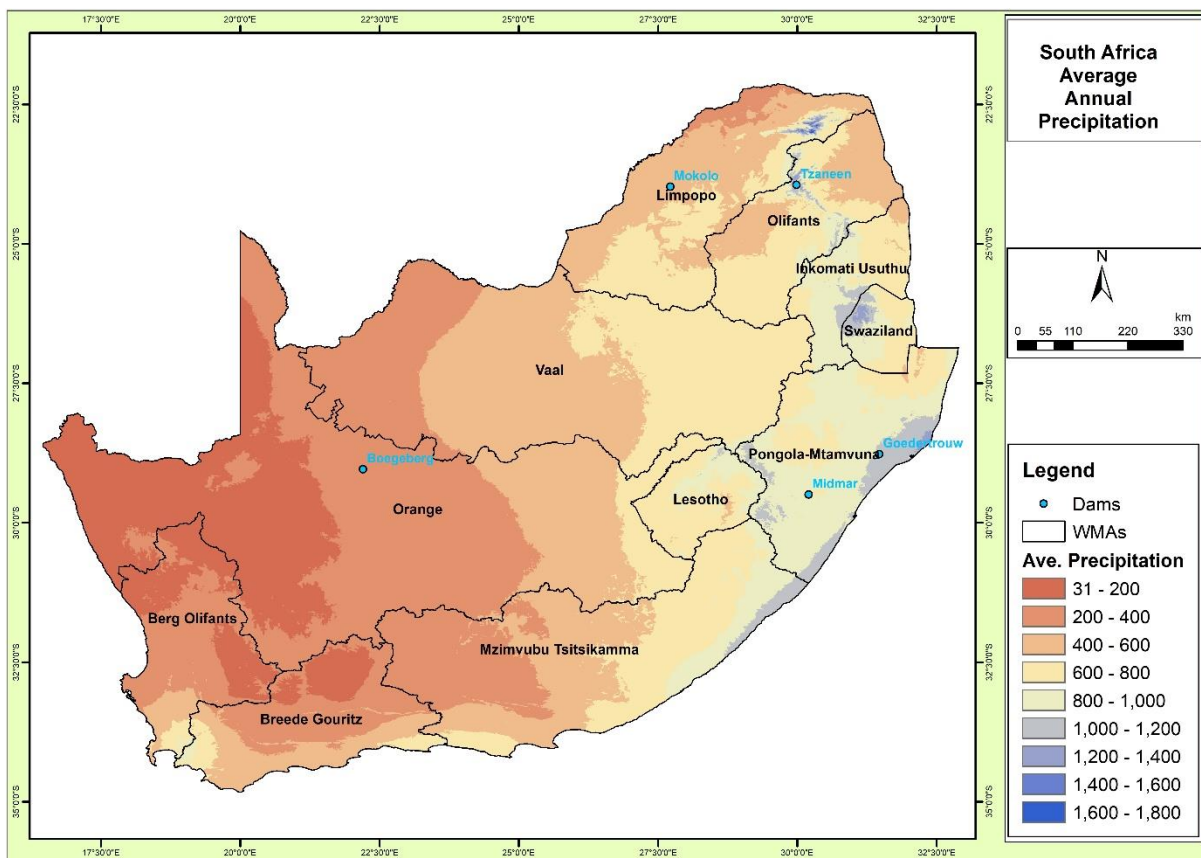


Figure 3.3: Map showing water resources used in the sensitivity analysis.

### 3.3 Comparative analysis of two options for increasing system yield of water and related economic benefits from the WCWSS

Given that the yield from a water resource is inversely proportional to its assurance of supply, this comparative analysis aims to assess economic benefits, if any, that can be derived because of increasing the yield of the WCWSS either through the BRVAS infrastructural project or through reduction of its existing assurance of supply. To

facilitate the irrigation venture via infrastructural augmentation (BRVAS), four costs were to be incurred. These were the capital cost of the infrastructure, cost of additional land to be acquired, production cost of wine grapes, and the annual cost due to risk of failure. The capital cost of the infrastructure and the cost of land to be acquired are normally significant and are therefore normally funded by loans that are serviced over a long period (years). Therefore, for them to be used in the computation of total annual costs, they needed to be converted into annual costs (capital recovery cost). Capital recovery cost is the annual cost that is incurred to service a loan (Linsey *et al.*, 1964) and was computed based on Equation 3.1.

$$\text{Capital recovery cost} = \text{Capital cost} \times \frac{i(1+i)^n}{[(1+i)^n - 1]} \quad (3.1)$$

Where  $i$  = interest rate per annum

$n$  = years of estimated life

Using the social interest rate from Economist (2014), and lifespan of the pipeline from ORASECOM (2020), the capital recovery cost of the loan was computed. Unlike the conventional infrastructural development option, increasing the yield of a water resource through reduction of its assurance of supply requires no capital cost. Nonetheless, since both the infrastructural development option (BRVAS) and reduction of assurance of supply option increased the yield of the WCWSS by a similar yield margin ( $23 \times 10^6 \text{ m}^3/\text{a}$ ), costs for land acquisition and production costs were virtually the same. Thereafter, the study used the data collated in Table 3.2 to compute the net benefits emanating from the BRVAS infrastructural option and the reduction of reliability option.

Using the annual wine grape irrigation water requirements, computed by equation 3.2 and the increased yield of water, the area of land that could be irrigated by the increased yield of water was computed by equation 3.3.

$$\text{Annual irrigation demand per ha} = \text{depth (m)} \times \text{area (m}^2\text{)} \quad (3.2)$$

$$\text{Additional acreage} = \frac{\text{Total yield increment (m}^3\text{)}}{\text{annual irrigation demand per hectare } \left(\frac{\text{m}^3}{\text{ha}}\right)} \quad (3.3)$$

Thereafter, the cost of land to be irrigated was computed using the additional acreage and the cost of land per hectare in Swartland area. The study then computed the total production cost required to facilitate an economically viable wine grape production on the irrigated land using equation 3.4.

$$\text{Total production cost (R)} = \text{Additional acreage (ha)} \times \text{production cost/ha (R/ha)} \quad (3.4)$$

In this study, the total production cost is composed of the direct costs, labour costs, mechanisation, fixed improvements, and general expenditure. General expenditure includes electricity and water charges.

Irrigation water is normally allocated at specific assurance of supply. Given that allocation of water at different assurances of supply results in different volumes of water, and therefore different crop yield amounts and economic benefits. It can therefore be argued that when water is allocated at a specific assurance of supply, say 99.5% (1:200), the revenue that would have been generated when allocated at a lower assurance of supply, say 99% (1:100), is foregone. Economists refer to this revenue as the opportunity cost (revenue forgone). Though normally neglected, costs associated with water allocation at different assurances of supply play a major role in maximisation of the productivity of an irrigation venture and ultimately optimisation of the water resources system. It was therefore important to incorporate the cost associated with the risk of failure in this analysis as it helps in selecting the most optimal assurance of supply that would result in more benefits but at a relatively acceptable risk of failure of the water resource system, or rather maximum benefits at a minimum opportunity cost. Costs associated with assurances of supply form the basis of this study to assess prospects of optimising economic benefits of water resources systems and are further discussed in subsequent subsections.

From Section 2.6.1, a cost is always incurred when water is allocated at a specific assurance of supply. Therefore, since the BRVAS infrastructural project was expected to increase the yield of the WCWSS by  $23 \times 10^6 \text{ m}^3/\text{a}$  at 1:50 assurance of supply, and the reduction of assurance of supply option was also expected to increase the

WCWSS's yield by a similar  $23 \times 10^6 \text{ m}^3/\text{a}$ , albeit at a lower reliability than the existing 1:50, both options incurred annual costs due to risk of failure. The annual costs due to the risk of failure of the two options were therefore computed using Equation 2.4. With the two options having the same size of land, irrigation water and production, it was expected that both water yields will produce similar crop yields and therefore similar benefits. Benefits from the irrigation venture were computed using equation 3.5.

$$\text{Total wine grape income (R)} = \text{Additional acreage (ha)} \times \text{wine grape income/ha (R/ha)} \quad (3.5)$$

The net benefits from both conventional infrastructural option (BRVAS) and the reduction of reliability option were then computed by subtracting the total cost (capital recovery cost for the infrastructure for the infrastructural option, cost of land, production cost, and the annual cost due to risk of failure) incurred throughout the project from the total benefits from the project.

To ensure that the difference in project costs and difference in lives of the hydraulic infrastructure were accounted for while still maintaining consistency in the evaluation process, a life cycle cost analysis (LCCA) was conducted to compare the BRVAS infrastructural option and the reduction of reliability option. In this study, the LCCA used the following capital budgeting methods: net present value (NPV), internal rate of return (IRR), and the benefit-cost ratio (BCR). The three capital budgeting methods, NPV, IRR and BCR were computed using equations 2.5, 2.6 and 2.7, respectively, which were incorporated in a Microsoft excel computation program.

Data required for this comparative analysis was obtained from reports from relevant organizations. DWS (2019) and TCTA (2019) provided information on the capital cost of the Berg River Voelvlei Augmentation Scheme (BRVAS) and the intended yield to be augmented. The average cost of land in the WCWSS was based on prices of land within the Swartland Municipality as obtained from the Farmer's Weekly (2015). The study used Swartland municipality of the Western Cape Province because of its sole dependence on the Voelvlei Dam in the WCWSS (Figure 3.1). Irrigation water requirements for wine grapes were obtained from Fruitrop (2014). The total cost of production, average wine grape yield per hectare, and income from crop yield per

hectare were obtained from Vinpro (2019). The life span (operating period) of the augmentation infrastructure and South Africa's discount rate factor were obtained from Economists (2014). Table 3.2 shows the summarised data and information acquired for the comparative analysis.

Table 3.2: Data and information acquired for the comparative analysis.

Variable	Value
Water resource yield increase by the BRVAS	23 x10 <sup>6</sup> m <sup>3</sup> /a at 1:50 assurance of supply
Capital costs of the BRVAS project	R 933 x10 <sup>6</sup>
Cost of irrigable land in WCWSS	R 45000
Cost of wine grape production per hectare	R 30301
Annual irrigation depth for wine grape per hectare	650 mm
Income from wine Grape yield per hectare (Rand /ha)	R63,396
Interest rate applicable in South Africa	8%
Operation period/ lifespan of infrastructure	30 years

### 3.4 Deriving the optimal assurance of supply of a water resource system

According to Barnard *et al.* (2019), a reduction in the assurance of supply, by adjusting priority classification tables, can result in further increase in yield of water and economic benefits of a water resource. But does this statement imply that all reductions in assurances of supply result in increasing corresponding net benefits? It can be conjectured that by associating the risk of failure of a water resource to a cost, and in turn incorporating this cost in economic analysis of water allocation processes, there is a prospect of finding an optimal assurance of supply. In any case, Ndiritu (2003) suggested that economic analysis on the cost of failure to supply water, among other things, need to be considered as a necessary optimization process.

A sensitivity analysis of the assurance of supply was conducted to test the study's hypothesis. This would in turn also highlight another method that can be used to determine the most optimal assurance of supply. Water allocation at an optimal

assurance of supply facilitates reduction of opportunity cost of water as there is more allocable water to cater for both existing and emerging water users. This study's sensitivity analysis entailed assessing the economic impacts (annual benefits) emanating from allocation of water at progressively decreased assurances of supply, using Tzaneen Dam as the water resource.

To determine the yields emanating from the reservoir at different assurances of supply, a yield analysis of Tzaneen Dam was conducted using the Water Resources Yield Model (WRYM) which was developed by the South African Department of water and sanitation (DWS). The study collected the yield model set-up and pre-processed hydrological files required to conduct a yield analysis of Tzaneen Dam from the Department of Water and Sanitation (DWS). The hydrological files from DWS contained the following data sets: monthly rainfall, naturalised streamflow, water requirements, monthly streamflow reductions (SFR's) due to commercial forestry and, stochastically generated stream flows. The period used for the yield analysis was from 1920 to 2004. Appendix A1 shows the long-term yield curve generated by DWS using the said data. Similarly, this study also used the same data to generate yield reliability curves and thereafter determined target drafts (volume of water) at 1:5, 1:10, 1:20, 1:50, 1:100 and 1:200 assurances of supply. For this study, the 1:200 assurance of supply (99.5% reliability) was assumed to be the base assurance of supply.

Unlike the comparative analysis of the WCWSS that used wine grape production for its economic analysis, the sensitivity analysis used citrus production to conduct its economic analysis. Citrus production was selected for use in this sensitivity analysis because it is a common crop around Tzaneen and across South Africa. Data required for economic analysis of this sensitivity analysis included annual citrus water irrigation requirement, production cost of citrus per hectare, and citrus produce per hectare, all of which were obtained from Mankhili (2015) as provided in Table 3.3. The cost of citrus produce per tonne was obtained from (DAFF, 2019).

Table 3.3: Data and information used for deriving the optimum assurance of supply.

Variable	Value
Annual citrus irrigation requirement	1500 mm
Cost of establishing a hectare of citrus plantation	R 125,000
Cost of citrus production per hectare	R 55,000
Citrus production per hectare	45 tonnes
Price of citrus per tonne	R 4,664
Lifespan of citrus establishment	30 years
Discount rate applicable in South Africa	8%

Different regions in South Africa have different costs of land. Therefore, to ensure uniformity in the sensitivity analysis, the study assumed that farmers already had land and therefore water was the only limiting factor. As a result, the cost of land was not incorporated in these economic analyses. However, even without the cost of land, the cost of establishing citrus plantations was still significant for this analysis. Given that establishment costs are “once-off” costs, there was a need to ensure that they (establishment costs) were commensurable with other annual costs (production costs and annual cost due to risk of failure). Establishment costs were therefore converted to annual costs as capital recovery cost for citrus establishment using Equation 3.1. For this computation, the discount rate was obtained from Economists (2014), while the lifespan of the establishment and cost of establishing a hectare of citrus were obtained from Mankhili (2015).

Using the expected damage and the risk of failure at each assurance of supply, the annual cost due to risk of failure at each assurance of supply was computed using Equation 2.3. With the production costs of citrus, establishment costs, annual costs due to the risk of failure and benefits from the citrus harvest, the study computed the annual net benefits that would be derived at each of the six assurances of supply.

### **3.5 Sensitivity analysis of optimum assurance of supply to hydrological regimes of water resource systems**

Each water resource has distinctive yield-reliability characteristics that are dependent on the hydrological regime of the catchment that varies both temporally and spatially (Basson *et al.*, 1994). Rugumayo *et al.* (2001) reiterates Basson *et al.* (1994) arguments by stating that the yield of a reservoir is dependent on target demand (D), hydrology of the water basin supplying the reservoir, and the desired reliability (R). As a result, it may not be always correct to assume that all water resources can have their maximum benefits at the same assurance of supply. Therefore, in line with this study's third specific objective, the study extended the sensitivity analysis in Section 3.4 to include four more water resources characterized by different hydrological regimes. The extension of the sensitivity analysis to include more water resources from catchments characterised by different hydrological regimes was done to investigate if the optimal assurance of supply of Tzaneen Dam in Section 3.4 was same to the hydrologic regimes of Midmar, Goedertouw, Mokolo and Boegeberg Dams.

Therefore, similar to the sensitivity analysis conducted in Section 3.4, yield analyses for Midmar, Goedertouw, Mokolo and Boegeberg Dams were also undertaken. The yield model set-up, and data sets for: monthly rainfall, naturalised streamflow, water requirements, monthly streamflow reductions (SFR's) due to commercial forestry and stochastically generated stream flows for the four dams were also obtained from the Department of Water and Sanitation (DWS). Appendix A2, A3, A4 and A5 show the long-term yield reliability curves that were generated by DWS using the said data. This study used the same data sets above to generate yield reliability curves for the four dams. Table 3.4 lists the dams, water catchments, mean annual precipitation and periods used in the analyses.

Table 3.4: Different water resources systems used in the sensitivity analysis of optimum assurance of supply to hydrological regimes.

<b>Water resource (dam)</b>	<b>Catchment</b>	<b>Mean Annual Precipitation (MAP)</b>	<b>Period of analysis</b>
Tzaneen	Luvuvhu-Letaba Catchment	608	1920-2004
Midmar	Upper UMngeni Catchment	921 mm	1920-1994
Goedertrouw	Mhlatuze Catchment	932 mm	1920-1994
Mokolo	Mokolo River Catchment	400 – 600 mm	1920-2003
Boegeberg	Orange Catchment	50 -230 mm	1920-1994

Using the target drafts at 1:5, 1:10, 1:20, 1:50, 1:100 and 1:200 assurances of supply from the four dams, and data from Table 3.3, citrus production costs, establishment costs, annual cost due to risk of failure and benefits at each assurance of supply of the four water resources were computed. Thereafter, the annual net benefits at each assurance of supply from each water resource was also computed.

## CHAPTER 4: RESULTS AND DISCUSSIONS.

### 4.1 Preamble

This chapter entails the analysis, results, and discussion of this study. The chapter is divided into three sections. The first section is based on a comparative analysis of interventions aimed at increasing the yield of the WCWSS for better economic productivity, either through the BRVAS infrastructural project or through reduction of WCWSS's current assurance of supply. The second section is based on analysis and results of a sensitivity analysis aimed at testing the study's hypothesis. The third section is based on analysis and results of a sensitivity analysis aimed at investigating if the optimal assurance of supply in Section 3.4 is sensitive to hydrological regimes of other water resources.

### 4.2 Comparative analysis of interventions aimed at increasing water availability in the WCWSS.

#### ***4.2.1 Net benefits resulting from increased yield due to the BRVAS infrastructural project and the reduction of reliability.***

From Section 3.1, it was assumed that the increased yield from the BRVAS infrastructural project would be used for irrigation of wine grapes. Therefore, the costs involved would be derived from construction of the augmentation infrastructure, cost of irrigable land for the farming venture, production cost of wine grapes and the annual cost due to risk of failure resulting from water allocation at the assurance of supply (1:50). The benefits would be derived from the income of wine grapes.

The BRVAS infrastructural project in the WCWSS is supposed to increase the yield of the system by  $23 \times 10^6 \text{ m}^3/\text{a}$  at a 1:50 assurance of supply. The project's capital cost of R 933 million is borrowed by Trans-Caledon Tunnel Authority (TCTA), a state-owned entity tasked with financing and implementing bulk raw water infrastructure projects. This cost is a "once-off" cost and hence there was a need to convert it into a capital recovery cost (annual cost) for it to be commensurable with other annual costs. The capital cost for the augmentation infrastructure was therefore converted into a capital recovery cost using Equation 3.1 and was found to be R 82,875,995.

Increased yield of water from the system would ensure that there is more water for irrigation for wine grapes and hence more land would be required for the irrigation venture. Grape vines growing in a Mediterranean climate such as the Western Cape Province have an average water requirement depth of 650 mm per year. The annual irrigation water demand per hectare was computed using equation 3.2 and was found to be 6,500 m<sup>3</sup>. Using the annual irrigation demand, the additional acreage that can be irrigated by the increased yield was computed using equation 3.3 and was found to be 3539 ha. The total cost of additional acreage was then computed, and was found to be R 159,255, 000. Similar to the capital cost, the total cost of additional acreage was also converted to the capital recovery cost (annual cost) using Equation 3.1. The capital recovery cost for the land to be acquire would therefore be R 14,176,858.

According to Vinpro (2019), there has been a progressive increase in the production cost of wine grapes over the years. Different wine grape producing areas in the Western Cape Province have different costs of production per hectare. The production cost consists of labour, mechanisation, fixed improvements, and general expenditure that include both electricity and water charges. The total cost of production of wine grape produce from the increased acreage was then computed using equation 3.4 and was found to be R 107,235,239. Income generated from the farming venture included benefits (revenue) derived from wine grapes produced. The total income to be generated from the irrigation venture was computed using equation 3.5 and was found to be R 224,358,444.

From Section 3.4, there is always a cost associated with the risk of failure when water is allocated at a specific assurance of supply. Therefore, since the increased yield from the BRVAS infrastructural project is to be allocated at a 98% assurance of supply, there was a cost incurred due to this 2% risk of failure. From the BRVAS infrastructural development, the target draft of the WCWSS was to be increased from its current 545 x10<sup>6</sup> m<sup>3</sup>/a to 568 x10<sup>6</sup> m<sup>3</sup>/a. Therefore, the expected damage/loss would be equivalent to income lost by a farmer when a yield of 23 x10<sup>6</sup> m<sup>3</sup>/a was allocated at a risk of 2%. Using Equation 2.4, the annual cost due to the risk of failure was computed and was found to be R 4,487,168. With the total costs and total income, the annual net benefits

due to the increased yield emanating from the BRVAS infrastructural project was computed and was found to be R 15,583,184.

As demonstrated in Table 3.1 and 3.3, the reliability of a water resource system has an inverse relationship with its target draft. Using this relationship on WCWSS's long-term yield reliability curve (Figure 3.2), this study assessed prospects of increasing water availability in the WCWSS by  $23 \times 10^6 \text{ m}^3/\text{a}$ , which is a similar yield increase like that by the BRVAS infrastructural project. By reducing the assurance of supply of the WCWSS from the current 1:50 reliability level to approximately 1:30 assurance of supply, there is an approximately  $23 \times 10^6 \text{ m}^3/\text{a}$  increase in yield of water (see Table 4.1).

Table 4.1: Water availability at the two levels of assurance of supply of the WCWSS.

Assurance of Supply	1:50	1:30
Yield ( $\times 10^6 \text{ m}^3/\text{a}$ )	545	568

Since both BRVAS infrastructural project and reduction of assurance of supply options provided the same increase in volume of allocable water, the cost of additional acreage due to the increased volume of water, cost of wine grape production, and income from wine grape production were also the same. Given that the reduction of reliability approach did not have a capital cost, the only cost that was different from that of the BRVAS infrastructural augmentation project was the annual cost due to risk of failure. Using Equation 2.3, the annual cost due to risk of failure at 1:30 assurance of supply can be computed and was found to be R 6,730,753. The net benefit resulting from the increased yield due to reduction of the assurance of supply option was then computed and was found to be R 96,215,594.

It can be seen that the BRVAS infrastructural project had a lower net benefit of R  $15.5 \times 10^6$  when compared to R  $96.2 \times 10^6$  resulting from the reduction of assurance of supply (see Table 4.2). Table 4.2 illustrates the increased yield and the annual net benefits from both infrastructural development option and reduction of reliability option of the WCWSS. It is evident that augmenting water availability is more costly when an

infrastructural option is undertaken as compared to when a reduction of reliability option is undertaken.

Unlike the conventional infrastructural development option (BRVAS) for increasing yield of water, using the reduction of reliability option does not incur capital costs (see Table 4.2). Therefore, the R 80.7 x 10<sup>6</sup> difference in the annual net benefits between the infrastructural development option and the reduction of reliability option can be majorly attributed to the capital recovery cost of the BRVAS augmentation infrastructure since almost all other costs were the same except for annual cost due to the risk of failure.

Table 4.2: Summary of increased yield, costs, income, and net benefits of the BRVAS infrastructural approach and the reduction of assurance of supply of the WCWSS.

<b>Inputs</b>	<b>BRVAS infrastructural approach</b>	<b>Reduction of reliability approach</b>
Increased yield	23 x10 <sup>6</sup> m <sup>3</sup>	23 x10 <sup>6</sup> m <sup>3</sup>
Capital recovery cost for the augmentation infrastructure	R 82.9 x10 <sup>6</sup>	No cost
Capital recovery cost for additional acreage due to the increased irrigation water	R 14.2 x10 <sup>6</sup>	R 14.2 x10 <sup>6</sup>
Total annual cost of grape production	R 107.2 x10 <sup>6</sup>	R 107.2 x10 <sup>6</sup>
Annual cost due to risk of failure	R 4.5 x10 <sup>6</sup>	R 6.7 x10 <sup>6</sup>
Total cost	R 208.8 x10 <sup>6</sup>	R 128.1 x10 <sup>6</sup>
Gross Income	R 224.3 x10 <sup>6</sup>	R 224.3 x10 <sup>6</sup>
Net benefits	R 15.5 x10 <sup>6</sup>	R 96.2 x10 <sup>6</sup>

#### **4.2.2 Life cycle cost analysis of the two interventions for increasing yield from WCWSS.**

Other than the costs incurred in a water project, time is also an important factor to be considered. As normally put “time is money”. It is common knowledge that capital projects such as the BRVAS project are normally funded by loans that accrue interest over time and given that capital projects take a long time to be completed, huge capital recovery costs are incurred. Additionally, when capital projects stall because of certain challenges (as in the case of the BRVAS project), resources that had already been invested since the inception phase are considered as wasted because they still accumulate interest yet there is no income from the project.

These observations concur with Pearce (1998) arguments that poor decision making in water resources management is normally due to absence of economic analyses that spanned through the life of a water resource. It is therefore imperative to also factor in the aspect of time in this study’s economic analyses. Therefore, although results of the annual net benefits (Table 4.2) had already highlighted the reduction of reliability option as being the best alternative to increase water availability for the WCWSS, the study also conducted a life cycle cost analysis to further affirm the decision.

The NPV, IRR, and BCR were used as the capital budgeting methods for the life cycle cost analysis of this study. According to Economists (2014), South Africa uses discount rate of 8% in its project evaluation in the public sector. Therefore, this study also used a discount rate of 8% in its computations. The study assumed a life period of 30 years (life of a pipeline) for both the BRVAS infrastructural development approach and the reduction of reliability approach as assumed in ORASECOM (2020). Table 4.3 shows the computation of the NPV, IRR, and BCR of the BRVAS infrastructural project, which were found to be -R 32,599,807, 7.73% and 1.84, respectively.

Table 4.3: NPV, IRR and BCR for the BRVAS infrastructural development project.

YEAR(n)	COST (a)	BENEFITS (b)	CASHFLOW (b –a)	Discount rate (c)	DISCOUNTED BENEFITS (d) = (b * c)	DISCOUNTED COST (e) = (a * c)	DISCOUNTED CASHFLOW (f) = (d – e)
	1,092,255,000	0	1,092,255,000		0	0	1,092,255,000
1	111,725,407	0	-111,725,407	1.1	0	103,449,451	-103,449,451
2	111,725,407	224,300,000	112,574,593	1.2	192,301,097	95,786,529	96,514,569
3	111,725,407	224,300,000	112,574,593	1.3	178,056,572	88,691,230	89,365,341
4	111,725,407	224,300,000	112,574,593	1.4	164,867,196	82,121,509	82,745,687
5	111,725,407	224,300,000	112,574,593	1.5	152,654,811	76,038,435	76,616,376
6	111,725,407	224,300,000	112,574,593	1.6	141,347,047	70,405,958	70,941,089
7	111,725,407	224,300,000	112,574,593	1.7	130,876,896	65,190,702	65,686,194
8	111,725,407	224,300,000	112,574,593	1.9	121,182,311	60,361,761	60,820,550
9	111,725,407	224,300,000	112,574,593	2.0	112,205,843	55,890,519	56,315,324
10	111,725,407	224,300,000	112,574,593	2.2	103,894,299	51,750,481	52,143,818
11	111,725,407	224,300,000	112,574,593	2.3	96,198,425	47,917,112	48,281,313
12	111,725,407	224,300,000	112,574,593	2.5	89,072,616	44,367,696	44,704,920
13	111,725,407	224,300,000	112,574,593	2.7	82,474,645	41,081,200	41,393,444
14	111,725,407	224,300,000	112,574,593	2.9	76,365,412	38,038,148	38,327,263
15	111,725,407	224,300,000	112,574,593	3.2	70,708,714	35,220,508	35,488,207
16	111,725,407	224,300,000	112,574,593	3.4	65,471,032	32,611,581	32,859,451
17	111,725,407	224,300,000	112,574,593	3.7	60,621,326	30,195,909	30,425,417
18	111,725,407	224,300,000	112,574,593	4.0	56,130,857	27,959,175	28,171,683
19	111,725,407	224,300,000	112,574,593	4.3	51,973,016	25,888,125	26,084,891
20	111,725,407	224,300,000	112,574,593	4.7	48,123,163	23,970,486	24,152,677
21	111,725,407	224,300,000	112,574,593	5.0	44,558,484	22,194,894	22,363,590
22	111,725,407	224,300,000	112,574,593	5.4	41,257,856	20,550,828	20,707,028
23	111,725,407	224,300,000	112,574,593	5.9	38,201,718	19,028,544	19,173,174
24	111,725,407	224,300,000	112,574,593	6.3	35,371,961	17,619,023	17,752,939
25	111,725,407	224,300,000	112,574,593	6.8	32,751,816	16,313,910	16,437,906
26	111,725,407	224,300,000	112,574,593	7.4	30,325,756	15,105,472	15,220,284
27	111,725,407	224,300,000	112,574,593	8.0	28,079,403	13,986,548	14,092,855
28	111,725,407	224,300,000	112,574,593	8.6	25,999,448	12,950,508	13,048,940
29	111,725,407	224,300,000	112,574,593	9.3	24,073,563	11,991,211	12,082,352
30	111,725,407	224,300,000	112,574,593	10.1	22,290,336	11,102,973	11,187,363
					2,317,435,619	1,257,780,426	-32,599,807
						NPV	-32,599,807
						IRR	7.73%
						BCR	1.84

Table 4.4 shows the computation of NPV, IRR, and BCR for the reduction of reliability approach, which was found to be R 875,176,172, 33.74%, and 1.81, respectively. The

NPV highlights the time value for money, therefore, the negative NPV of the BRVAS infrastructural project implied that the project would have to incur an extra R 32.6 x 10<sup>6</sup> to achieve an annual net benefit of R 224.3. The positive NPV of the reduction of reliability option implied that despite the project saving on a R 875.1 x 10<sup>6</sup> cost, an annual benefit of R 224 x 10<sup>6</sup>, would still be achieved. The results of the IRR indicated that the BRVAS project would have a much slower rate of return of 7.73% on its investment when compared to 33.74% of the reduction of reliability option.

Both interventions had a positive BCR, therefore implying that both interventions were profitable. However, the BRVAS infrastructural option had a higher BCR of 1.84 when compared to 1.81 of the reduction of assurance of supply option. These results imply that the ratio of benefits to costs of the option of reducing reliability was much higher than that of the BRVAS project. It can be concluded that results from all three capital budgeting methods (NPV, IRR and BCR) highlighted that reduction of assurance of supply is the most cost-effective and time-efficient method of increasing the yield of the WCWSS water resource.

Table 4.4: NPV, IRR and BCR computation for the Reduction of Reliability OF WCWSS approach.

YEAR(n)	COST (a)	BENEFITS (b)	CASHFLOW (b –a)	Discount rate (c)	DISCOUNTED BENEFITS (d) = (b * c)	DISCOUNTED COST (e) = (a * c)	DISCOUNTED CASHFLOW (f) = (d – e)
	159,255,000	0	159,255,000				-159,255,000
1	113,965,992	0	113,965,992	1.1	0	105,524,067	-105,524,067
2	113,965,992	224,300,000	110,334,008	1.2	192,301,097	97,707,469	94,593,628
3	113,965,992	224,300,000	110,334,008	1.3	178,056,572	90,469,879	87,586,693
4	113,965,992	224,300,000	110,334,008	1.4	164,867,196	83,768,406	81,098,790
5	113,965,992	224,300,000	110,334,008	1.5	152,654,811	77,563,339	75,091,472
6	113,965,992	224,300,000	110,334,008	1.6	141,347,047	71,817,907	69,529,141
7	113,965,992	224,300,000	110,334,008	1.7	130,876,896	66,498,062	64,378,834
8	113,965,992	224,300,000	110,334,008	1.9	121,182,311	61,572,279	59,610,031
9	113,965,992	224,300,000	110,334,008	2.0	112,205,843	57,011,370	55,194,474
10	113,965,992	224,300,000	110,334,008	2.2	103,894,299	52,788,305	51,105,994
11	113,965,992	224,300,000	110,334,008	2.3	96,198,425	48,878,061	47,320,365
12	113,965,992	224,300,000	110,334,008	2.5	89,072,616	45,257,463	43,815,153
13	113,965,992	224,300,000	110,334,008	2.7	82,474,645	41,905,059	40,569,586
14	113,965,992	224,300,000	110,334,008	2.9	76,365,412	38,800,980	37,564,431
15	113,965,992	224,300,000	110,334,008	3.2	70,708,714	35,926,834	34,781,881
16	113,965,992	224,300,000	110,334,008	3.4	65,471,032	33,265,587	32,205,445
17	113,965,992	224,300,000	110,334,008	3.7	60,621,326	30,801,469	29,819,857
18	113,965,992	224,300,000	110,334,008	4.0	56,130,857	28,519,879	27,610,978
19	113,965,992	224,300,000	110,334,008	4.3	51,973,016	26,407,295	25,565,721
20	113,965,992	224,300,000	110,334,008	4.7	48,123,163	24,451,199	23,671,964
21	113,965,992	224,300,000	110,334,008	5.0	44,558,484	22,639,999	21,918,485
22	113,965,992	224,300,000	110,334,008	5.4	41,257,856	20,962,962	20,294,893
23	113,965,992	224,300,000	110,334,008	5.9	38,201,718	19,410,150	18,791,568
24	113,965,992	224,300,000	110,334,008	6.3	35,371,961	17,972,361	17,399,600
25	113,965,992	224,300,000	110,334,008	6.8	32,751,816	16,641,075	16,110,741
26	113,965,992	224,300,000	110,334,008	7.4	30,325,756	15,408,403	14,917,352
27	113,965,992	224,300,000	110,334,008	8.0	28,079,403	14,267,040	13,812,363
28	113,965,992	224,300,000	110,334,008	8.6	25,999,448	13,210,222	12,789,225
29	113,965,992	224,300,000	110,334,008	9.3	24,073,563	12,231,687	11,841,875
30	113,965,992	224,300,000	110,334,008	10.1	22,290,336	11,325,636	10,964,699
					2,317,435,619	1,283,004,446	875,176,172
						NPV	875,176,172
						IRR	33.74%
						BCR	1.81

Though this comparative analysis only used capital cost and farm operation costs, it should also be noted that when undertaking infrastructural development for mega

projects, there are other significant costs such as compensation (social impact) costs and environmental costs that can be incurred (see Section 2.5). Even though the BRVAS infrastructural project did not incur compensation cost, according to an environmental impact assessment conducted on the BRVAS project by Ellis *et al.* (2017), there was an estimated loss of almost 20 – 50 hectares of arable land due to the BRVAS project. Obviously, adopting the approach of reducing the prevailing assurance of supply as another method of increasing water availability would ensure that such compensation and environmental costs are avoided.

Typical firm yield versus storage capacity (size of project) curves normally illustrates a continued rise in firm yield from a water resource with increase in storage capacity, but only up to a point. Typically, it will come to a point (peak) at which it will start reducing in the yield as the storage capacity increases. This phenomenon can be attributed to the fact that the yield of a water resource is not limited by the storage capacity alone, but also by the availability of water in the resource system (hydrology). It can therefore be concluded that at this point infrastructural engineering alone cannot suffice to meet the increasing water demands as they can be deemed uneconomical or environmentally unfriendly. Under such conditions, non-infrastructural policy-based approaches rather than infrastructural approaches are required. Given that South Africa is already in the water allocation phase, adoption of non-infrastructural policy-based measures such as the reduction of assurance of supply in some water resources systems offer prospects of increasing water availability of a country and in turn increase its economic productivity.

#### **4.3 Analysis to determine the optimum assurance of supply level for maximum economic benefits from a water resource system.**

From yield analysis conducted on Tzaneen Dam, long-term yield reliability curves were generated (Figure 4.1). Using the long-term yield reliability curves, target drafts at different assurances of supply were determined. The target draft at 1:5 assurance of supply was the highest yield at  $110 \times 10^6 \text{ Mm}^3/\text{a}$ , whereas the target draft at 1:200 was the lowest at  $84 \times 10^6 \text{ Mm}^3/\text{a}$ . It is evident that there is an increase in available water (firm yield) with each reduction of the assurance of supply (see Table 4.5). Using the determined target drafts at different assurances of supply, citrus irrigation water

requirements, total costs of citrus production per hectare (inclusive of water charges), citrus income per hectare, and the cost due to risk of failure, the net benefits emanating from Tzaneen Dam at each assurance of supply were computed. However, only computations of net benefits resulting from water allocation at 1:100 assurance of supply will be illustrated in this section. Computations of net benefits resulting from water allocation at 1:50, 1:20, 1:10 and 1:5 assurances of supply are illustrated in Table 4.6.

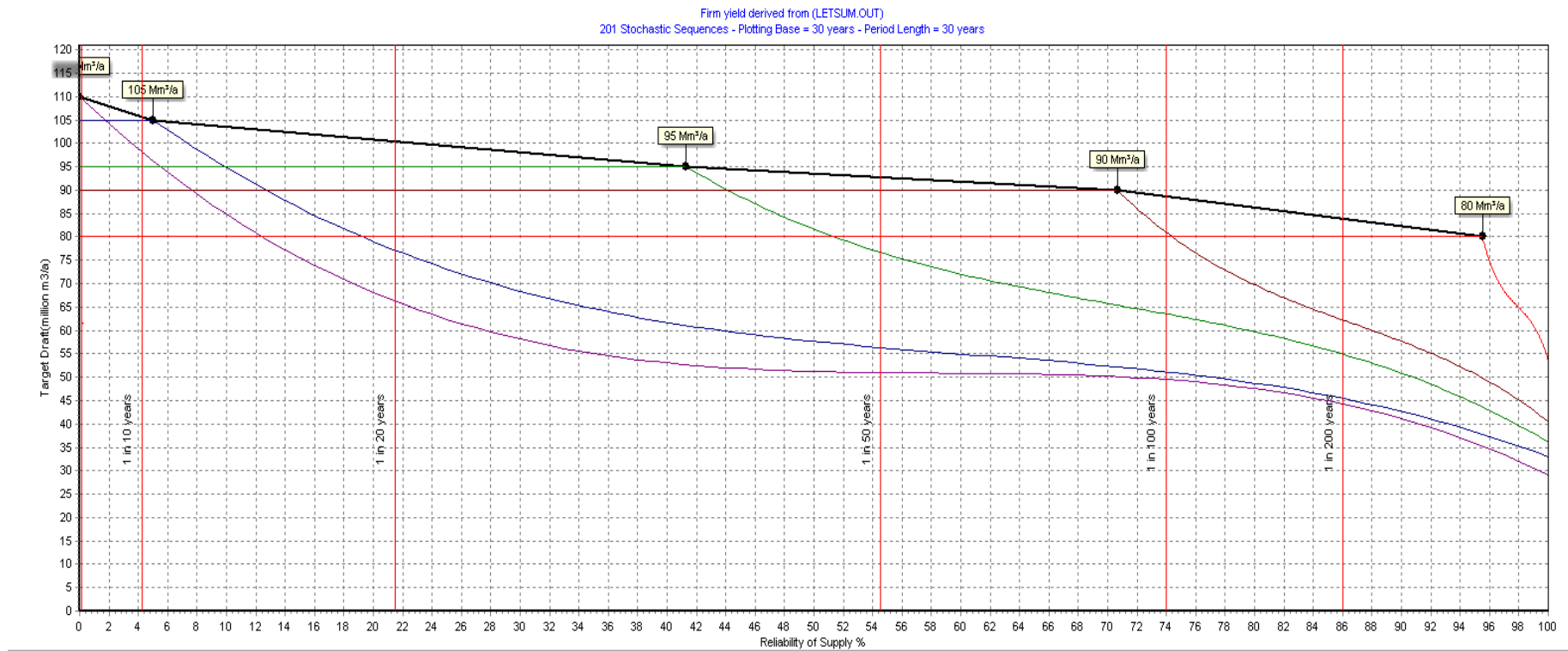


Figure 4.1: Tzaneen Dam long-term yield reliability curves

Table 4.5: Water availability of Tzaneen Dam at various assurances of supply

Assurance of Supply	1:200	1:100	1:50	1:20	1:10	1:5
Yield ( $\times 10^6 \text{m}^3/\text{a}$ )	84	88	92	101	106	110
Incremental yield ( $\times 10^6 \text{m}^3/\text{a}$ )	-	4	4	9	5	4

Citrus has an average water requirement depth of 1500 mm per year. Therefore, the annual citrus irrigation water demand per hectare was computed by equation 3.2 and was found to be 15,000 m<sup>3</sup>. Thereafter, the acreage that can be irrigated by the 88 x 10<sup>6</sup> m<sup>3</sup>/a corresponding to a 1:100 assurance of supply was computed by equation 3.3 and was found to be 5867 ha. The total cost for citrus establishment on the 5867 ha would then be R 733 x 10<sup>6</sup>. To commensurate establishment cost with other annual costs such as production costs, it was converted to the capital recovery cost (annual cost) using equation 2.3 and was found to be R 65.1 x 10<sup>6</sup>. The total citrus production cost for the 5867 ha would then be R 323 x 10<sup>6</sup>.

Income generated from the farming venture included benefits (revenue) derived from citrus produced. Given that a hectare of land produces an average 45 tonnes, the total citrus income to be generated from the 5867 ha would then be R 1231 x 10<sup>6</sup>. From Section 2.6.1, there is always a cost associated with the risk of failure when water is allocated at a specific assurance of supply. Therefore, at a 1:100 assurance of supply, there is also a cost that is incurred. In this scenario, the expected damage/loss is equivalent to income a farmer would lose if the dam was to fail at 1:100 assurance of supply. Using equation 2.4, the annual cost due to the risk of failure was computed and was found to be R 12.3 x 10<sup>6</sup>. With the total costs and total income, annual net benefits resulting from the 88 x 10<sup>6</sup> m<sup>3</sup>/a yield at 1:100 assurance of supply was computed and found to be R 831 x 10<sup>6</sup>.

Table 4.6 illustrates the computations and results of the annual net benefits emanating from Tzaneen Dam at 1:100, 1:50, 1:20, 1:10 and 1:5 assurances of supply. Column B shows the selected assurances of supply. Column C shows the yields that can be derived at selected assurances of supply, whereas Column D shows the increased yield due to reduction of assurance of supply as hypothesised in the study. Column D shows irrigable land that is irrigated by the increased yield. It is computed by:

$$\text{Irrigable land} = \frac{\text{Total yield increment (m}^3\text{)}}{\text{annual irrigation demand per hectare } \left(\frac{\text{m}^3}{\text{ha}}\right)}$$

Column F shows the annual gross income, it is computed by:

$$\text{Gross income} = \text{irrigable land} \times \text{Citrus production per hectare} \times \text{Price of citrus per tonne}$$

Column G is the establishment costs, it is computed by:

$$\text{Establishment costs} = \text{irrigable land} \times \text{cost of establishing a hectare of citrus}$$

Column H shows the capital recovery cost for establishing citrus plantations, it is computed by:

$$\text{Capital recovery cost for citrus establishment} = \text{establishment cost} \times \frac{i(1+i)^n}{[(1+i)^n - 1]}$$

Column J shows the risk of failure due to allocation of water at specific assurance of supply whereas, Column K shows the expected damage. Column L is the annual cost due to risk of failure, which is computed by:

$$\text{Annual cost due to risk of failure} = \text{expected damage} \times \text{risk of failure}$$

Column M is the total cost, computed by:

$$\text{Totals costs} = \text{Capital recovery costs} + \text{Production costs} + \text{Costs due to risk of failure to supply water}$$

Column N is the net benefits, computed by:

$$\text{Net benefits} = \text{Gross income} - \text{Total costs}$$

It can be observed that each reduction in assurance of supply resulted in an increase in the volume of water that could be allocated. Additionally, each increase in allocable water resulted in an increase in the size of land that could be irrigated and ultimately an increase in the cost and benefits involved in the project. Table 4.6 also demonstrated an inverse relationship between the assurances of supply and the annual cost due to risk of failure.

Table 4.6: Computations of net benefits emanating from Tzaneen dam due to reduction of assurance of supply.

Water resource	Assurance of supply	Yield (m <sup>3</sup> )	Increased volume of water	Irrigable land	Gross income	Establishment cost (Rands)	Capital recovery cost for the establishment cost @11.26% (Rands)	Total cost of orange production. (Rands)	Risk of failure	Expected damage (Rands)	Annual cost due to risk of failure (Rands)	Total annual cost (Rands)	net benefits (Rands)
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)
TZANEEN	1:200	84 x 10 <sup>6</sup>	-	5,600	1,175,328,000	700,000,000	62,181,000	308,000,000	0.005	1,175,328,000	5876640	376,057,640	799,270,360
	1:100	88 x 10 <sup>6</sup>	4 x 10 <sup>6</sup>	5,867	1,231,296,000	733,333,333	65,142,000	322,666,667	0.01	1,231,296,000	12312960	400,121,627	831,174,373
	1:50	92 x 10 <sup>6</sup>	4 x 10 <sup>6</sup>	6,133	1,287,264,000	766,666,667	68,103,000	337,333,333	0.02	1,287,264,000	25745280	431,181,613	856,082,387
	1:20	101 x 10 <sup>6</sup>	9 x 10 <sup>6</sup>	6,733	1,413,192,000	841,666,667	74,765,250	370,333,333	0.05	1,413,192,000	70659600	515,758,183	897,433,817
	1:10	106 x 10 <sup>6</sup>	5 x 10 <sup>6</sup>	7,067	1,483,152,000	883,333,333	78,466,500	388,666,667	0.1	1,483,152,000	148315200	615,448,367	867,703,633
	1:5	110 x 10 <sup>6</sup>	4 x 10 <sup>6</sup>	7,333	1,539,120,000	916,666,667	81,427,500	403,333,333	0.2	1,539,120,000	307824000	792,584,833	746,535,167

Figure 4.2 illustrates the graphical results of the net benefits and yield against the assurance of supply of Tzaneen Dam. Generally, it can be observed that there is increase in yield with each reduction of the assurance of supply. However, the trend is not the same for the net benefits curve. It is observed that though the net benefits were increasing with each reduction of the assurance of supply, an optimum point is reached after which, the net benefits started reducing despite continued reduction in the assurance of supply. It is therefore determined that Tzaneen Dam has its optimum net benefits when water is allocated at 1:18 assurance of supply.

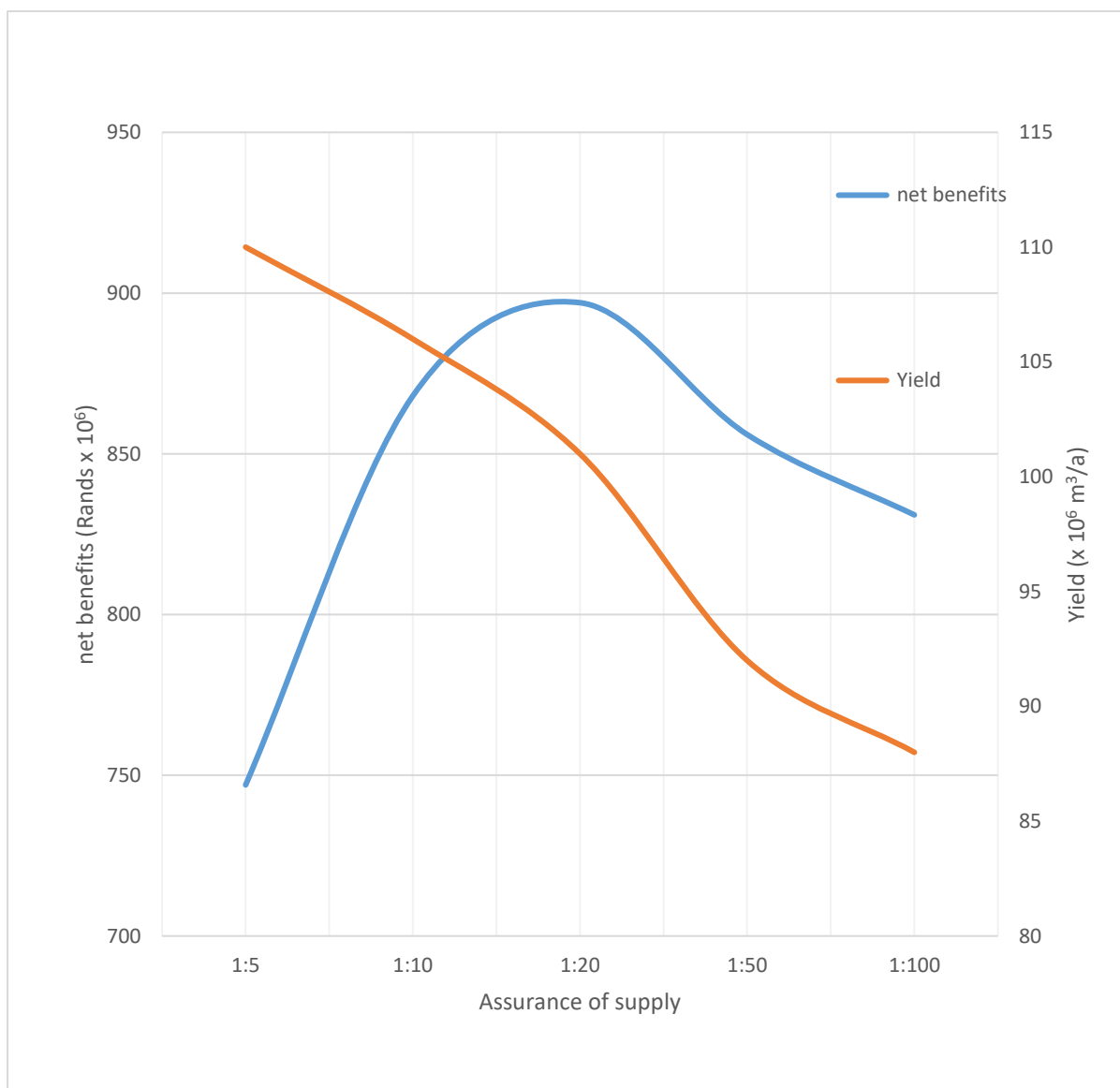


Figure 4.2: Tzaneen Dam's net benefits and yield against assurance of supply.

Water resources allocation and management involves making sound decisions among various possible alternatives. For instance, with South Africa using a risk-based water allocation strategy, one of the biggest challenges has been to find an optimum assurance of supply that can ensure mitigation of failure of water supply of existing water resources systems, while still ensuring economic maximisation of the water resource. It is because of such challenges that there was a need to incorporate economic analysis in the process of water allocation. However, even with the incorporation of economic analysis in the decision-making process of water allocation, optimisation of water resources remains a daunting task for water authorities.

From results presented in Table 4.6, it can be argued that failure to optimise water resources can be attributed to past water resources economic analyses only focusing on capital, operation and maintenance costs as the only costs associated with water resources. When using a risk-based water allocation strategy, these two costs do suffice to conduct a comprehensive economic analysis that can help in selecting an optimum assurance of supply. It is obvious that, were it for capital costs (establishment cost in this case) and production costs only, then the maximum benefits would have been achieved at the lowest assurance of supply. This is because an increase in these costs accompanied by increased water availability can only result in more citrus production. Therefore, the phenomenon of not having the optimal net benefits at the lowest assurance of supply can only be attributed to the incorporation of the annual cost due to risk of failure in this economic analysis.

Results from this study second Barnard et al. (2019) arguments that water availability and in turn economic productivity (net benefits) from a water resource can be further increased by reducing its assurance of supply. However, unlike Barnard et al. (2019) who focused on assessing implications of reducing a water resource's assurance of supply, this study also assessed cost associated with allocation of water at different assurance of supply. It was determined that not all subsequent reductions of assurances of supply resulted in an increment of benefits from a water resource system. At some point, net benefits emanating from the water resource will start to decrease despite continued reduction of assurance of supply. It can therefore be concluded that analysing annual costs due to risk of failure provides new insights and

prospects of optimising water resources as it highlights costs associated with different risks when water is allocated at different assurances of supply. It additionally offers a new approach that can be used to incorporate economic models into hydrological models and therefore allow for further economic optimization of water resources systems.

Apart from annual costs due to risk of failure, opportunity costs due to allocation of water at unnecessarily high assurance of supply emerged as a significant cost that need to be considered in economic analyses of water resources allocation processes. Opportunity cost due to allocation of water at unnecessarily high assurance of supply is the revenue that is forfeited when the excessive assurance of supply is applied. From Figure 4.2, each reduction in the assurance of supply resulted in an increased yield. However, it can be observed that not all reductions in the assurance of supply result in a subsequent increase in the net benefits. Normally, it would have been expected that the highest revenue would be achieved when water is allocated at the lowest reliability (in this case 1:5 assurance of supply). But on assessment of each revenue (net benefit) from each assurance of supply, the highest revenue of R 899 x 10<sup>6</sup> was achievable at 1:18 assurance of supply. In other words, if water was to be allocated at 1:10 assurance of supply, then the R 899 x 10<sup>6</sup> would be forfeited for a lesser revenue of R 867 x 10<sup>6</sup> or even R 746 x 10<sup>6</sup> if water was allocated at a 1:5 assurance of supply.

Generally, most South African water resources systems serve all sectors of the economy (urban, agriculture, mining etc.). Therefore, given that South Africa uses a priority classification system in its risk-based water allocation process, sticking to high assurances of supply can result in severe implications to the economy. This is because, apart from the less prioritised users/sectors being denied access to water, even emerging users will be denied access to the limited resource to satisfy the high reliability of existing users. In this regard, revenue that would have been derived from less prioritised or emerging users would be forfeited (opportunity cost). Allocation of water to different sectors of the economy in a country that is already water stressed will always result in inter-sectoral conflicts. Stopping these conflicts would imply that all the country's sectoral demands are met, and hence avoiding opportunity costs.

However, a zero-opportunity cost moment is not feasible due to temporal variations of water availability. From Figure 2.1, it is seen that the government is already financially straining to increase its water availability. Nonetheless, sufficient water does not necessarily refer to peak flows, but rather a sustained flow. In any case, it is not only the volume of water that plays an important role but also the assurance of supply (or reliability). The opportunity cost associated with water allocation at excessive assurances of supply can be lowered by reducing the assurance of supply towards the optimal reliability for the resource of the licenced water allocations. This is because calculated reduction of assurance of supply will result in increased volume of allocable water that can cater for both existing and emerging water users/sectors.

#### **4.4 An evaluation to determine if the optimum assurance of supply level varies with the hydrological regime of the system.**

In previous section (Section 4.3) it was shown that a reduction in the assurance of supply will result in the increase of economic productivity of a water resource system up to a certain optimum level. However, each water resource has its unique characteristics and therefore may be economically optimised at different assurance of supply levels. Consequently, the aim of this section was to evaluate whether the optimum assurance of supply of 1:18, as determined for Tzaneen Dam system, remains the same or varies with different water resources systems. The evaluation was undertaken using four other systems that are characterized by different hydrological regimes, namely:

1. Midmar Dam in Thukela water management area
2. Goedertrouw Dam in Usuthu to Mhlathuze water management area
3. Mokolo Dam in Limpopo water management area
4. Boegeberg Dam in Lower Orange water management area

As was done for the Tzaneen Dam, yield analysis modelling was undertaken to produce the yield-reliability characteristic curves as illustrated in Figures 4.3, to 4.6 for Midmar, Goedertrouw, Mokolo, and Boegeberg Dams, respectively. Tables 4.7, to 4.10 show the water availability and corresponding assurances of supply, respectively.

Generally, there is increase in water availability with each reduction of assurance of supply for all dams.

Normally, shapes of YRC's take an inverted sigmoid curve shape, which can be relatively steep, gently sloping, or almost flat – with some dropping to almost zero yield at higher assurance of supply. Resources with YRCs that drop to almost zero yield at higher reliability indicate systems of less stable hydrological regimes, tending to seasonal systems. For example, from Figures 4.3 to 4.6, it is evident that while YRC's for Midmar and Goedertrouw Dams did not approach zero (Figures 4.3 and 4.4), the YRCs for Mokolo and Boegeberg Dams have relatively little water at higher reliability (Figures 4.5 and 4.6).

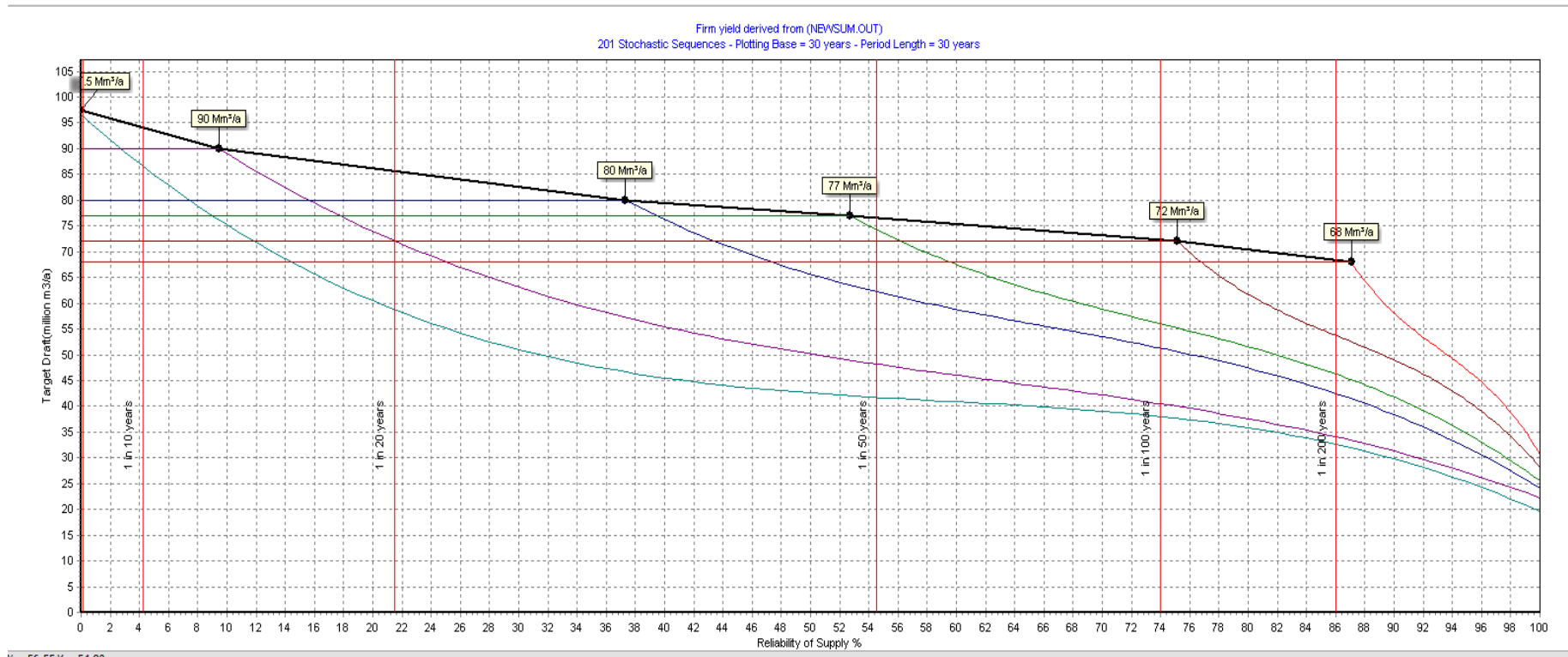


Figure 4.3: Yield-reliability characteristic curves for Midmar Dam

Table 4.7: Water availability at selected assurances of supply for Midmar Dam

Assurance of Supply	1:200	1:100	1:50	1:20	1:10	1:5
Yield ( $\times 10^6 \text{m}^3/\text{a}$ )	68	72	76.5	85.5	94	97.5
Incremental yield ( $\times 10^6 \text{m}^3/\text{a}$ )	-	4	4.5	9	8.5	3.5

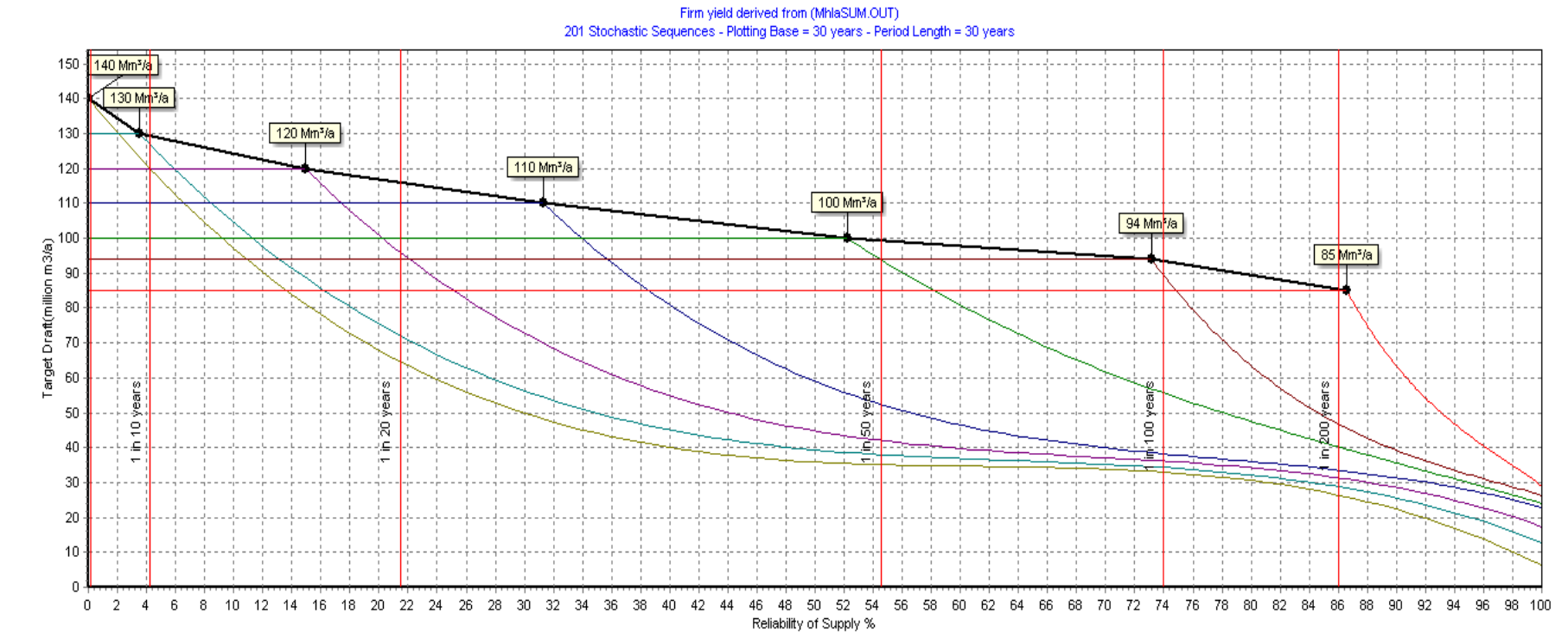


Figure 4.4: Yield-reliability characteristic curves for Goedertrouw Dam

Table 4.8: Water availability at selected assurances of supply for Goedertrouw Dam

Assurance of Supply	1:200	1:100	1:50	1:20	1:10	1:5
Yield ( $\times 10^6 \text{m}^3/\text{a}$ )	86	93	100	116	130	140
Incremental yield ( $\times 10^6 \text{m}^3/\text{a}$ )	-	7	7	16	14	10

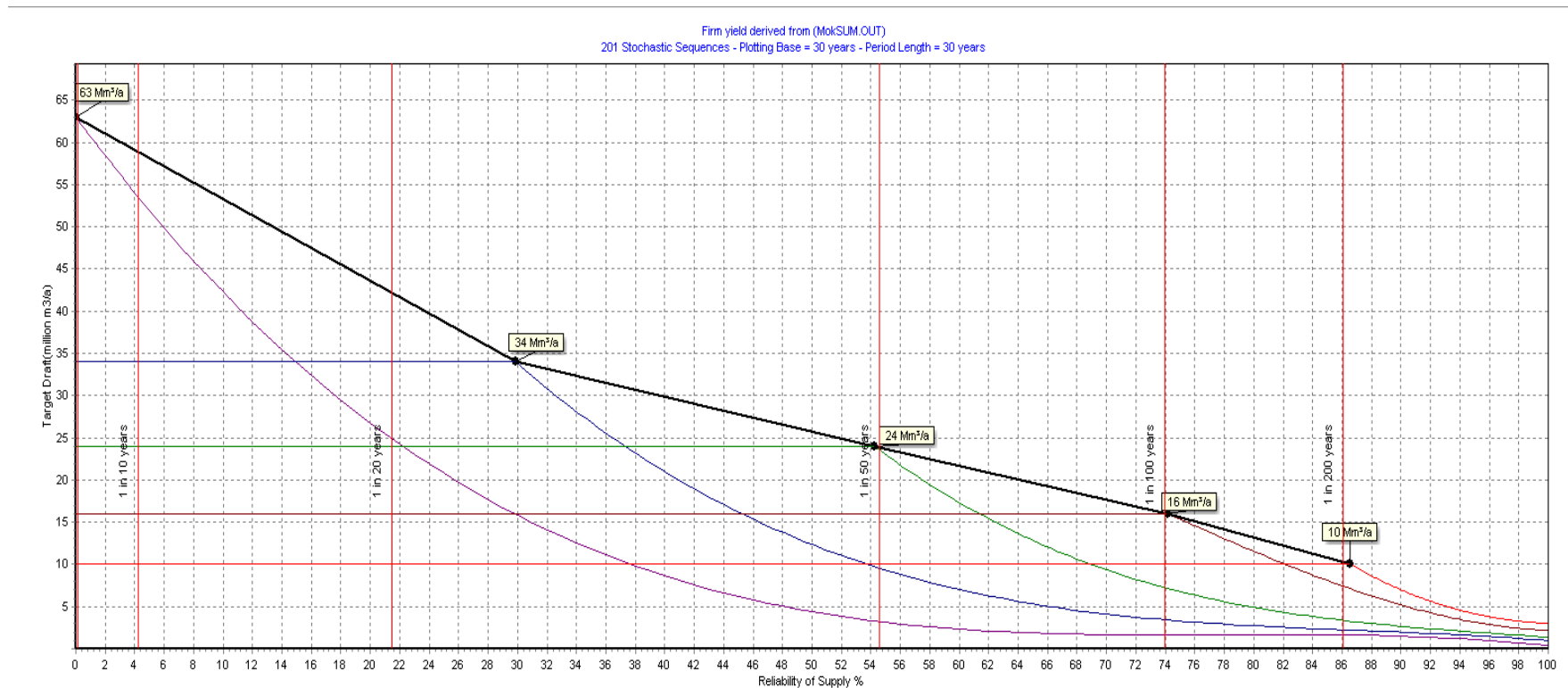


Figure 4.5: Yield-reliability characteristic curves for Mokolo Dam

Table 4.9: Water availability at selected assurances of supply for Mokolo Dam

Assurance of Supply	1:200	1:100	1:50	1:20	1:10	1:5
Yield ( $\times 10^6 \text{m}^3/\text{a}$ )	10.5	16	23.5	41.5	55	63
Incremental yield ( $\times 10^6 \text{m}^3/\text{a}$ )	-	5.5	7.5	18	13.5	8

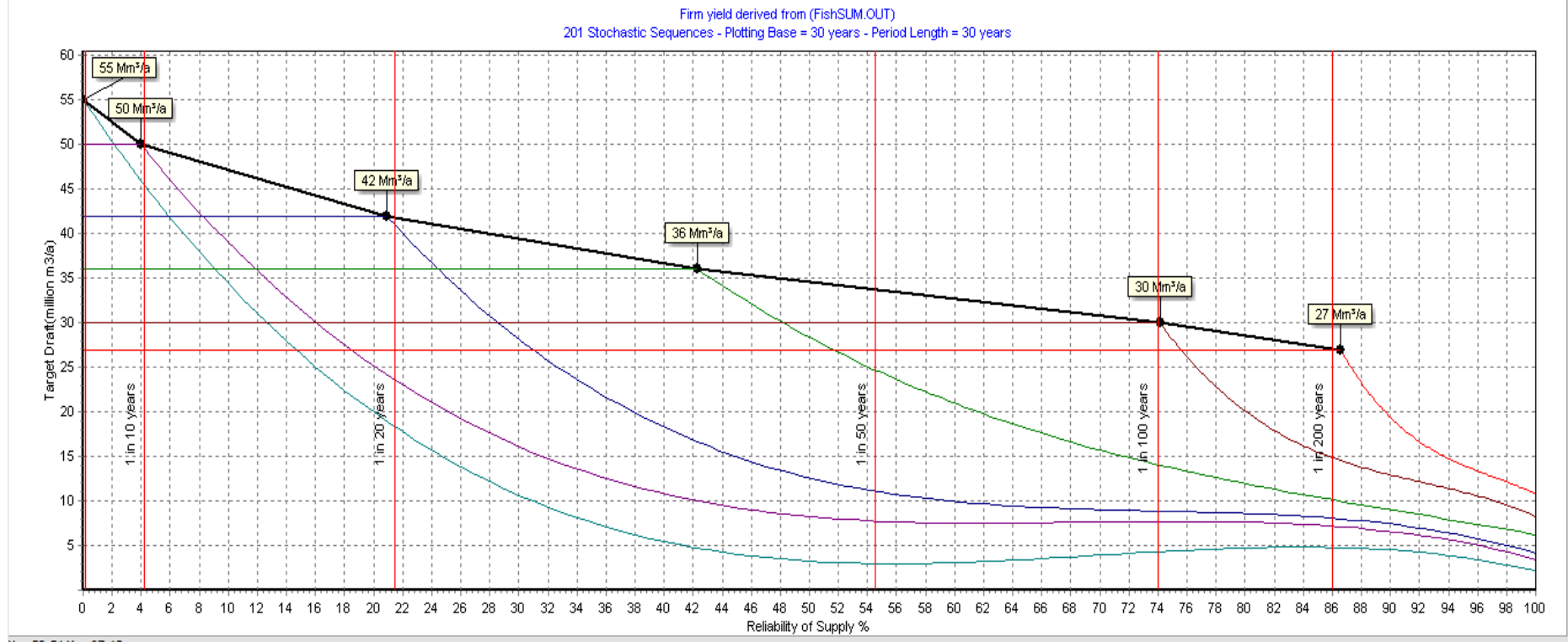


Figure 4.6: Yield-reliability characteristic curves for Boegeberg Dam

Table 4.10: Water availability at selected assurances of supply Boegeberg Dam

Assurance of Supply	1:200	1:100	1:50	1:20	1:10	1:5
Yield (x10 <sup>6</sup> m <sup>3</sup> /a)	27.5	30	34	42	50	55
Incremental yield (x10 <sup>6</sup> m <sup>3</sup> /a)	-	2.5	4	8	8	5

Similar to the analysis in Section 4.3, this analysis also used citrus production for its economic analysis. The same procedure used to carry out the economic analysis of the net benefits emanating from Tzaneen Dam at different assurances of supply was also adopted in this analysis. Therefore, with the determined yields from the four water resources at each assurance of supply, the cost of production, establishment costs and the annual cost due to risk of failure, the net benefits emanating from the four water resources at the different assurances of supply were computed.

Table 4.11 was similarly computed as was done for Table 4.6 to provide results for the evaluation analysis. It illustrates the annual net benefits emanating from Midmar Dam, Goedertrouw, Mokolo and Boegeberg Dams at 1:100, 1:50, 1:20, 1:10 and 1:5 assurances of supply, respectively. It was observed that each reduction in assurance of supply from each water resource resulted in an increase in the volume of allocable water. With each increase of allocable water, there was a resultant increase in the irrigable land and ultimately an increase in the production costs, establishment costs, annual cost due to risk of failure and the benefits generated. Despite the reductions in assurances of supply resulting in increase of yield of water, land for irrigation and therefore increase in citrus produce, not every reduction in assurance of supply resulted in increase of net benefits. It is also noted that different water resources systems have their optimum benefits at slightly different assurances of supply.

Table 4.11: Computations of net benefits emanating from different water resources at selected assurances of supply.

Water resource	Assurance of supply	Yield (m <sup>3</sup> )	Increased volume of water	Increased irrigable land	Gross income	Establishment cost (Rands)	Capital recovery cost for the establishment cost @11.26% (Rands)	Total cost of orange production. (Rands)	Risk of failure	Expected damage (Rands)	Annual cost due to risk of failure (Rands)	Total annual cost (Rands)	net benefits (Rands)
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)
MIDMAR	1:200	68 x 10 <sup>6</sup>	-	4,533	951,456,000	566,666,667	50,337,000	249,333,333	0.005	951,456,000	4,757,280	304,427,613	647,028,387
	1:100	72 x 10 <sup>6</sup>	4. x 10 <sup>6</sup>	4,800	1,007,424,000	600,000,000	53,298,000	264,000,000	0.01	1,007,424,000	10074240	327,372,240	680,051,760
	1:50	76.5 x 10 <sup>6</sup>	4.5 x 10 <sup>6</sup>	5,100	1,070,388,000	637,500,000	56,629,125	280,500,000	0.02	1,070,388,000	21407760	358,536,885	711,851,115
	1:20	85.5 x 10 <sup>6</sup>	9 x 10 <sup>6</sup>	5,700	1,196,316,000	712,500,000	63,291,375	313,500,000	0.05	1,196,316,000	59815800	436,607,175	759,708,825
	1:10	94 x 10 <sup>6</sup>	8.5 x 10 <sup>6</sup>	6,267	1,315,248,000	783,333,333	69,583,500	344,666,667	0.1	1,315,248,000	131524800	545,774,967	769,473,033
	1:5	97.5 x 10 <sup>6</sup>	3.5 x 10 <sup>6</sup>	6,500	1,364,220,000	812,500,000	72,174,375	357,500,000	0.2	1,364,220,000	272844000	702,518,375	661,701,625
GOEDERTO UW	1:200	86 x 10 <sup>6</sup>	-	5,733	1,203,312,000	716,666,667	63,661,500	315,333,333	0.005	1,203,312,000	6016560	385,011,393	818,300,607
	1:100	93 x 10 <sup>6</sup>	7 x 10 <sup>6</sup>	6,200	1,301,256,000	775,000,000	68,843,250	341,000,000	0.01	1,301,256,000	13012560	422,855,810	878,400,190
	1:50	100 x 10 <sup>6</sup>	7 x 10 <sup>6</sup>	6,667	1,399,200,000	833,333,333	74,025,000	366,666,667	0.02	1,399,200,000	27984000	468,675,667	930,524,333
	1:20	116 x 10 <sup>6</sup>	16 x 10 <sup>6</sup>	7,733	1,623,072,000	966,666,667	85,869,000	425,333,333	0.05	1,623,072,000	81153600	592,355,933	1,030,716,067
	1:10	130 x 10 <sup>6</sup>	14 x 10 <sup>6</sup>	8,667	1,818,960,000	1,083,333,333	96,232,500	476,666,667	0.1	1,818,960,000	181896000	754,795,167	1,064,164,833
	1:5	140 x 10 <sup>6</sup>	10 x 10 <sup>6</sup>	9,333	1,958,880,000	1,166,666,667	103,635,000	513,333,333	0.2	1,958,880,000	391776000	1,008,744,333	950,135,667

Table 4.11: Continued

MOKOLO	1:200	10.5 x 10 <sup>6</sup>	-	700	146,916,000	87,500,000	7,772,625	38,500,000	0.005	146,916,000	734580	47,007,205	99,908,795
	1:100	16 x 10 <sup>6</sup>	5.5 x 10 <sup>6</sup>	1,067	223,872,000	133,333,333	11,844,000	58,666,667	0.01	223,872,000	2238720	72,749,387	151,122,613
	1:50	23.5 x 10 <sup>6</sup>	7.5 x 10 <sup>6</sup>	1,567	328,812,000	195,833,333	17,395,875	86,166,667	0.02	328,812,000	6576240	110,138,782	218,673,218
	1:20	41.5 x 10 <sup>6</sup>	18 x 10 <sup>6</sup>	2,767	580,668,000	345,833,333	30,720,375	152,166,667	0.05	580,668,000	29033400	211,920,442	368,747,558
	1:10	55 x 10 <sup>6</sup>	13.5 x 10 <sup>6</sup>	3,667	769,560,000	458,333,333	40,713,750	201,666,667	0.1	769,560,000	76956000	319,336,417	450,223,583
	1:5	63 x 10 <sup>6</sup>	8 x 10 <sup>6</sup>	4,200	881,496,000	525,000,000	46,635,750	231,000,000	0.2	881,496,000	176299200	453,934,950	427,561,050
BOEGERBER G DAM	1:200	27.5 x 10 <sup>6</sup>	-	1,833	384,780,000	229,166,667	20,356,875	100,833,333	0.005	384,780,000	1923900	123,114,108	261,665,892
	1:100	30 x 10 <sup>6</sup>	2.5 x 10 <sup>6</sup>	2,000	419,760,000	250,000,000	22,207,500	110,000,000	0.01	419,760,000	4197600	136,405,100	283,354,900
	1:50	34 x 10 <sup>6</sup>	4 x 10 <sup>6</sup>	2,267	475,728,000	283,333,333	25,168,500	124,666,667	0.02	475,728,000	9514560	159,349,727	316,378,273
	1:20	42 x 10 <sup>6</sup>	8 x 10 <sup>6</sup>	2,800	587,664,000	350,000,000	31,090,500	154,000,000	0.05	587,664,000	29383200	214,473,700	373,190,300
	1:10	50 x 10 <sup>6</sup>	8 x 10 <sup>6</sup>	3,333	699,600,000	416,666,667	37,012,500	183,333,333	0.1	699,600,000	69960000	290,305,833	409,294,167
	1:5	55 x 10 <sup>6</sup>	5 x 10 <sup>6</sup>	3,667	769,560,000	458,333,333	40,713,750	201,666,667	0.2	769,560,000	153912000	396,292,417	373,267,583

Figure 4.7 illustrates graphically the results of net benefits and yield against assurance of supply of Midmar Dam, Goedertrouw Dam, Mokolo Dam and Boegeberg Dam, respectively. From the Figure 4.7, it can be seen that the yield from each water resource increased with each reduction of the assurance of supply. However, different water resources systems exhibited different increments with each reduction of the assurance of supply. For instance, whereas a reduction from 1:100 to 1:50 assurance of supply, in Goedertrouw Dam resulted in a  $7 \times 10^6 \text{ m}^3/\text{a}$  increment, the same reduction margin resulted in a  $16 \times 10^6 \text{ m}^3/\text{a}$  increment for Mokolo Dam. It was also observed that both Mokolo and Boegeberg Dams had the same yield  $40 \times 10^6 \text{ m}^3/\text{a}$ , at 1:20 assurance of supply. Therefore, with both Mokolo and Boegeberg Dams having an approximate similar yield at 1:20 assurance of supply, they also had approximately similar net benefits of R  $580 \times 10^6$  at the same assurance of supply.

It was also observed that all dams exhibited increase in net benefits with increasing reduction in assurance of supply up to a certain point. The plots were however not the same as different water resources systems exhibited different net benefits at different levels of assurance of supply and therefore their optimum net benefits occurred at different assurances of supply. This phenomenon can be attributed to different water resources experiencing different and unique hydrological regimes. Midmar, Goedertrouw, Mokolo and Boegeberg Dams exhibit their optimum net benefits at 1:12, 1:12, 1:8 and 1:10 assurances of supply, respectively.

Given that different water resources systems have their maximum annual net benefits at different assurances of supply, it can be concluded that the relationship between economic productivity and assurance of supply of a water resource is sensitive to the hydrologic regime of the resource. These results signify that different water resources systems can be optimised at different assurances of supply. The results concur with Basson *et al.* (1994) and Rugumayo *et al.* (2001) arguments, that each water resource has its own unique characteristics, and therefore, different water resources systems will have their optimum net benefits at different reliabilities.

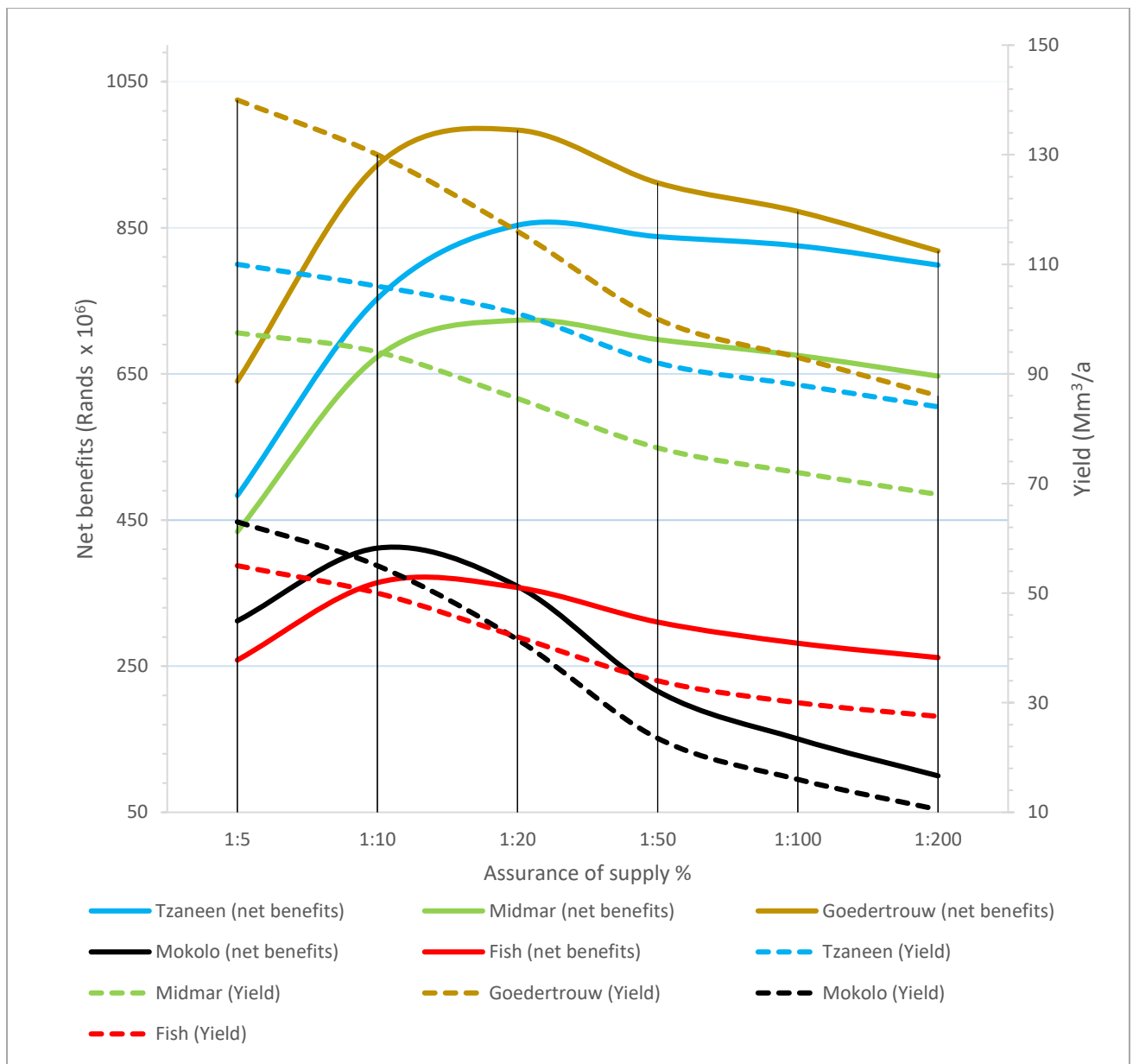


Figure 4.7: Relationships of net benefits and yield against assurances of supply of the different water resources systems

Results from Table 4.11 illustrated that water resources characterized by less stable regimes could only be optimized at relatively lower assurances of supply than those with more stable regimes. This conclusion can be attributed to the fact that allocation of water at high assurance of supply on resources with less stable regimes will have more severe impacts – because the systems will tend to be closed much earlier from further allocation to users. In contrast, allocation of water at high assurance of supply on resources with relatively stable hydrological regimes has less impacts because it takes longer before closing the system from allocating more water to more users.

## CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusion

The study aimed at developing an alternative framework for availing additional water in a given water resource system. This would enable progressive water allocation from systems with a growing demand and also mitigate water losses through spillage during wetter seasons. In this regard it was hypothesised that the yield of water from a dam or system could be increased by reducing its assurance of supply to achieve better economic productivity. To achieve its objectives, the study formulated three specific analyses (section 1.5).

The comparative analysis entailed assessing whether economic benefits of the WCWSS could be achieved by reducing its current assurance of supply and comparing it with the benefits obtained by the intended BRVAS project development. The BRVAS project is being developed to increase WCWSS's yield by  $23 \times 10^6 \text{ m}^3$  at its present reliability of 1:50. The same yield increase could be achieved by reducing the system's present assurance of supply from 1:50 to 1:30 (Table 3.3). Results are summarised in Table 4.2, showing that increasing the yield of WCWSS by reducing the assurance of supply has more economic benefits of R  $91.7 \times 10^6$  when compared to increasing the yield by the BRVAS infrastructural project of R  $15.5 \times 10^6$ . The economic benefits due to the option of reducing the system's reliability is superior to the BRVAS development option even before considering other costs associated with such infrastructural development options, such as compensation to displaced people or assets, environmental costs associated with damage to the environment and costs related protestations linked to those denied access to water of the resource, which are avoided when the yield of the water resource is increased by the option of reducing assurance of supply.

Given that water resource augmentation developments are long-term projects, for better decision making that take into account time value of money, a life cycle cost analysis (LCCA) of the two interventions (BRVAS project and reduction of WCWSS's present assurance of supply) was also undertaken. Results from the LCCA (Tables 4.3 and 4.4) supported the results obtained by the annual net benefits comparative

analysis. Considering prevailing limitation of financial resources in the country and the growing water demand situation in the basin, it can be seen that the option of reducing the assurance of supply offers a more cost-effective and time-efficient method for increasing the necessary yield of water from the WCWSS.

The second objective was based on the hypothesis that through well-calculated reductions of assurance of supply of a given water resource system, its yield can be increased to some optimal level and offer progressive water allocation that would improve the system's economic productivity. Using Tzaneen Dam, the hypothesis was assessed by analysing the trend of economic benefit changes as the assurance of supply of allocable water was reduced in steps at 1:200, 1:100, 1:50, 1:20, 1:10 and 1:5. The economic benefits continued to increase as the assurance of supply was reduced up to a certain point then started falling again (column N of Table 4.6). Plot of the results show that the maximum economic benefits occur at about 1:18 assurance of supply (Figure 4.2), which is therefore taken as the optimum assurance of supply for Tzaneen Dam.

Given that different water resources are unique hydrologically, the third objective aimed at testing if the optimum assurance of supply is sensitive to different hydrological regimes. The study therefore performed a similar sensitivity analysis as conducted for Tzaneen Dam to four other water resources, namely, Midmar Dam, Goedertouw Dam, Mokolo Dam and Boegeberg Dam. Results from this analysis demonstrated that different water resources are optimized at slightly different assurances of supply. It was observed that Midmar, Goedertouw, Mokolo and Boegeberg Dams exhibited their maximum net benefits at 1:12, 1:12, 1:8 and 1:10 assurances of supply, respectively (Figure 4.7).

Overall, the study highlighted the prospects of using reduction of assurance of supply as an alternative method of increasing water availability from a system. It also highlighted the need of incorporating the cost associated with risk of failure in economic analysis of water resources as necessary optimization process.

## 5.2 Recommendations

Although the study demonstrated that allocation of water resources at relatively excessive assurance of supply result in opportunity costs, it was based on only the irrigation sector meant to simplify the economic analysis. Economic analyses of water resources in real world water allocation processes, with several sectors/users like the urban, irrigation, hydropower, industrial and mining users, among others, can be much more complex than presented here. The complexity may be attributed to different water users having different marginal benefits, risk tolerance, priority ranking, besides other things. Further research of economic analysis in water resources allocation processes that can put other water use sectors into consideration is therefore recommended.

## REFERENCES

Adeyemo, J.A., 2011. Reservoir operation using multi-objective evolutionary algorithms-a review. Available from: [https://www.researchgate.net/publication/49941840\\_Reservoir\\_Operation\\_using\\_Multi-objective\\_Evolutionary\\_Algorithms-A\\_Review](https://www.researchgate.net/publication/49941840_Reservoir_Operation_using_Multi-objective_Evolutionary_Algorithms-A_Review)

Andersson, L., Wilk, J., Todd, M.C., Hughes, D.A., Earle, A., Kniveton, D., Layberry, R. and Savenije, H.H., 2006. Impact of climate change and development scenarios on flow patterns in the Okavango River. *Journal of Hydrology*.

Ansink, E. and Ruijs, A., 2008. Climate change and the stability of water allocation agreements. *Environmental and Resource Economics*, 41(2).

Bailey, AK and Pitman, WV., 2016. Water resources for South Africa, 2012 study (WR2012), Books of maps. (WRC REPORT NO. TT 685/16), Pretoria, South Africa.

Armer, D. (1998). *The management of water resources through simulation*. Faculty of Economic and Management Sciences. The University of Pretoria.

Barnard, S. and Cloete, R., 2019. Economic study of assurance of supply requirements for water resource management with reference to irrigation agriculture. *WRC Report*, (TT775/1/18).

Basson, M.S., Allen, R.B., Pegram, G.G.S. and Van Rooyen, J.A., 1994. *Probabilistic management of water resource and hydropower systems*. Water Resources Publications.

Ben-Haim, Y., 2006. Info-gap decision theory: decisions under severe uncertainty. Elsevier.

Bronkhorst, S., Pengelly, C. and Seyler, H., 2017. Water 2017 Market Intelligence Report. *Greencape: Cape Town, South Africa*.

Briscoe, J., 1996, September. Water as an economic good: The idea and what it means in practice. In *World Congress of the International Commission on Irrigation and Drainage, Cairo*.

Campos, J.N.B., 2010. Modeling the yield–evaporation–spill in the reservoir storage process: The regulation triangle diagram. *Water resources management*, 24(13).

Chang, L.C., and Chang, F.J., 2001. Intelligent control for modelling of real-time reservoir operation. *Hydrological processes*, 15(9), pp.1621-1634.

Chen, L., and Chang, F.J., 2007. Applying a real-coded multi-population genetic algorithm to multi-reservoir operation. *Hydrological Processes: An International Journal*, 21(5), pp.688-698.

City of Cape Town (CoCT) 2018a. Water Outlook 2018 (Updated May 2018).

Cui, L.J. and Kuczera, G., 2003. Optimizing urban water supply headworks using probabilistic search methods. *Journal of water resources planning and management*, 129(5), pp.380-387.

DAFF (Department of Agriculture, Forestry & Fisheries). 2019. Local market fruit sales data. Pretoria: Directorate of Agricultural Statistics, Pretoria, South Africa.

Dennis, I. and Dennis, R., 2012. Climate change vulnerability index for South African aquifers. *Water SA*, 38(3), pp.417-426.

Department of Water Affairs (DWAf), 2010. Preliminary design of the raising of Tzaneen Dam: Volume 7. Report number P WMA 02/B810/00/0608/7, Department of Water Affairs, Pretoria, South Africa.

Department of Water Affairs South Africa, 1986. Management of the water resources of the Republic of South Africa.

System Reconciliation Strategy Study. Prepared by Ninham Shand (Pty) Ltd and UWP Consulting (Pty) Ltd.

Department of Water and Sanitation (DWS) 2017. Strategic overview of the water sector in South Africa 2017. Pretoria, South African Government.

Department of Water and Sanitation (DWS), 2015. Support to the continuation of the water reconciliation strategy for the Western Cape water supply system: status report October 2015. Pretoria, South African Government.

Department of Water and Sanitation, DWS (2021). Mokolo system annual operating analysis (2020/2021), Department of Water and Sanitation, Pretoria, South Africa.

Department of Water and Sanitation (DWS), South Africa. 2019. Western Cape Water Supply System Annual Operating Analysis for 2018/2019 prepared by Aurecon South Africa (Pty) Ltd. Final. Report number P RSA 000/00/23019, Department of Water and Sanitation, Pretoria, South Africa

Department of Water and Sanitation (DWS), . 2019. Determination of water availability (yield & assurance of supply) and water allocation considerations (Unpublished), Department of Water and Sanitation, Pretoria, South Africa

Department of Water and Sanitation (DWS). 2018. National water and sanitation master plan, Volume 1: Call to action, Department of Water and Sanitation, Pretoria, South Africa

Department of Water and Sanitation, South Africa, 2019. Gazette Notice on proposal to construct the BERG RIVER – VOELVLEI AUGMENTATION SCHEME in terms of section 110 of the national water act, 1998 (ACT NO. 36 OF 1998), Department of Water and Sanitation, Pretoria, South Africa

Department of Water and Sanitation, 2016. Environmental Impact Assessment for the Proposed Surface Water Developments for Augmentation of the Western Cape Water Supply System, Department of Water and Sanitation, Pretoria, South Africa.

Department of Water and Sanitation, DWS (2018a). Water Outlook 2018 Report, Department of Water and Sanitation, Pretoria, South Africa.

Economists, C., 2014. A manual for cost-benefit analysis in South Africa with specific reference to water resource development (Vol. 8). WRC Report Pretoria, South Africa.

Ekierman, C., Mejia, J., Rodrigues, C., Berry, R.S. and Tolley, G.S., 2015. The Construction of the Baihetan Dam: A Cost-Benefit Analysis. A project report submitted to the University of Chicago USA. [online][accessed 16th March 2017] via <http://franke.uchicago.edu/bigproblems/BPRO29000-2015/Team15-CostBenefitAnalysisoftheBaihetanDamProject.pdf>.

Ellis, F. and Laubscher, J., 2017. EIA for the proposed Berg River Voelviei Augmentation Scheme (also known as the first Phase Augmentation of the Voelviei Dam), Boland sub-region, Western Cape Province.

Faaiaqa, H., James, C., and Kenneth, M. S., 2021. Hydro-economic modelling of the Western Cape Water Supply System, Pretoria, South Africa.

Farmers Weekly Magazine 2015, Buying agricultural land-know your market. Available from <https://www.farmersweekly.co.za> [15 December 2021].

Flyvbjerg, F.B., Ansar, A. and Budzier, A., 2013. Dam downsides. *New Scientist*, 218(2921).

Fruitrop online magazine 2014,'Cultivation of table grapes. Available from: <https://www.fruitrop.com/en/Articles-by-subject/Agronomy/2014/Cultivation-of-table-grapes> [14th July 2021].

Griffin, R.C., 2006. *Water resource economics: The analysis of scarcity, policies, and projects*. MIT press.

Gude, V.G., 2017. Desalination and water reuse to address global water scarcity. *Reviews in Environmental Science and Bio/Technology*, 16(4), pp.591-609.

Haque, M.M., Ahmend, A. and Rahman, A., 2013. Impacts of water price and restrictions on water demand: A case study for Australia. *Water conservation: Practices, challenges and future implications*, pp.127-145.

Hussain, I., Turrall, H. and Molden, D., 2007. Measuring and enhancing the value of agricultural water in irrigated river basins. *Irrigation Science*.

Jawad, D. and Ozbay, K., 2006, January. The discount rate in life cycle-cost analysis of transportation projects. In *85th Annual TRB Meeting, Washington, DC*.

Konikow, L.F. and Kendy, E., 2005. Groundwater depletion: A global problem. *Hydrogeology Journal*, 13(1), pp.317-320.

Labadie, J.W., 2004. Optimal operation of multireservoir systems: State-of-the-art review. *Journal of water resources planning and management*, 130(2), pp.93-111.

Lange, G.M., 2007. Case studies of water valuation in Namibia's commercial farming areas. *The Economics of Water Management in Southern Africa: An Environmental Accounting Approach*; Lange, GM, Hassam, R., Eds, pp.237-255.

Linsley, R.K. and Franzini, J.B., 1964. *Water-resources engineering* (No. 628.1 L5).

Liuzzo, L., Notaro, V. and Freni, G., 2016. A reliability analysis of a rainfall harvesting system in southern Italy. *Water*, 8(1).

Loomis, J.B., 2000. Environmental valuation techniques in water resource decision making. *Journal of water resources planning and management*, 126(6), pp.339-344.

Makungo, R. (2009). An operating strategy of run-of-river abstractions for typical rural water supply schemes using Siloam Village as a case study (Doctoral dissertation).

Mankhili, N., 2015. BUSINESS PLAN FOR MAKONDE LUNGANE CITRUS AND MANGO PRIMARY CO-OPERATIVE LTD IN VHEMBE DISTRICT THULAMELA LOCAL MUNICIPALITY. Available from: <http://webapps.daff.gov.za/AmisAdmin/upload/MANKHILI%20LUNGANE%20%20%20Business%20Plan.pdf> [29th November 2021]

Maré, H.G., Mwaka, B. and Sinha, P., 2007. Development of simplified drought operating rules.

Martinez-Ibarra, E. (2015). Climate, water and tourism causes and effects of droughts associated with urban development and tourism in Benidorm (Spain). *International Journal of Biometeorology*, 59(5), 487-501.

Midgley, G.F., Hannah, L., Millar, D., Thuiller, W. and Booth, A., 2003. Developing regional and species-level assessments of climate change impacts on biodiversity in the Cape Floristic Region.

Mirrilees, R.I., Forster, S.F., and Williams, C.J., 1994. *The application of economics to water management in South Africa* (No. 99). Water Research Commission.

Molobela, I.P. and Sinha, P., 2011. Management of water resources in South Africa: A review. *African Journal of Environmental Science and Technology*, 5(12), pp.993-1002.

Ndiritu, J.G., 2003. Reservoir system optimisation using a penalty approach and a multipopulation genetic algorithm. *Water SA*, 29(3), pp.273-280.

Ndiritu, J.G., 2005. Maximising water supply system yield subject to multiple reliability constraints via simulation-optimisation. *Water SA*, 31(4), pp.423-434.

Oliveira, R. and Loucks, D.P., 1997. Operating rules for multireservoir systems. *Water resources research*, 33(4), pp.839-852.

ORASECOM 2020. Optimized IWRMP core scenario economic approach: Preparation of climate resilient water resources investment strategy and plan and Lesotho-Botswana water transfer multipurpose transboundary project, Draft 2. Report number: ORASECOM 009/2020

Ozbay, K., Parker, N.A., Jawad, D. and Hussain, S., 2003. Guidelines for Life Cycle Cost Analysis, Final Report.

Pearce, D., 1998. Cost-benefit analysis and environmental policy. *Oxford review of economic policy*, 14(4).

Pengelly, C., Seyler, H., Fordyce, N., Van Vuuren, P.J., Van Der Walt, M., Van Zyl, H. and Kinghorn, J., 2017. Managing water as a constraint to development with decision-support tools that promote integrated planning: The case of the Berg Water Management Area. *Water Research Commission and Western Cape Government. Pretoria, South Africa.*

Perret, S. and Geysler, M., 2007. The cost of irrigation: adapting existing guidelines to assess the full financial costs of irrigation services. The case of smallholder schemes in South Africa. *Water SA.*

Pienaar, L.O.U.W. and Boonzaaier, J.O.H.A.N.N., 2018. Drought policy brief Western Cape Agriculture. Western Cape Department of Agriculture (WCDoA) and the Bureau for Food and Agricultural Policy (BFAP), Elsenburg.

Quibell, G., Le Quesne, T. and Speed, R., 2013. Basin Water Allocation Planning: International Experience and Lessons. *WWF, Gland (unpublished).*

Rocha, R. and Soares, R.R., 2015. Water scarcity and birth outcomes in the Brazilian semiarid. *Journal of Development Economics.*

Rugumayo, E. and Kizza, M., 2001. Reservoir capacity yield reliability analysis. Available from: <https://wedc-knowledge.lboro.ac.uk/resources/conference/27/Rugumayo.pdf> [17 December 2022]

SANCOLD. (2020). *SA Register of Large Dams*. Available from: <https://sancold.org.za/sa-register-of-large-dams/> [17 December 2022]

SAWIS (2014). South African Wine Exports Analysis 2008 – 2013. Paarl: Analytix Business

Simon, H.A., 1956. Rational choice and the structure of the environment. *Psychological review*, 63(2).

Svoboda, S., 1999. Note on life cycle analysis. *Environmental management: Readings and cases*.

Tahmiscioğlu, M.S., Anul, N., Ekmekçi, F. and Durmuş, N., 2007, March. Positive and negative impacts of dams on the environment. In *International Congress on River Basin Management*.

Trade and Industrial Policy Strategies (TIPS) 2016. The real economy bulletin - second quarter 2016. Briefing note: impacts of the drought. <https://goo.gl/Vf8F6p>.

Trans-Caledon Tunnel Authority (TCTA) 2019, Trans-Caledon Tunnel Authority (TCTA) briefing on the Corporate Plan & Budget for 2020/21, Pretoria, South Africa.

Vinepro 2017. *The 2017 vintage: VINPRO PRODUCTION PLAN SURVEY*. Available from: [https://www.namc.co.za/wp-content/uploads/2018/05/Vinpro-Production-plan-2017\\_English.pdf](https://www.namc.co.za/wp-content/uploads/2018/05/Vinpro-Production-plan-2017_English.pdf) [12 December 2021]

Vinepro 2019. *The 2018 Vintage: A Watershed year for the South African wine industry*. Vinpro production plan survey. Available from: <https://www.namc.co.za/wp-content/uploads/2019/05/Wine-grape-production-cost-2018-harvest.pdf> [11 March 2021]

Young, R.A. and Loomis, J.B., 2014. Determining the economic value of water: concepts and methods. Routledge.

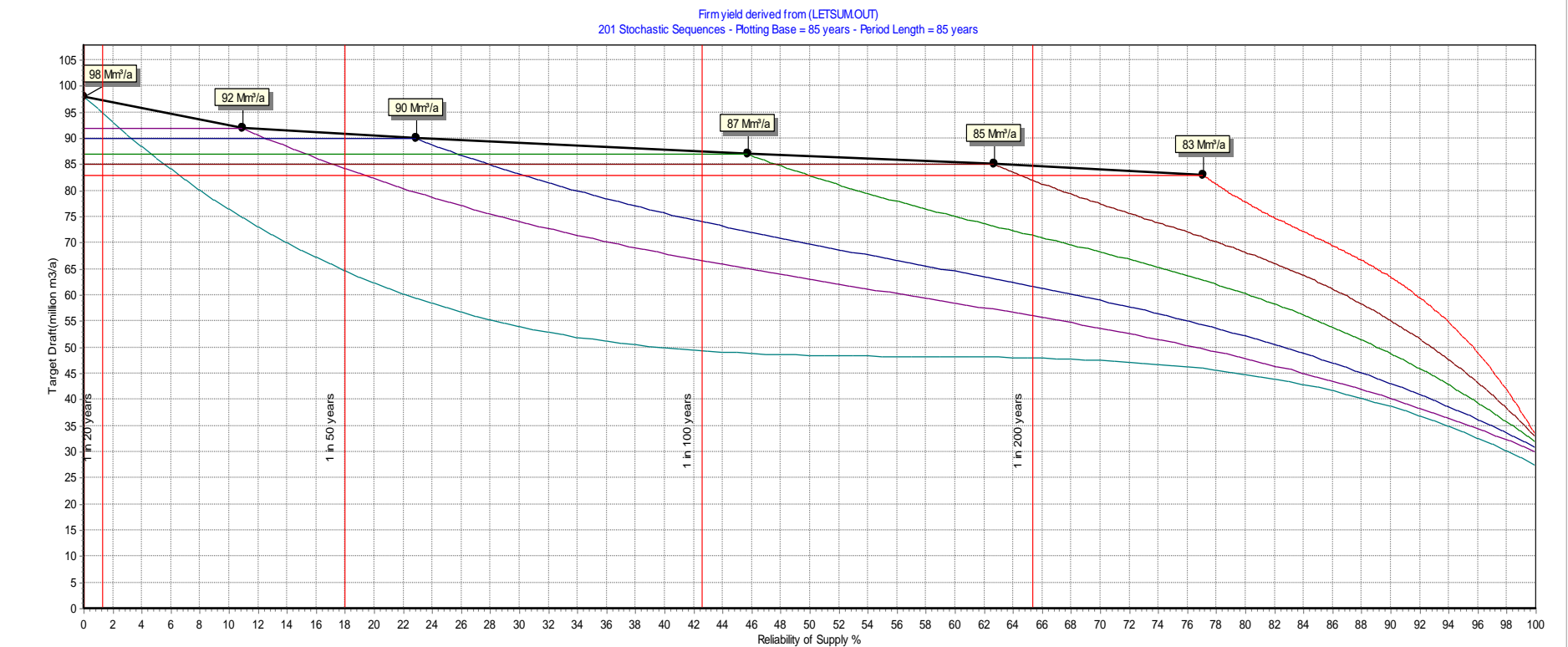
Young, M. and Esau, C., 2015. CHARTING OUR WATER FUTURE: Economic frameworks to inform decision-making. In *Investing in Water for a Green Economy*. Routledge.

## APPENDICES

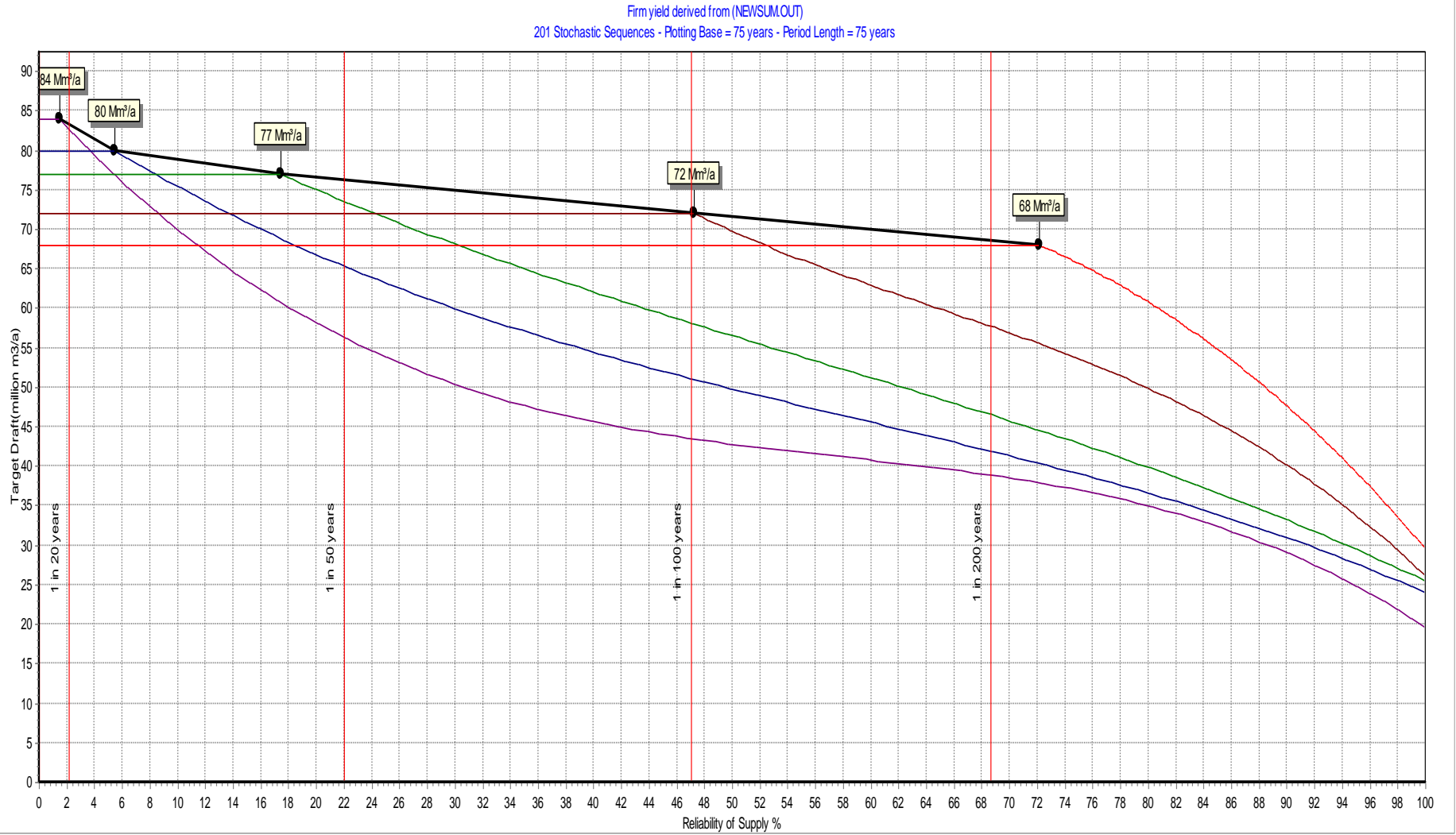
This section provides some results (Figures) that are not presented in the computation results discussion chapters for readers' perusals.

### Appendix A

#### Appendix A1: Long-term yield reliability curves for Tzaneen Dam

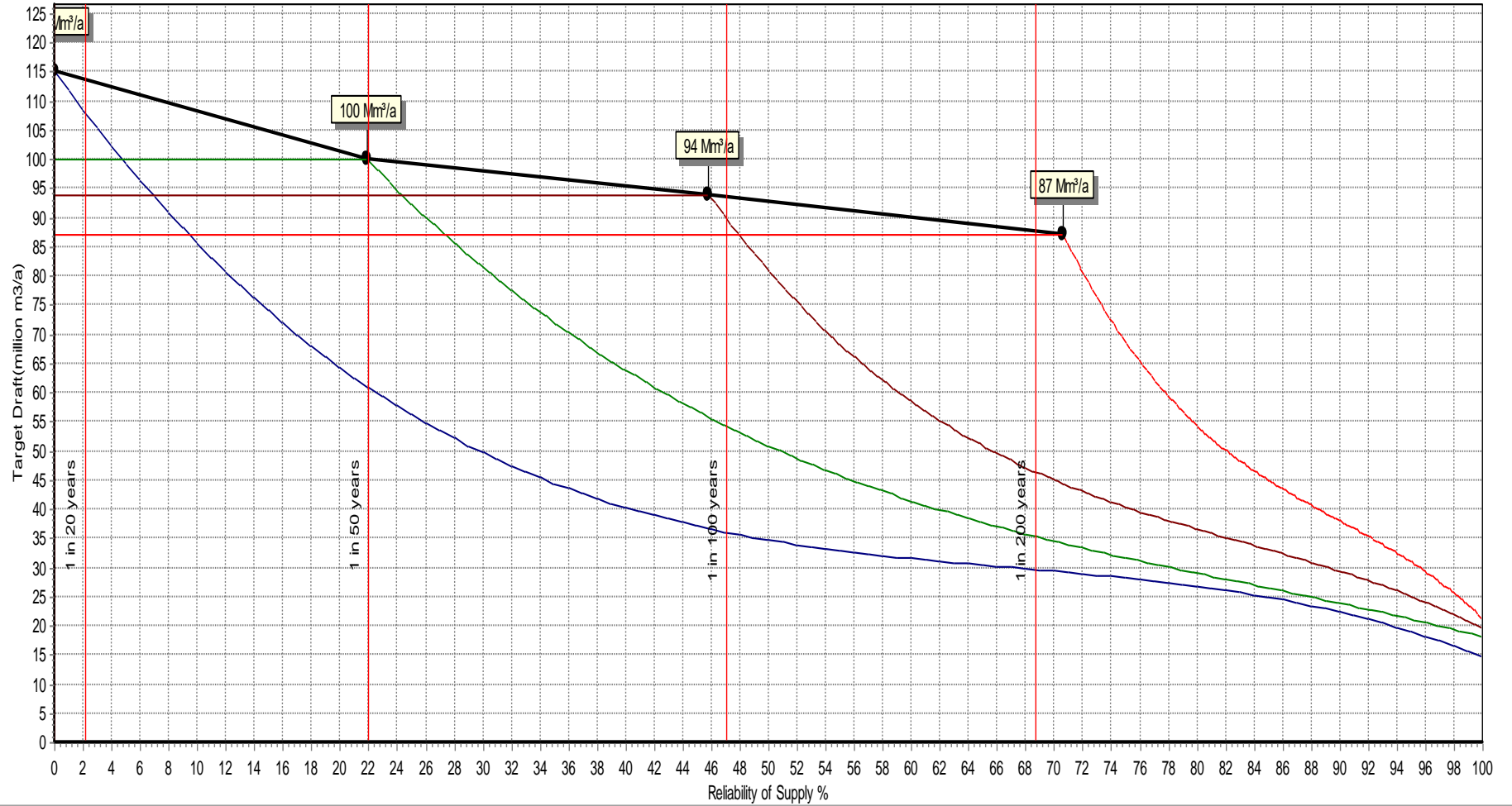


## Appendix A2: Long-term yield reliability curves for Midmar Dam

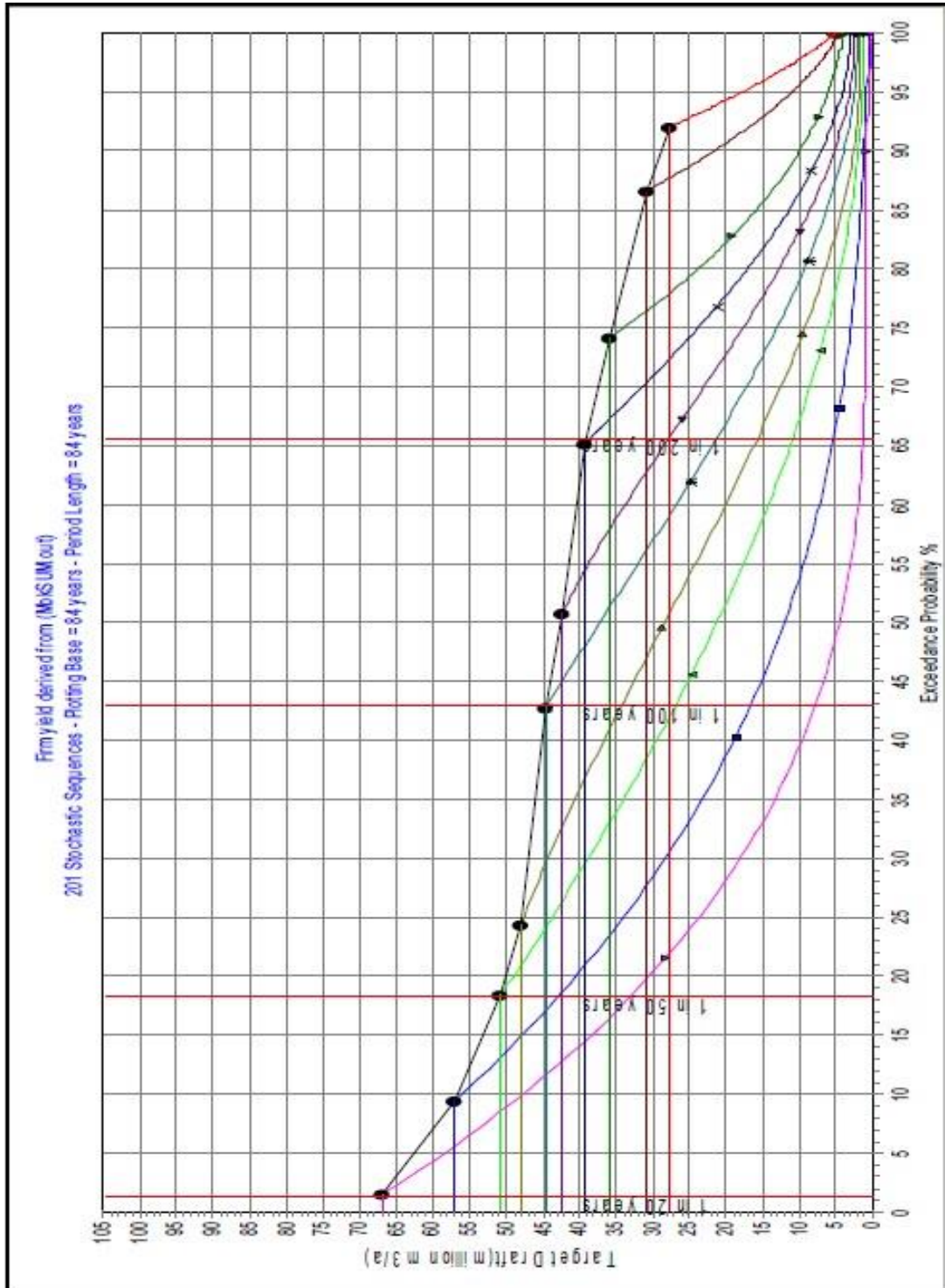


### Appendix A3: Long-term yield reliability curves for Goedertrouw Dam

Firm yield derived from (MhaSUM.OUT)  
201 Stochastic Sequences - Plotting Base = 75 years - Period Length = 75 years



Appendix A4: Long-term yield reliability curve for Mokolo Dam



## Appendix A5: Long-term yield reliability curves for Boegeberg Dam

Firm yield derived from (FishSUM.OUT)  
201 Stochastic Sequences - Plotting Base = 75 years - Period Length = 75 years

