CRANFIELD UNIVERSITY

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MODELLING CATCHMENT SCALE RESPONSE TO DROUGHT RISK, A CASE STUDY IN SOUTH AFRICA

SCHOOL OF WATER ENERGY AND ENVIRONMENT
Advance Water Management

MSc THESIS
Academic Year: 2020- 2021

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

South Africa is a water scarce country with future water availability threatened by climate change, an increasing population leading to urbanization, increasing agricultural production, and industrialization. Past droughts have highlighted the country's vulnerability to drought leading to economic losses in the Agricultural sector, inadequate water, and supply for basic domestic needs and failure to meet ecological water requirements. A case study was carried out in the water scarce, 4,937 km^2 agricultural intensive Groot Letaba catchment located in the Limpopo province. Water Evaluation and Planning (WEAP) model was used to simulate the water supply system in the catchment, from 1981 to 2016. The Nash–Sutcliffe Efficiency was used to validate the model's accuracy providing a value of 0.91 and 0.86 during calibration (1981-2000) and 0.69 and 0.65 during validation (2001-2016) for streamflow and Tzaneen reservoir levels, respectively. A reference scenario to assess water resources and water demand sites' vulnerability should droughts experienced between 1981 to 2016 be repeated under current demand was developed. 10% Agricultural water supply reduction, 50% per capita use rate reduction, Tzaneen reservoir storage increase and rerouting domestic return flow to the river were explored as drought adaptation measures. Drought response measures prevented reservoir drawdown in moderate droughts and delayed drawdown in severe droughts, reducing their temporal extents. Improvements in water resources availability correlated with improving demand coverage and reliability. Pairing drought response scenarios amplified benefits realized resulting in 100% demand coverage and reliability for two demand sites. All drought response measures were insufficient to fully circumvent droughts with a magnitude like the 1992-1996 drought. These findings show that effectiveness of response measures is dependent on the intensity and duration of the drought.

Word count: 7,959, including 2 tables, 11 figures and 1 equation

Keywords: Drought risk, WEAP, Groot Letaba, Drought Response

ACKNOWLEDGEMENTS

I would like to thank my supervisors Prof. Ian Holman and Prof. Tim Hess for their guidance and support during my thesis research. I am entirely grateful to Cranfield University and the Commonwealth Scholarship Commission for financing my studies. Special appreciations to Jon McCosh and Mlungisi Shabalala from the Institute of Natural Resources who provided information on the catchment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
ECMWF	European Centre for Medium-Range Weather Forecasts
EWR	Environmental Water Requirements
FAO	Food and Agriculture Organization
INR	Institute of Natural Resources
NASA	National Aeronautics Space Administration
SEI	Stockholm Environment Institute
UNDRR	United Nations Office for Disaster Risk Reduction
WEAP	Water Evaluation and Planning

1 INTRODUCTION

Drought is a complex natural disaster with adverse effects on natural water supply, agriculture, and ecology (Zhao et al., 2019). The complexity stems from the slow setting nature of droughts with uncertain impact and timing leading to cascading risk (Cole et al., 2021). Its impacts are either direct (water shortage, crop failure) or indirect (immigration, increased food prices, death), mostly prolonged and extensive. Drought impacts account for approximately 15% of global natural disaster economic losses (Lu, Shang and Zhang, 2020), being the largest losses from natural disasters (Bruntrup and Tsegai, 2017). In recent years, they have become more severe, widespread and have increased in duration (FAO, 2016). With increasing impacts of climate change this trend is projected to intensify in the future (UNDRR, 2021). Inevitably, this will exacerbate drought impacts.

There is not one general definition for drought, however, can be classified into four types: meteorological, agricultural, hydrological, and socio-economic drought (Zhao et al., 2014). Meteorological drought occurs when lower than long-term average rainfall is received. Prolonged it leads to reduced soil moisture onsetting an agricultural drought. Hydrological droughts are evident through the reduction in surface water and groundwater (Nalbantis and Tsakiris, 2009). Socioeconomic drought occurs when water demand exceeds water supply (Edalat and Stephen, 2019).

The imbalance between water supply and demand will increase as agricultural, energy and industrial expansion associated with population increases water demand Li et al., (2020). This will increase the likelihood of unmet water demand also exacerbating drought impacts during drought periods. In a study of the water supply system in the Olifants River Basin in South Africa, Olabanji et al., (2020) found that increasing water demand accompanied by climate changed will lead to a decline in runoff, increasing unmet water demand by 58% in 2050 and 80% in 2080. Madani, AghaKouchak and Mirchi (2016) cited rapid population growth, urbanization, and inefficient agricultural water use as major causes of increasingly unmet water demands in Iran. Despite demand having significant impacts on water resources availability, subsequently, drought intensity, not much research has been done on socioeconomic drought (Zhao et al., 2019).

Drought risk is defined as the probability of incurring losses due to an interaction between hazard, exposure, and vulnerability (Vogt et al., 2018). The magnitude of drought risk and subsequent impacts are not the same across poor and rich countries (FAO, 2019; Vogt et al., 2018). Poor countries and communities are most at risk, due to high dependence on natural resources for food and income, inadequate preparedness, limited financial resources (Gray and Mueller, 2012) and poor policy (Sam et al., 2017). Despite being adversely affected by drought, drought response in developing countries has continuously been characterized by reactive response to impact, rather than proactive response to risk. This does not address nor change the status quo of drought vulnerability, moreover, add no value towards reducing future drought risk and improving strategic drought management (Sifundza, van der Zaag and Masih, 2019). In the era of climate change and population growth, drought preparedness ought to become central in drought risk and impact mitigation.

South Africa is a semi-arid and drought-prone country with a long-term average annual rainfall of 450 mm/year (Botai et al., 2019; Sadiki and Ncube, 2020). The average annual potential evapotranspiration is 3 times the average annual precipitation received (Colvin et al., 2016). In the past, the country has experienced severe multi-year droughts, mostly induced by the recurrent El Nino Southern Oscillation (ENSO) (Makaya et al., 2020), characterized by a one in a ten-year return period lasting for an average period of 12 to 18 months per drought event (FAO, 2014). The latest 2015/2016 national El Nino drought was considered amongst the worst in history (Ndlovu and Demlie, 2020), resulting in an 8.4% reduction in agricultural production and approximately US$250 million worth of economic losses (Mare, Bahta and van Niekerk, 2018). National reservoir levels were 24% lower than in previous years (DWA, 2016), leading to water restrictions for agriculture and domestic water use across the country (Fasemore, n.d.; South African Government, 2015a).

The country is considered water scarce with overexploited renewable water sources. Approximately 60% of all catchments are already over allocated (Donnenfeld, Crookes and Hedden, 2018). Despite being a water scarce country, South Africa has a per capita water usage that is 61.8% more than the global average, moreover, has approximately 40% potable water conveyance losses (South African Government, 2015b). The domestic water sector at 25.1% is the second leading consumer of water, after the agricultural sector consuming 59% (Businesstech, 2015). In the future, due to increased demand, water competition within these two sectors is projected to increase and is expected to be met through improved water resources management and water use efficiency.

Despite being drought prone and water scarce, the country's drought risk response is mainly reactive and has been criticized by researchers. Baudoin et al., (2017) state that complex bureaucratic procedures, and limited capabilities, due to lack of funds from governmental authorities, municipalities, and provinces to respond to vulnerabilities undermining the country's effort towards proactive response to drought. Vogel, Koch and van Zyl (2010) added that the lack of risk communication to relevant stakeholders who need to implement risk reduction measures is a hindrance to risk response in South Africa. Poor risk communication is due to confusion on who bears the responsibility to disseminate information, risk being communicated late or not at all further weakening the drought risk preparedness infrastructure (Andersson et al., 2020).

The Groot Letaba catchment is as a typical example of a drought prone, and water stressed catchment in South Africa. The catchment has experienced 13 droughts in 35 years (1981-2016), the most severe being in 1991/1992 and 2015/2016 (Nembilwi et al., 2021). The catchment's water resources are over allocated and as such are severely impacted during drought, and consequently, the sectors relying on them for water supply. Environmental water requirements for the Kruger National Park, a national conservation site, are often not met (Gokool et al., 2017; Pramod, 2015). To ensure continued water availability, irrigated agriculture is often operated at 50% of the allocated amount (Pollard and du Toit, 2011), especially when reservoir levels are running low.

Considering the growing water stress and drought proneness of the Groot Letaba Catchment, the aim of this study was to evaluate feasible drought risk response measures to inform future decision making. The aim was achieved through specific objectives which were:

1. To conceptualize the catchment representing the water balance in the system.
2. To develop a model that will simulate the hydrology and water demands in the catchment.
3. To assess the impacts of climate variability and drought on present water demand in the catchment.
4. To simulate and evaluate different drought risk response measures and identify the appropriate ones for adoption.

2 MATERIALS AND METHODS

2.1 Study Area

The Groot Letaba is a 4,937 km^2 catchment found in the Limpopo province of South Africa. It is part of the Limpopo River basin under the Livhuvhu-Letaba water management area (Katambara and Ndiritu, 2010). The catchment is agricultural intensive (Figure 2-1), dominated by commercial agriculture consisting of forestry and sub-tropical fruits accounting for more than 50% of surface water abstractions (Querner et al., 2016). Smallholder agriculture is mostly rainfed and supplemented by groundwater (Querner et al., 2016). Agriculture is the main economic activity in the catchment. The catchment is predominantly rural with three small towns of Nkowankowa, Tzaneen, and Modjadisjskloof. Downstream the catchment is a national conservation area, the Kruger National Park.

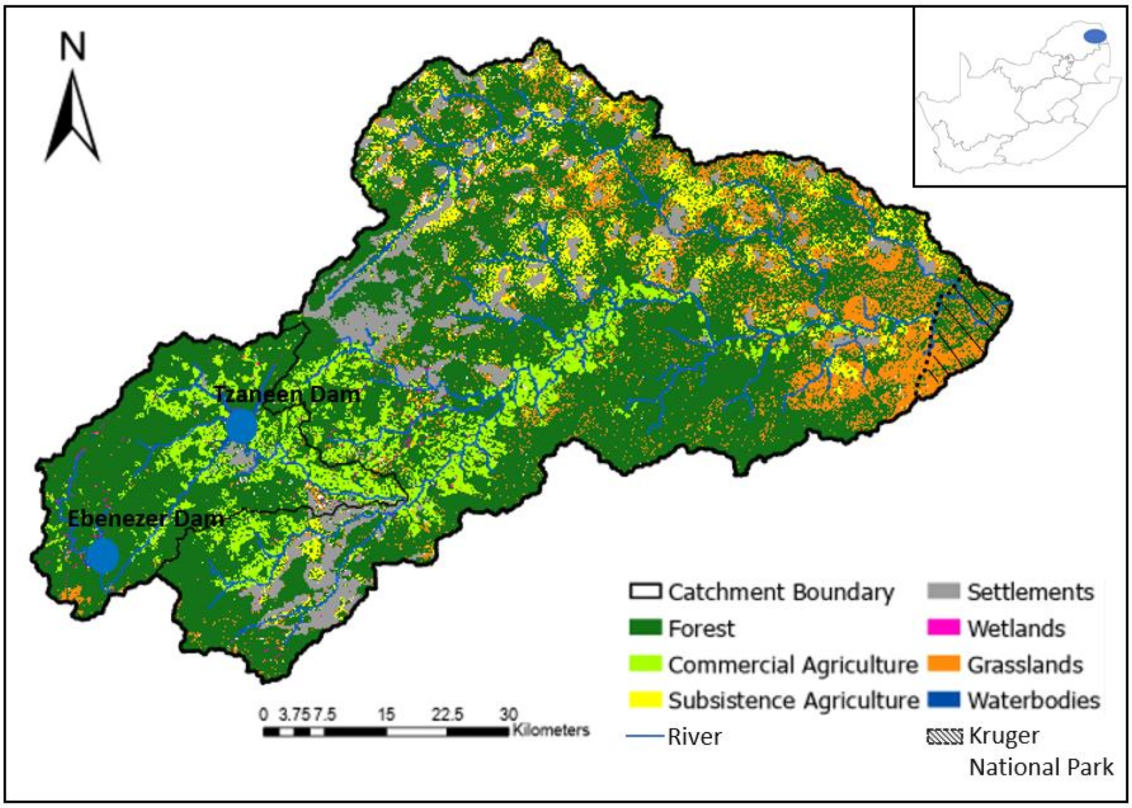

Figure 2-1: A Landcover map of the Groot Letaba catchment (SANLC, 2014).

The catchment has a significant climate variation from the upland upstream and the lowland downstream. The upstream areas have a long term annual average precipitation above 1200 mm/year while the downstream receive as low as 300 mm/year (Querner et al., 2016). The mean rainfall is 612 mm/year, with temperatures varying from 18 to 28°C (Gokool et al., 2019). High temperatures and precipitation are experienced in the summer months, October to March. Cold and dry weather is experienced in winter (April-August).

2.2 Methodology

2.2.1 WEAP Hydrological Model

The WEAP hydrological model was developed by the Stockholm Environment Institute (SEI) (SEI, 2015). WEAP aims to incorporate limited water resources, environmental quality, and policies for sustainable water use into a practical tool for water resources planning (SEI, 2015). Modellers and researchers attest to its usefulness in managing water resources and developing water resources management policies (Höllermann, Giertz and Diekkrüger, 2010). The model not only simulates the natural hydrology of the catchment but allows the representation of sectoral water demand, water quality, irrigation demands, and scheduling. Through scenarios, it allows for the evaluation of the influence of socio-economic changes and/or climate change on demand and water availability in the system.

2.2.2 Catchment Conceptualization

Catchment conceptualization was based on the understanding of the hydrology and water demands in the system which was developed through literature, landcover maps, and data from the Institute of Natural Resources, South Africa. Tzaneen and Ebenezer reservoirs, the main sources of water for agriculture and domestic water use, are located upstream of the Groot Letaba catchment. Therefore, the catchment was delineated to represent the hydrology of the Groot Letaba River upstream these reservoirs. Inflows from the Groot Letaba tributaries into the reservoirs were represented in the main Groot Letaba River, all as runoff from catchments 1 and 2 (Figure 2-2). The immediate downstream of Tzaneen reservoir was included in the modelled catchment to represent environment water requirement releases from the reservoir to Kruger National Park and commercial agriculture catchment. Due to limited information on aquifer properties in the catchment, the modelled aquifer was considered to have unlimited storage and recharge rate. Aquifer Recharge was determined through the preferred flow direction model parameter which partitioned runoff into interflow and deep percolation. Interflow was calibrated to match the observed streamflow level.

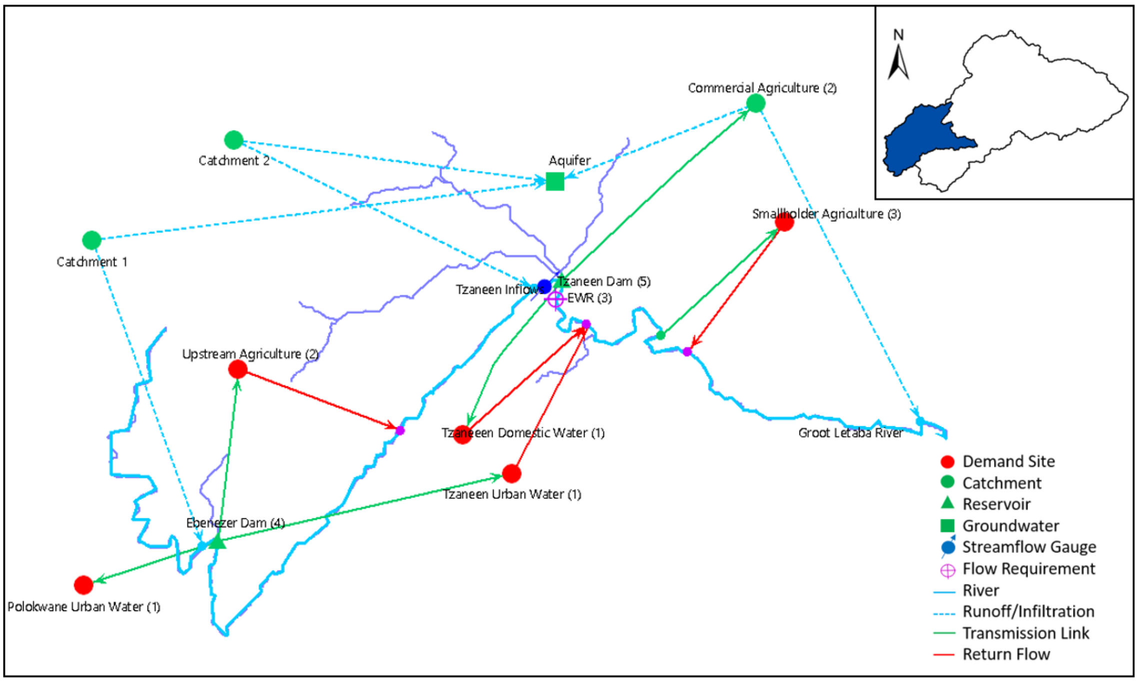

Figure 2-2: Schematic representation of the hydrology of the Groot Letaba (not to scale).

The location of return flows into the river from Tzaneen domestic and urban water was based on information from the South African Institute of Natural Resources. Polokwane urban water demand site is outside the catchment, as such represent water transfer out of the catchment. Return flows from the Polokwane urban demand site are discharged into the sand river which is outside the catchment thus not included in the initial catchment conceptualization (Figure 2-2). Redirecting return flows from the Polokwane urban demand site into the Groot

Letaba River was later explored as a scenario of drought risk response measures in the catchment.

Water resources in the model supply water in terms of priorities, shown in brackets () in Figure 2-2. Domestic water has the highest priority, assigned a value of 1, followed by agriculture. Based on reports of EWR often not being met due to abstraction from the agricultural and domestic sector, EWR was assigned 3rd priority. Smallholder agriculture, as shown in Figure 2-2, abstracts water after the EWR gauge, as such was assigned a priority equal to EWR, a higher priority would disregard the supply priority assigned to EWR. Reservoirs were assigned the least priority. Ebenezer reservoir, being upstream was given 4th priority while Tzaneen was 5th. Being that both reservoirs are instream and in a connected system, changes in one reservoir affect the other.

2.2.3 Catchment Parameterisation

2.2.3.1 Catchments

Catchment parameterisation was the primary step in model parameterisation, guided by the catchment hydrology method chosen. WEAP has different methods of representing catchment hydrology, each with varying data requirements, complexity, and accuracy. The rainfall-runoff (soil moisture method) is complex and more detailed, providing a comprehensive representation of catchment processes. It simulates actual evapotranspiration, surface runoff, interflow, and baseflow. It requires climate, soil, and landcover input data. Input Climate and landcover data are actual observed data or supported by literature. Other hydrological parameters are calibrated. This method was used to simulate the hydrology of catchments 1 and 2 (Figure 2-2).

The MABIA (FAO, Dual Kc, Daily) Method simulates daily actual evapotranspiration, irrigation demands, and scheduling. This method is used to represent agricultural catchments, as such is used for simulating agricultural water demands. It requires similar climate and landcover data as the soil moisture method. Added to that are requirements for irrigation characteristics. The MABIA method was used to model commercial agriculture catchment (figure 2-2) and its irrigation demands.

Weather data

Weather data of monthly average temperature, relative humidity, wind speed, and radiation from 1981 to 2016 were obtained from NASA Power data access viewer (NASA LaRC, 2021). Since climate varies across the catchment, the data were extracted for the locations (lat -23.81448, long 29.96514), (lat -23.88001, long 30.07964), and (lat -23.81752, long 30.16467). Each location corresponded to a random point upstream of the modelled sub-catchments. NASA data provided satisfactory data when compared to literature (Gokool et al., 2017; Pollard and du Toit, 2011; Querner et al., 2016), however, rainfall was underrepresented. NASA data provided a long-term annual average of 800 mm/year in the upstream of the catchment, where a long-term average of above 1200 mm of rainfall had been reported by several authors (Gokool et al., 2017; Pollard and du Toit, 2011; Querner et al., 2016). The poor correlation between NASA and Local rainfall data was consistent with observations made by Monteiro, Sentelhas and Pedra, (2018) in Brazil. As a result, monthly rainfall data used as model input was from the Westfalia plantation weather station. The station represented rainfall for catchment 2. It was adjusted by a factor of +0.2 to match catchment 1 rainfall (1200 mm) and -0.2 to match commercial agriculture catchment rainfall (800 mm). Monthly average sunshine hours were obtained from the ECMWF (2021).

Landcover

Only dominant land cover/land use types in catchments 1 and 2 were represented in the model, consisting mainly of forests and commercial orchards (avocado and citrus), see figure 2-1. A default soil water holding capacity of 1000 mm/m was assumed for both catchments 1 and 2. Avocados were assigned an average Kc of 0.98 (Mazhawu et al., 2018), citrus 0.64, under micro-irrigation (Malan, Raath and Vahrmeijer, 2020), and forests a value of 1.1 (Silva, Manzione and Filho, 2018). The commercial agriculture catchment only represented irrigated commercial crops, the predominant being avocado and citrus. Default MABIA crop parameters based on the FAO (2021) were used.

Other catchment hydrology parameters were calibrated after demands were incorporated into the system (table 2-1).

Table 2-1: WEAP model parameters that were calibrated.

Parameter	**Default Values**	**unit**	**Calibrated values**	
			Catchment 1	**Catchment 2**
Runoff resistance factor	2	(dimensionless)	Orchards: 4 Forests: 5	Orchards: 4 Forests: 5
Root zone conductivity	20	mm/month	Orchards: 150 Forests:180	Orchards: 400 Forests: 450
Preferred flow direction	0.15	(dimensionless)	0.3	0.76
Initial Z1 (initial soil moisture)	30	Per cent (%)	65	65

2.2.3.2 Demands

Tzaneen and Ebenezer reservoirs, shown in figure 2-2, have a capacity of 157 and 69 million m^3 at full supply, respectively. Ebenezer reservoir supplies domestic water to Polokwane city and Tzaneen town, also irrigation for farms located between the two reservoirs. Agriculture is allocated 10.3 million m^3/year while Tzaneen town and Polokwane city are allocated 2.3 million m^3/year and 12 million m^3/year, respectively (DWA, 2014). Polokwane City has been consistently abstracting more than allocated with an average of 16.2 million/year between 2004 and 2014 (DWA, 2014) and 18.8 million m^3/year by 2016 (Querner et al., 2016).

Tzaneen reservoir primarily supplies irrigation water for agriculture in the catchment. A volume of 105 million m^3/year is allocated to agriculture with 8.5 million m^3/year being allocated to domestic water (Rananga and Nyabeze, 2017). However, Tzaneen reservoir records show that domestic water abstractions have steadily increased, eventually exceeding the allocated volume. The 20-year domestic water abstraction average is 14 million m^3/year. The reservoir is mandated to release sufficient water to meet the 0.6 m^3/s flow requirement at Kruger National Park (Pramod, 2015). This requirement was added on releases to downstream smallholder irrigation needs and a 30% buffer for losses resulting in a flow requirement of 2.19 m^3/s at the Tzaneen reservoir outlet.

Assumptions had to be made in representing demands in the model. For cases where there were no observed data or updated literature records on actual abstractions, allocations were used. A detailed account of how demands were represented in the model is shown in Table 2-2.

Table 2-2: Detailed description of demand sites parameterisation.

Demand site	Annual activity level	Annual growth rate	Water use rate	Assumptions / comments
Polokwane Urban water	123,100 cap	2.3	69 m^3/cap/year	The annual water use rate was calculated based 189 L/cap/day usage rate from DWA (2014). Population growth rate was based on Stats SA (2021). Activity level for 1981 was calculated by depreciating observed abstractions by the growth rate thereafter dividing by the water use rate.
Tzaneen Domestic Water	120,000 cap	1.8	69 m^3/cap/year	
Urban Water Tzaneen town	33, 333 cap	-	69 m^3/cap/year	Annual activity was calculated based on 2.3 million m^3/year allocation (DWA, 2014) and the water use rate. Supply was assumed to remain constant, as there were no changes in water supply reported in literature. Increase in demand for Tzaneen urban water was assumed to be catered for under increasing demand of Tzaneen domestic water demand site.
Upstream Agriculture	1,477 ha	-	6904 m^3/ha/year	Average agricultural water use rate was based on data from the INR. For Upstream agriculture, the annual activity level was attained through dividing 10.2 million m^3 yearly allocation (DWA, 2014) by the average water use rate. For Smallholder agriculture average yearly abstraction from the river (8 million m^3/year) attained from INR was divided by the water use rate. Agricultural water use was assumed to remain constant as increase in demand area farmed was accompanied by more efficient water use and increasing groundwater abstraction for agriculture.
Smallholder agriculture	1,159 ha	-	6904 m^3/ha/year	
Commercial Agriculture	10,322 ha	-	10,172 m^3/ha/year	The activity level was based on records from INR. The water use rate was calculated from 105 m^3/year allocation and area irrigated as per INR data. MABIA irrigation scheduling was optimized to match 105 m^3/year irrigation allocation. Fixed irrigation intervals of 3 and 4 days and application depths of 9 and 7 mm were used for citrus and avocados irrigation scheduling, respectively. A 50% restriction was applied on the source to demand site transmission link to ensure that approximately 55 million m^3/year is delivered as per the restrictions on ground and observed abstractions.

2.2.4 Model Calibration

Model calibration was conducted using the first 19 years (1981-2000) of the study period. Observed data from the Institute of Natural Resources, South Africa, and simulated data of Tzaneen reservoir levels and Tzaneen inflows were statistically analysed through the Nash-Sutcliffe Efficiency (NSE). The NSE was calculated as shown in equation 2-1.

$$NSE = 1 - \frac{(\ \sum_{i=1}^{n}(observed\ flow - simulated\ flow)\ )^2}{(\sum_{i=1}^{n}(observed\ flow - observed\ flow\ mean))^2} \qquad \textbf{(2-1)}$$

The NSE is a widely used measure of accuracy for hydrological models (Amin et al., 2018; Naabil et al., 2017). An NSE value of less than 0.5 is considered a poor model fit with a value of above 0.5 being acceptable and an NSE value of 1 considered a perfect model fit.

2.2.5 Model Validation

The model's accuracy in representing the hydrology of the catchment was validated using observed and simulated data of Tzaneen reservoir inflows and water storage levels from 2001 to 2016. The NSE was used as the statistical measure of accuracy.

2.2.6 Scenarios

The calibrated and validated hydrology was considered the catchment baseline, from which the reference scenario was established. Risk response measures in the catchment were evaluated through different scenarios, all based on the reference scenario.

Reference scenario: A scenario to assess the system's drought risk should weather events experienced in 1981 to 2016 be repeated under current domestic water demand was developed. The domestic demand for the last year of simulation (2016) was assumed to have been constant since 1981. Reservoir levels, unmet and met demands from this scenario, and baseline scenario were contrasted.

Response scenario 1: Urban and domestic water demand reduction through 50% reduction in per capita water use rate, from 189 to 94.5 litres/capita/day.

Response scenario 2: Agricultural water demand reduction through reducing irrigation water supply by 10% of annual water allocation. Commercial agriculture is already operated at 50% of allocation hence low reduction rate applied to the agricultural sector.

Response scenario 3: Increasing water supply through Increasing Tzaneen reservoir storage capacity from 157 million m^3 to 203 million m^3.

Response scenario 4: Increasing system return flows by rerouting wastewater from Polokwane urban demand site to the Groot Letaba River

3 RESULTS

3.1 Model Calibration and Validation

Model calibration and validation were carried to ascertain the model's accuracy in representing the water system in the catchment. Results showed an overall impressive relationship between observed and simulated streamflow (Figure 3-1). The calibration period had an NSE value of 0.91 while the validation period had an NSE value of 0.69. Both values are above an NSE value of 0.5, which is the benchmark of model accuracy's acceptability.

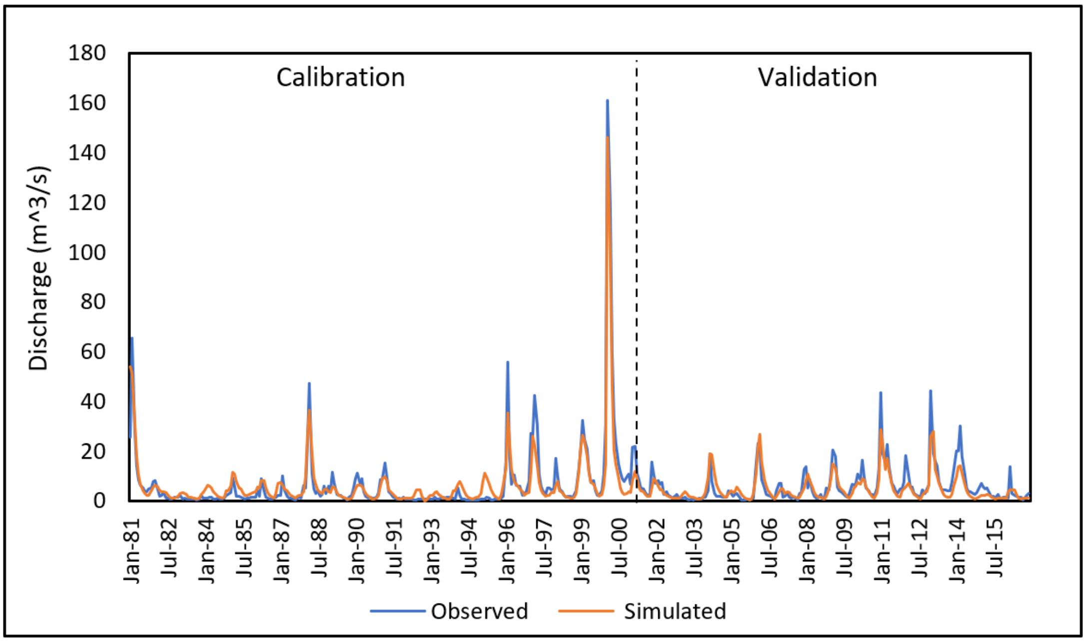

Figure 3-1: Hydrograph of observed and simulated Tzaneen reservoir inflows.

Results from observed and simulated Tzaneen reservoir levels illustrated a corresponding pattern in reservoir levels over the years (figure 3-2). NSE values of 0.86 for the calibration period and 0.65 for the validation period were obtained, confirming the accuracy of the model in representing not only the hydrology but also demands and abstractions from the reservoir.

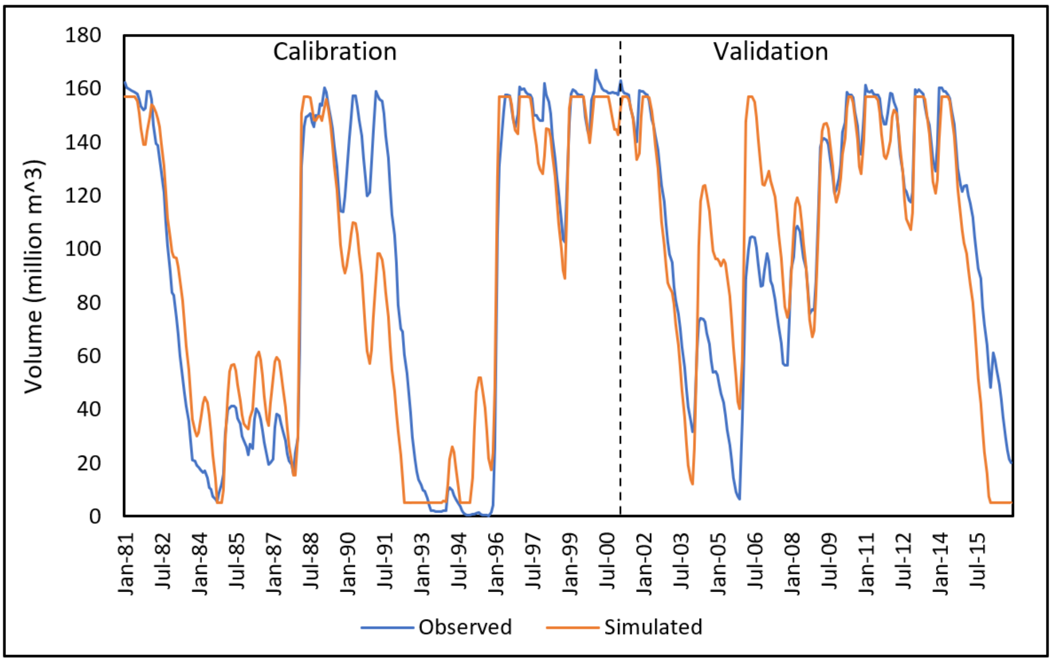

Figure 3-2: Observed and simulated Tzaneen reservoir levels.

Simulated streamflow in figures 3-1 and Tzaneen reservoir levels in figure 3-2 represent the baseline river flow and reservoir level. There was no observed data for Ebenezer reservoir, as such, the reservoir was not calibrated nor validated. However, the simulated mean annual runoff of 32.6 m^3/year matched the long-term average runoff (32.5 m^3/year) into the reservoir (Masangu, 2009). This provided the confidence to use simulated Ebenezer water levels as baseline reservoir levels for the reservoir.

3.2 Reference Scenario

If weather conditions like that of 1981 – 2016 were to be experienced under current domestic and/or urban water demand, reservoirs water availability demand coverage and reliability would be negatively impacted. Ebenezer reservoir would experience the most significant impact amongst the two reservoirs (figure 3-3). There would be an increased frequency of significant reservoir drawdown to dead storage or critical levels as in weather conditions like those experienced in 1984 – 1988, 2005, and 2007-2009. Also, the rate of reservoir drawdown will be rapid, increasing the temporal extent of hydrological and socioeconomic droughts.

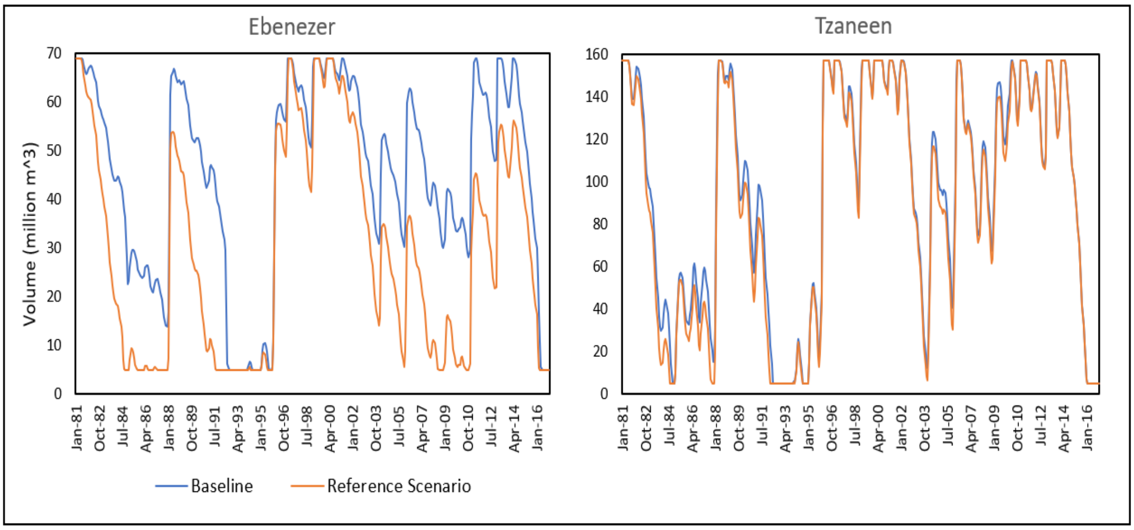

Figure 3-3: Baseline and reference scenario reservoir levels.

There is an insignificant difference in Tzaneen reservoir levels between the baseline and reference scenario (figure 3-3). It is only in drought seasons where marginal reductions in reservoir levels are observed. Tzaneen, being primarily for agricultural water supply is expected not to be as responsive as Ebenezer reservoir to the reference scenario. Considering differences in primary use, drought response measures for the two reservoirs might need to differ.

The reference scenario presents a greater drought risk on water demand sites as a decline in demand coverage is witnessed amongst sites with either previously met demands being unmet and unmet demands being exacerbated. Such is noticeable in 1983-1987 where there are new unmet demands and 1992-1995 where existing demand shortages worsen (figure 3-4). Incidences of unmet environmental water requirements (EWR) also increase under the reference scenario. Smallholder agriculture, located downstream a domestic water return flow discharge point, experienced an improved demand coverage due to increased return flows from the increased domestic water supply.

All these unmet demands in the system, both baseline and reference scenario occur while commercial agriculture is operating at 50% restriction in the model, representing regular restriction rules on the ground. If agriculture were to be operated at full allocations, more demands would not be met.

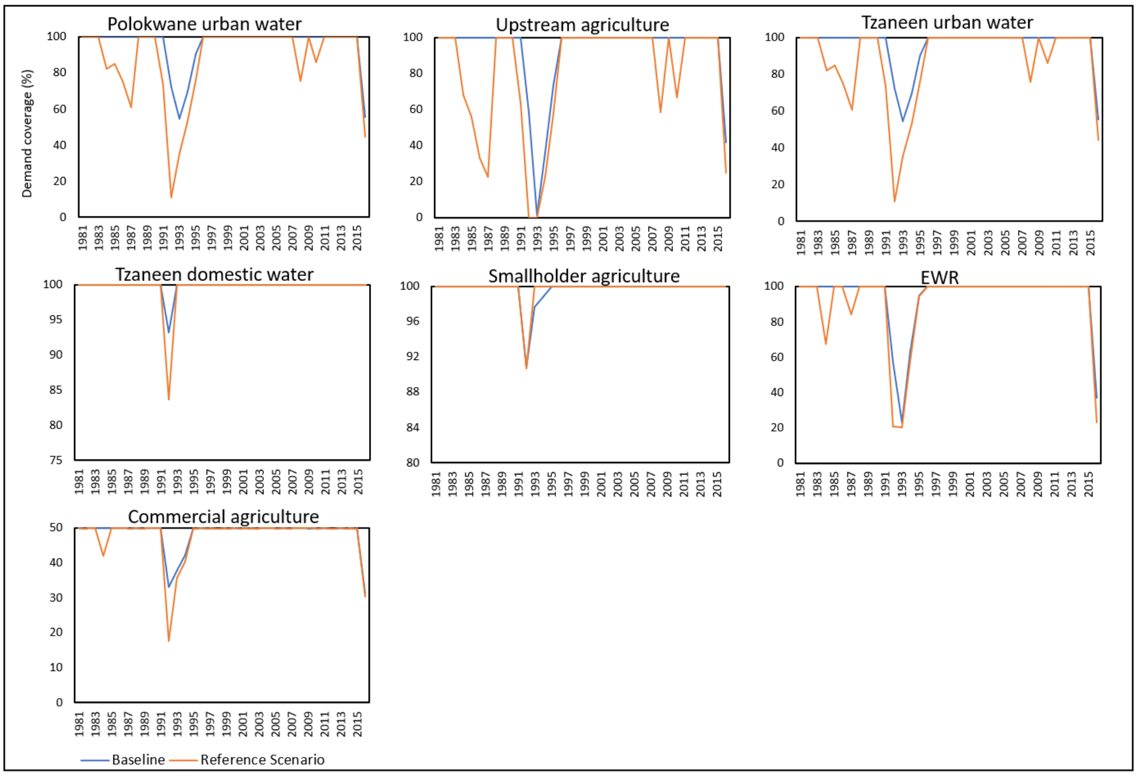

Figure 3-4: Water demand coverage under baseline and reference scenario

Like both water resource availability and coverage, reliability declines in the reference scenario. Demand sites supplied by Ebenezer reservoir, Polokwane urban water, Tzaneen urban water, and upstream agriculture are the most impacted, all with more than 10% reduction in supply reliability (Figure 3-5). EWR coverage reliability drops by 3.2%. Commercial agriculture being operated at 50% of allocation has a constant 0% reliability. Being represented through MABIA, the restriction could be applied only through the transmission link, unlike upstream and smallholder irrigation where reduction in amount of water delivered could be applied through the annual water user rate.

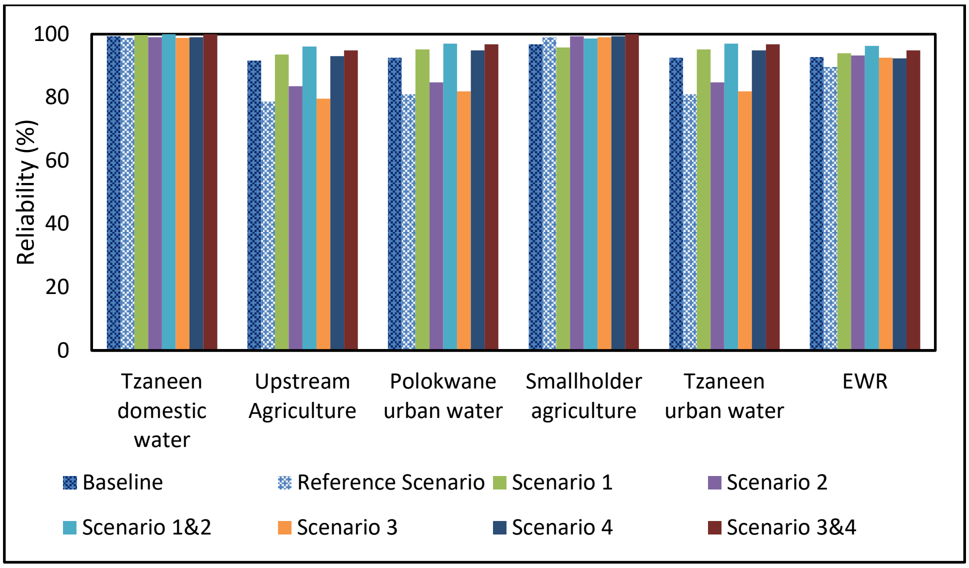

Figure 3-5: Demand site water supply reliability under different drought response scenarios.

3.3 Drought Risk Response Scenarios

3.3.1 Demand Focused Response Scenarios

Tzaneen reservoir is responsive to both domestic water demand reduction (scenario 1) and agricultural water demand reduction (scenario 2). The two scenarios provide almost an equivalent magnitude of improvement, with scenario 2 resulting in slightly higher reservoir levels than scenario 1. Both scenarios, however, are insufficient to evade the 1984, 1992-1995, and 2016 drawdown in reservoir storage. Nonetheless, they decelerate reservoir drawdown ensuring water demand sites have an available supply for an extended period. Simultaneous implementation of these scenarios provides an improved buffer during drought compared to the individual scenarios. As shown in figure 3-6, an improvement of about 20-60 m^3 in reservoir water availability is attained on the 1984-1987 drought magnitude. Also, the drawdown to dead storage in 1984 that could not be evaded during the individual implementation of scenarios 1 and 2 is evaded.

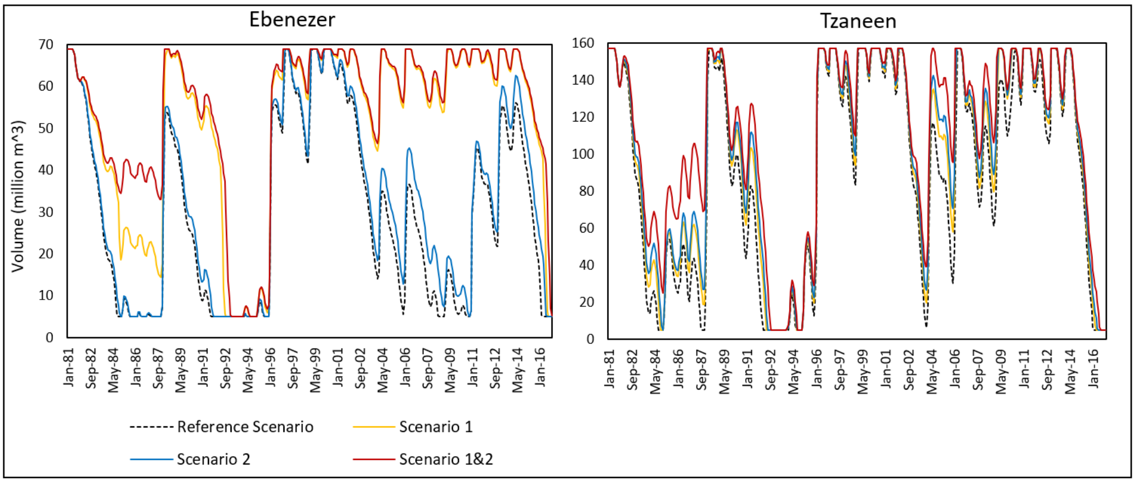

Figure 3-6: Reservoir levels under different demand reduction scenarios.

There is a significant difference in the responsiveness of Ebenezer reservoir to the two scenarios (Figure 3-6). Scenario 1 leads to significant improvement in reservoir levels, ensuring water resource availability on the 1984-1987 drought events. While the early 1990s drought could not be fully evaded, its temporal extent was reduced by approximately a year and a half. Such reduction is also witnessed during the 2016 drought, though by a few months. When only scenario 2 was implemented, however, marginal effects on water resources were observed, especially during drought periods. In addition, this scenario also improved water availability in the system, especially in 1984-1986. These Improvements were only sufficient to cater for unmet demands as a result not contributing towards improving reservoir levels. Improvements in reservoir water levels were noted when scenario 2 was combined with scenario 1, leading to approximately 20 m^3 increase in reservoir volume.

Scenarios 1 and 2 also improved demand coverage and reliability in all demand sites, with scenario 1 being more effective in improving coverage and reliability for Ebenezer reservoir dependant demand sites. Under scenario 1, unmet water demand in the early 1980s, 2007-2009 are fully evaded (Figure 3-7). For unmet demands in 1991-1994, coverage improves by a range of 10% in upstream agriculture and EWR to 50% in Polokwane urban water and Tzaneen urban water demand sites. The improvement in demand coverage is directly proportional to improvement in system reliability to meeting demand. EWR reliability improves by 5% while Tzaneen urban water, Polokwane urban water, and upstream agriculture improve by 14.1 -14.8% (Figure 3-5). Smallholder agriculture, on the other hand, experiences a decline in both coverage and reliability, with a new demand coverage deficit experienced during the 2015-2016 drought magnitude.

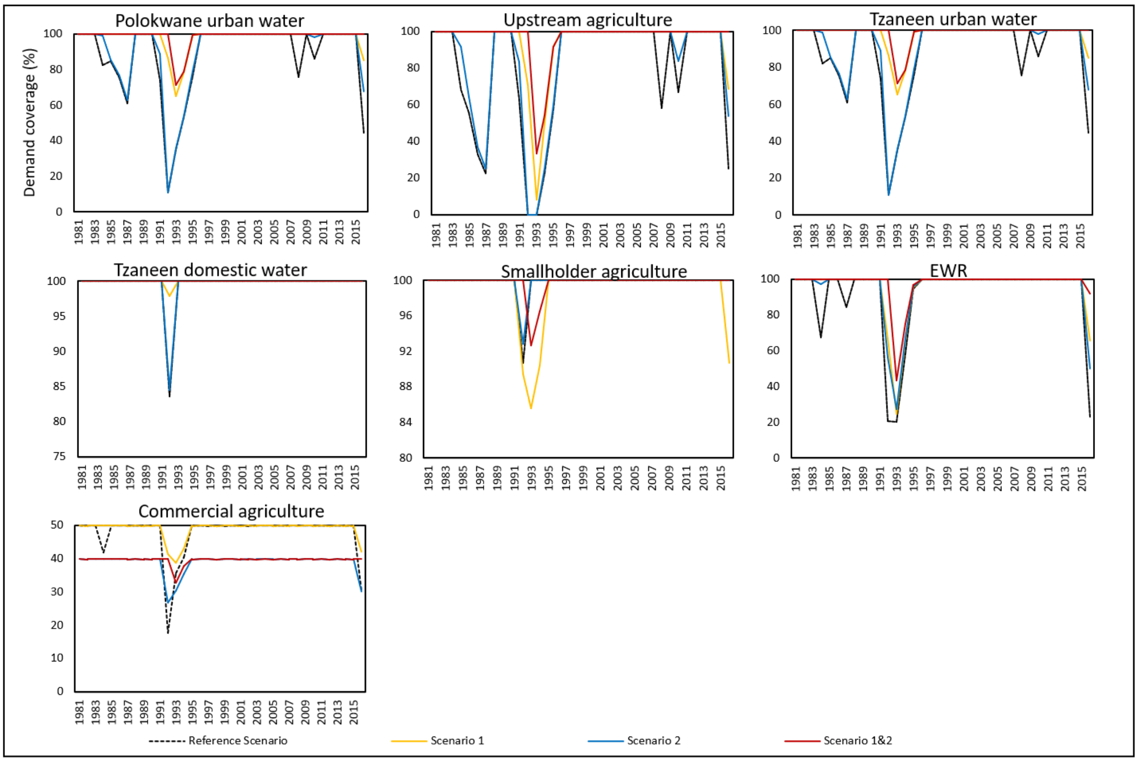

Figure 3-7: Demand coverage under demand reduction scenarios.

Scenario 2 offers a limited improvement in demand coverage, with a maximum improvement of about 30% in EWR in 1985 and upstream agriculture in 2015-2016. The scenario reduces the temporal extent to which full demand coverage is not achieved in Polokwane urban water, upstream agriculture, and Tzaneen urban water in 1985 drought conditions. Incidences of unmet demand for EWR, upstream agriculture, Tzaneen urban water, and Polokwane urban water are reduced. These reductions are accompanied by a marginal improvement in supply reliability, ranging from <1 to 5% (Figure 3-5).

Simultaneously implementing both drought response measures offer a slight improvement to what is achieved through scenario 1 alone. This results in the highest reliability of 100% and full coverage through the years for Tzaneen domestic water demand site. EWR coverage also improves by approximately

20% in 1993, compared to individual scenarios, with reliability increasing by about 2.5% to reach 96.3% (Figure 3-5).

3.3.2 Supply Focused Scenarios

Increasing Tzaneen reservoir (scenario 3) improves water resources availability by 46 m^3 in the catchment. This improvement in reservoir storage volume is witnessed in normal and/or above average rainfall years. In severe droughts, such as 1982-1987, 1992-1996 and 201-2016 reservoir levels still drop to extremely critical levels, with an added buffer of +/- 5 m^3 in 1984-1987. While the reservoir levels still drop to critical levels in droughts, but the demand coverage for demand sites dependant on the reservoir improves (Figure 3-9). Therefore, the marginal increase in volume is not because of scenario 3's ineffectiveness in drought mitigation but due to water withdrawal to meet previously unmet demands. Due to increased water availability in normal rainfall seasons, drawdown to critical reservoirs levels is delayed by months. This scenario is effective in Tzaneen reservoir only, see Figure 3-8.

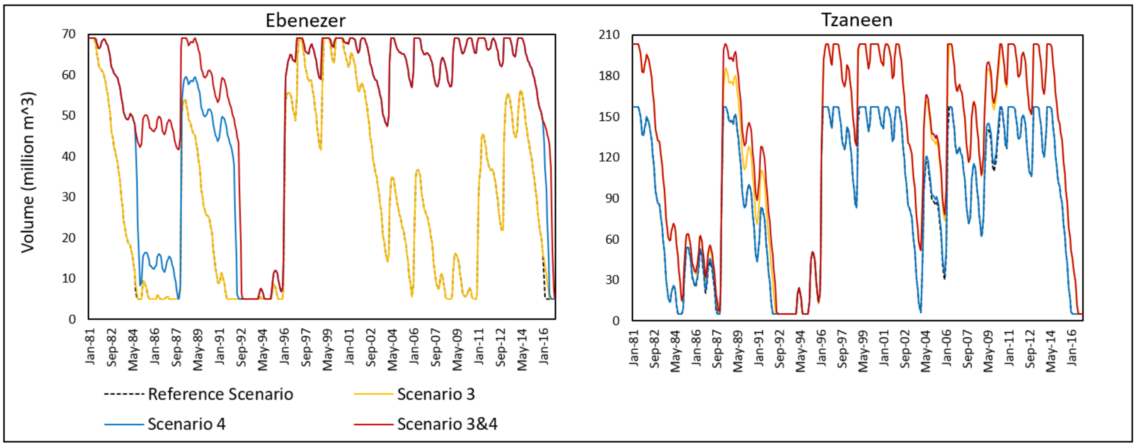

Figure 3-8: Reservoir water levels under supply improvement scenarios.

As seen in Figure 3-8, rerouting Polokwane urban water return flows to the river, upstream of Ebenezer reservoir (scenario 4) is not significantly effective in Tzaneen reservoir, with only negligible improvements in reservoir volume. In Ebenezer reservoir, scenario 4 presents similar improvements as scenario 1 in

Figure 3-6. Though reservoir volume still drops to critical levels in 1984-1987, reaching dead storage mostly evaded, with only one month where the reservoir reaches such levels compared to 4 years on the reference scenario and scenario 3. In all years, reservoir drawdown is delayed by a minimum of 4 months. In 2007-2009, the reservoir operates almost at fully supply level, contrary to critical levels in the reference scenario.

In Tzaneen reservoir, implementing both measures at the same time provides an insignificant improvement in water levels during drought years compared to scenario 3 alone (Figure 3-8). This is contrary to the response in Ebenezer reservoir, where simultaneous implementation of the drought response measures results in an improvement in reservoir water level and/or delayed drawdown process during drought years. The contrast in response in the reservoirs can be attributed to their filling up priorities, with Ebenezer being upstream and having a higher priority than Tzaneen that is downstream (see Figure 2-2). The filling up of the Ebenezer reservoir is prioritized once all the Tzaneen reservoir demands with higher priority are fully met. Since all Tzaneen demands were met under scenario 3 in 1984-1987, scenario 4 was dedicated to filling up Ebenezer reservoir, which resulted in significant increase Ebenezer reservoir volume during that period.

Scenario 3 is considerably effective in improving demand coverage in the 1983-1985 drought magnitude. It ensures 100% demand coverage for EWR from 65% in the reference scenario. Reduction in the magnitude of coverage deficit is also witnessed during other droughts, more so in 2015-2016, when improvement is also witnessed in Ebenezer dependent demand sites (Figure 3-9). There are Marginal changes in reliability for all demand sites except EWR that improves by 3%.

In the 1992-1996 drought a maximum of approximately 60% improvement in Tzaneen urban water and Polokwane urban water coverage is achieved through scenario 4. This is coupled with the elimination of incidences of unmet demands on Ebenezer reservoir dependent demand sites in 1983-1989 and 2007-2011 with increased coverage in 2015-2016 (Figure 3-9). A 14.4% increase in upstream agriculture demand coverage reliability and an improvement from 81.0% to 94.9% for Tzaneen and Polokwane urban water demand sites are achieved.

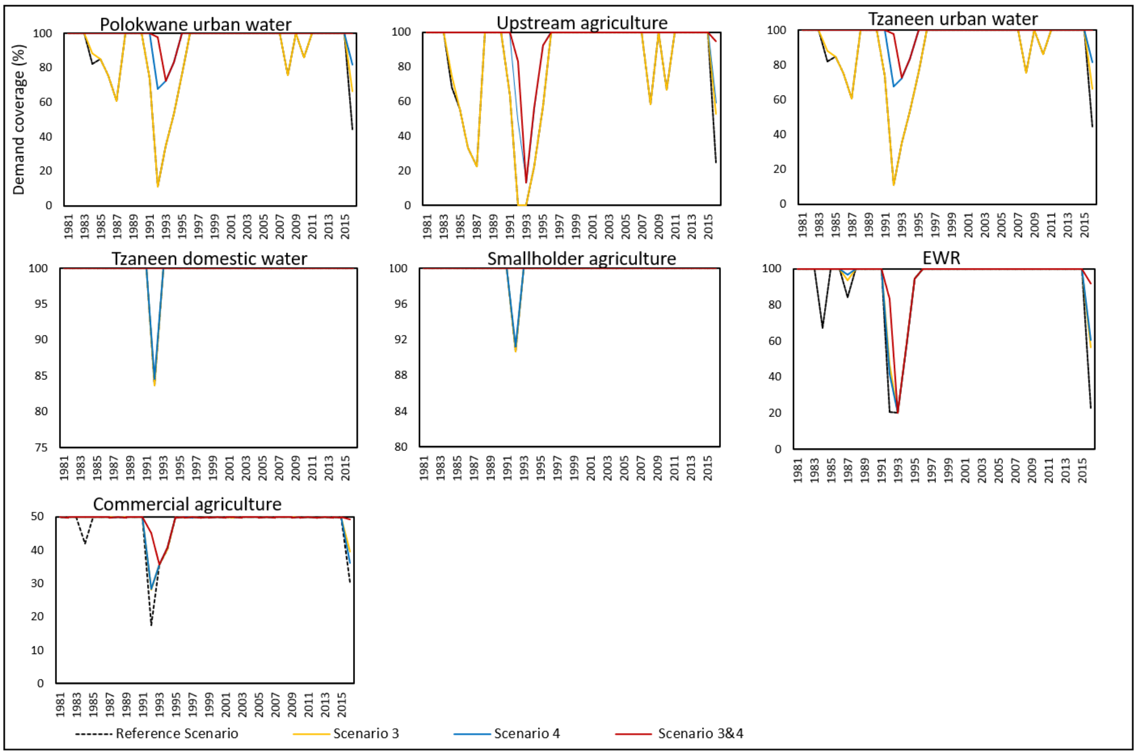

Figure 3-9: Water demand coverage in the supply improvement scenarios.

Combined, scenarios 3 and 4 lead to 100% coverage in all years and 100% reliability for Tzaneen domestic and smallholder agriculture demand sites. EWR improves by 5% in comparison to the reference scenario with a full demand coverage attained in 1987 and above 90% coverage in 2015-2016.

4 DISCUSSION

4.1 Feasibility of Drought Response Measures

Results from this study suggested that the evaluated drought response measures, 50% domestic water use rate and 10% agricultural water reduction, increasing reservoir storage capacity and rerouting return flows to the catchment will improve the systems resilience to droughts. Similar measures as domestic water reduction and increased grey infrastructure storage were evaluated by Amin et al., (2018) using WEAP, who also concluded on their effectiveness towards improving water availability in the Indus basin.

Fifty per cent reduction in domestic water use rate saved approximately 18 million m^3/year, which is almost equivalent to domestic water requirement of Polokwane city under no restrictions. The improvements in water resources availability were more pronounced in Ebenezer reservoir and its supply dependent sites. This responsivity was relative to the domestic water allocation to reservoir capacity ratio, Ebenezer having the highest ratio at 32% with Tzaneen at 6%. Ebenezer reservoir demand sites experienced up to 14.8% improvement contrary to 3.2% witnessed in Tzaneen dependant EWR. The trend of different response rates amongst reservoirs in relation scenario was noted across all scenarios, which could suggest that drought risk response measures should be prioritized differently for water resources in the same catchment. Nevertheless, both reservoirs and demand sites followed the same trend in response to scenarios, with the difference being only in magnitude.

Reducing per capita water use had negative effects on smallholder agriculture while all other demand sites and reservoir were positively impacted. This occurrence highlighted the importance of using more than one metric in evaluating effectiveness of a drought response measures in a catchment. Had effectiveness only been based water resource availability, this trade-off would have not been identified, exposing smallholder agriculture to increased drought risk. This was emphasized through all scenarios as simultaneously monitoring the responsiveness of demand sites and reservoir water levels to drought showed that while some response measures are insufficient to improve reservoir volumes during severe drought, they improve demand coverage and reliability. This was evident through scenario 3 (Figures 3-8 and 3-9) where increased Tzaneen reservoir storage eliminated incidences of unmet demand in the 1980s drought while reservoir levels remained at critically low levels.

Reducing domestic water use by 50% correlated with a reduction in incidences of unmet water demands and events of total reservoir drawdown. These Improvements compare well with observations during the millennium droughts in Australia, where 50% per capita use reduction was one of the measures adopted to sustain water resources and supply (Low et al., 2015). In South Africa, the effectiveness of per capita use reduction was witnessed during the Cape Town drought, where 48% reduction in household water use was achieved, subsequently evading imminent drought risk (Booysen, Visser and Burger, 2018). The study in Cape Town also proves the practicability of attaining 50% domestic water use rate reductions in South Africa.

Attaining such depths of demand reduction is highly dependent on water users' risk perception and water use behaviour than institutional restrictions. Booysen, Visser and Burger (2018) stated that inciting fear of taps running dry "day zero", compared to restrictions, was the most successful intervention in reducing water use rate during the 2017-2018 Cape Town drought. The fear resulted in improved drought risk perception informing water use behavioural change. Therefore, realizing scenario 1 would require an investment in drought risk communication, education, and water conservation campaigns. Quesnel and Ajami (2017) highlighted the importance of public awareness of drought risk on demand management as increasing media coverage of the 2011-2016 California drought correlated with a decline in residential water use. While mainstream media and social media can play a significant role in disseminating drought risk information and suggested conservation measures, they rely on risk communication from the government and institutions. In South Africa, this will call for an improvement in the much-criticized vertical flow of information and drought risk communication within the government (Andersson et al., 2020; Vogel, Koch and van Zyl, 2010) , to ensure that risk is communicated well in advance and the media surge onsets at an early stage of drought.

Like domestic water demand reduction, achieving 10% reduction in agricultural water demand will need to be preceded by efforts to change farmers' water use behaviour. During an online meeting, Mccosh (2021) stated that the most efficient farmers use around 2,500 m^3/ha/year while others use up to 10,000 m^3/ha/year. Since most farms in the catchment are under drip and micro irrigation, which are considered the most efficient irrigation methods (Wang et al., 2021), differences in water use rate can be attributed to farmers' drought risk perception and water use behaviour, which if positively changed can facilitate the realization of scenario 2. Alternatively, water trade amongst the most efficient commercial farmers, smallholder agriculture, and the least efficient farmers can facilitate agricultural sector's compliance to restriction. It was adopted by high-value fruit commercial farmers in Australia, and it sustained production at maximum yield throughout the millennium drought (Kirby et al., 2014).

Implementing Scenario 2 means commercial agriculture will operate at 40% restriction. While this seems like a very rigid restriction, one that might not be accepted by many farmers, its realization is possible, considering that some farms are irrigated with 2,500 m^3/ha/year, representing 36% of the average agricultural water use rate. In Australia agricultural production was sustained with approximately 33% of allocations during the millennium drought (Kirby et al., 2014). Therefore, with more efficient water use and conservation measures in place, commercial agriculture can be sustained under this level of restriction.

These measures are necessary to realize improvements in the water supply system brought by scenario 2, which are more pronounced for Tzaneen reservoir and its dependant demand sites than Ebenezer reservoir. As such, in drought response planning, its implementation should be of higher priority in Tzaneen reservoir, while scenario 1 is given higher priority in Ebenezer reservoir. Furthermore, scenario 2 facilitate the highest improvement in EWR reliability of all scenarios. When paired with scenario 1, it counteracts the negative impacts of scenario 1 on smallholder agriculture.

Though scenario 2 was based on a fixed demand reduction rate, results achieved under this scenario, as well as scenario 1, provide evidence of the effectiveness of demand reduction in drought response. Since smallholder agriculture and upstream agriculture have the capacity to accommodate stricter restrictions, increased benefits can be achieved through irrigation demand reduction. The flexibility of demand reduction measures makes them applicable drought response measures in droughts of differing magnitudes and duration. Under more intense droughts with extended temporal extents like the 1992-1996 droughts, demand reduction rates can be adjusted to increase resilience to drought, reducing the severity of socio-economic droughts.

Increasing Tzaneen reservoir storage is already underway. Once completed, the reservoir will provide capacity to evade the early 1980s drought intensity, most importantly, meet all demands. Reservoir drawdown will be evaded in some droughts and delayed in severe droughts in like the early 1990s and 2015-2016 droughts. Guo et al., (2021) made similar discoveries where increased water grey storage capacity was responsible for delaying the progression of meteorological drought into a hydrological drought. Institutional reaction to drought is reportedly slow in South Africa (Sifundza, van der Zaag and Masih, 2019), thus, delayed reservoir drawdown will not only reduce the temporal extent of socio-economic and hydrological droughts, but also sustain water availability and demand coverage while institutions are concluding on drought response measures such as instigating and intensifying restrictions. Considering the improvements attained under demand reduction measures, implementing them under increased storage will strengthen drought response capacity in the catchment, more specially during severe droughts like the 1992-1996 drought.

Improvements in reservoir levels, reliability, and coverage from this scenario were slightly low when compared to scenarios 1 and 2 during droughts. However, the increased storage resulted in increased water availability during normal rain years, which could enable commercial agriculture to irrigate at full capacity. Unlike demand reduction measures that are short term, scenario 3 is a long-term measure, thus the high investment costs required for its implementation are rightly justified. Additionally, Realization of benefits from scenario 3 is more certain than in scenarios 2 and 1, as it is not dependent on water users' behaviour and institutional reaction, rather reservoir operation rules.

Benefits realized from scenario 4 in Ebenezer reservoir and its demand sites are like those from scenario 1. Unlike scenario 1, implementing scenario 4 must be preceded by significant financial investment. Polokwane wastewater treatment plants are overloaded and inefficient in treating phosphorus and other minerals (Seanego and Moyo, 2013). Redirecting wastewater to the river must be preceded by financial investment towards increasing the capacity of treatment works and water treatment technology to ensure maintenance of good ecological status of water bodies. As an alternative, return flows can be redirected directly to agriculture, eliminating agricultural abstraction from the reservoir, thus attaining similar drought response benefits like when return flows are redirected to the river. Reboll et al., (2000) concluded that wastewater is a suitable alternative source of water for citrus irrigation, without causing any detrimental effects to the plant.

Limitation to achieve scenario 4 are beyond water quality concerns. Currently, only 41.1% of flush toilets in Polokwane are currently connected to sewerage (Stats SA, 2021). All households supplied by Ebenezer reservoir will need to be connected to the central sewer network before modelled results are achieved. In the future, possibly due to development and increasing population density (reducing area available for septic tanks) more households will become connected to the sewer network improving the prospects of this measure.

Pairing drought response measures proved effective in amplifying catchment wide benefits. The highest level of demand coverage and reliability, 100%, was achieved through this action. However, this should be applied with caution, especially for measures based on the same variable. Scenario 1 and 4 are both based on domestic water, therefore if they are implemented concurrently they will not provide significant benefits as with non-domestic water centred scenarios. benefits of scenario 4 will be reduced by half, following the implementation of scenario 1.

4.2 Responsiveness of Droughts to Drought Response Measures

Findings from the study illustrated the impacts of demands towards the severity of droughts. Increasing demand in the reference scenario led to Ebenezer reservoir drawdown to dead storage in the 1980s and to critical levels in the 2003-2010 period. This occurrence, coupled with increase in unmet demands show that if system's demands are not sufficiently managed, water shortages are imminent. These droughts events were significantly reactive to changes in water supply and or demand. While climate variability was the main cause of these droughts, their severity was due imbalance in demand and supply as such their nature being more socio-economic.

All drought response measure explored were insufficient to fully circumvent the 1992-1997 and 2015-2016 droughts. Based on failure to be fully evaded and less responsiveness to trialled measures, these droughts can be assumed to be purely hydrological as such requiring more diverse drought response measures. This does not discredit the effectiveness of explored drought response measures, however, it highlights the need of further research on drought risk response measures which will build on this study.

4.3 Environmental Water Requirements

Environmental water requirements are important for the sustenance of aquatic life. Increasing concern on incompliance, was amongst the main reasons for undertaking this this study. From the results of this study, EWR were not met 7.2% of the time in the baseline, which was low when compared to observations of 41% before 1993 and 22% between 1994-2008 (Pollard and du Toit, 2011). One possible result could be that the model being in monthly time steps, it based reliability on the total amount delivered each month, therefore days and weeks with less flow could be compensated by those with above EWR flow, resulting in conformation to monthly total flow delivered. Also, the reported incidences of illegal and undocumented abstractions that occur from Tzaneen reservoir and the river (DWS, 2015), could be the reason for lower EWR unreliability observations. As these illegal abstractions are not quantified, they could not be represented in withdrawals in the model.

The threat brought by increasing population and demand on the ecology of the catchment was highlighted through the 3.2% decline EWR reliability in the reference scenario. Reverting the impacts resulting from increased demand is more effective through scenario 1 and 2, individually and when paired. These scenarios are not only economical but also environmentally clean options. While scenario 4, offers admirable benefits as well, it carries the risk of degrading the ecological status of water bodies.

4.4 Limitations

There was limited information on the catchment, especially for Ebenezer reservoir, as such educated assumptions had to be made. This might affect the accuracy of the baselines and refence scenario, but not results for drought response scenarios. Furthermore, there are reported incidents of illegal water abstractions, which affects water resource availability in the system, however, since their quantities and abstraction points were unknown, they could not be represented in the study.

5 CONCLUSION

The aim of this study was to evaluate feasible drought response measures for the Groot Letaba Catchment using the WEAP hydrological model. First, a reference scenario depicting current water demands was developed and compared to baseline, demonstrating a correlation between increased demand and system vulnerability to drought which was more pronounced in drought magnitude like 1982-1987, 1992-1997 and 2015-2016. Four Drought response measures were explored which consisted of Tzaneen reservoir storage increase, return flow rerouting, 50% domestic water use rate reduction and 10% agricultural water reduction. While all response measures had their prerequisites, merits and demerits, rerouting return flows to the river had more demerits and prerequisites. Based on that, of the four measures, it should have the least priority for implementation. Reducing agricultural and domestic water demand are economic measures with positive prospects on water resources, demand coverage and reliability. Though they are feasible measure for both reservoirs, their priority of implementation should be unique to each reservoir, domestic water restrictions being a primary response measure for Ebenezer reservoir, while irrigation water reduction should be a primary measure for Tzaneen reservoir. Increasing Tzaneen reservoir storage capacity is underway and it will bring long-term benefits in the water supply system, hence a feasible measure.

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APPENDICES

Appendix A

Table A1 Input model parameters for the commercial agricultural catchment modelled using the MABIA method.

Parameter	Commercial agriculture catchment
Area	10,322
Total soil thickness	1
Soil water capacity	Clay loam
Direct recharge to groundwater	20%
Fraction covered	0.5
Effective precipitation	80
Latitude	-23.8
Irrigation scheduling (avocado)	4 days interval, 7 mm depth
Irrigation scheduling (citrus)	3 days interval, 9 mm depth
Fraction wetted	0.4
Irrigation efficiency	85
Loss to groundwater	15
Priority	2