FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

SCHOOL OF CIVIL, MINING AND PROCESS ENGINEERING

WATER EVALUATION AND PLANNING SYSTEM MODEL ASSESSMENT FOR OPERATION OF HARDAP DAM AND WATER RESOURCE MANAGEMENT STRATEGIES IN ITS CATCHMENT, NAMIBIA

BY

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Thesis presented in partial fulfilment of the requirements for the degree Master of Integrated Water Resources Management at the Namibian University of Science and Technology

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DECLARATION

I, **Victoria Mwatala Iyambo**, hereby declare that the work contained in this thesis entitled *Water Evaluation And Planning System model assessment for operation of Hardap Dam and water resource management strategies in its catchment, Namibia*, is my own original work and that I have not previously in its entirety or in part submitted it at any university or higher education institution for the award of a degree.

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ABSTRACT

Management of water supply and demand remains a major challenge in most developing countries, especially in a semi-arid country like Namibia, where surface water supplies are limited mostly during drought periods. Given the extremities, the Hardap catchment is exposed to, water supply and demand management is a challenge. This results in water resource allocation problems, which threaten the sustainable water resource management in the catchment. A baseline study was conducted to develop and assess a calibrated WEAP model for the Hardap Dam operation and water resource management strategies. Water demand and supply availability were evaluated for three water use sectors, namely, domestic (tourism and livestock included), aquaculture, and irrigation.

The WEAP model was structured according to four scenarios with a current account (1999) and reference period (2000-2021). These scenarios are as follows: Scenario 1: 10% demand saving management for Mariental Town and improved irrigation efficiency by changing from the current flood irrigation method to the drip irrigation method. Scenario 2: increased irrigation area for the Hardap Irrigation Scheme. Scenario 3: hydrological seasons for high and low flows which evaluated the change in the hydrological regime; very wet, wet, normal, dry and very dry years. Scenario 4: the discharge of water made from Hardap Dam in 2017 for the downstream demand, Neckartal Dam.

The modelling results show that the operation of the Hardap Dam is challenging and the change from 100% to 70% operation rule of full supply capacity has greatly reduced the availability of water supply. The water management strategy results indicate that the 10% demand saving management for Mariental Town has reduced the domestic water demand by 10% hence no impact on the water availability of the Hardap Dam. Improved irrigation efficiency has a positive impact of about 30% reduction in water demand and 13% increase in water availability, with a significant impact of improvements during the drought seasons. Under the increased irrigation area scenario, the irrigation demands are increased by 3.8 Mm^3/m for an area of 213 ha and little impact is observed on the storage volumes during dry years. However, the model forecasted a critical and an extreme threshold of 300 and 1000 ha respectively. This has a major impact on demand coverage which was reduced to 90% for the 300 ha. While the 1000 ha has a significant impact on the water supply which depleted the dam levels to below the dead zone. The hydrological seasons were evaluated and the results show that there is a major effect during drought years, due to an increase in storage volumes. The forecasted inflows of 2015 and 2016 were within the observed water year type of dry and very dry. The result of the discharge of 10.7 Mm^3 for Neckartal Dam from Hardap Dam in 2017 showed no threat to the water demands and supply as both demands are met.

Keywords: Management strategies, Water resource management, Water availability, Dam operation, Hardap Dam, Water allocation, WEAP model, Scenarios.

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List of Abbreviations

DWA	Department of Water Affairs
FAO	Food and Agricultural Organisation
GWP	Global Water Project
IWRM	Integrated Water Resource Management
MAWF	Ministry of Agriculture Water and Forestry
MAWLR	Ministry of Agriculture Water and Land Reform
NamWater	Namibia Water Corporation
WEAP	Water Evaluation And Planning
WRM	Water Resource Management

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CHAPTER 1: INTRODUCTION

1.1 Background of the Study

Namibia is one of the most arid countries in Sub-Saharan Africa. Thus, it is regularly affected by severe water shortages and droughts. There are no perennial rivers within Namibia, only along the northern and southern borders. Therefore, limited water resources are a big challenge in central Namibia, particularly surface water which has been under strain for the past five years. The Hardap Catchment mostly receives low rainfall, with average annual rainfall ranging between 100 and 200 mm per annum (mm/a) and the evaporation rate is high with a mean of 3 389 mm per annum (mm/a) (Du Plessis, 2020).

The Hardap Dam, with a capacity of 294.6 million cubic meters (Mm^3), impounds the ephemeral Fish River and its tributaries and it has a surface area of 28.7 km^2 at Full Supply Level (FSL) with an annual average gross evaporation (loss from FSL) of 64.6 Mm^3 (NamWater,2014). The dam's water level is operated at a maximum of 70 per cent of its capacity to prevent flood storage capacity and spilling over its non-overspill crest (Denys, 2014). The main consumers of the Hardap Dam water include the Hardap Irrigation Scheme (representing the largest demand at 40 Mm^3/a, consisting of an area of 2260 ha cultivating mainly maize, wheat, lucerne, and vegetables (Hattingh, 2007a); the town of Mariental with a population of approximately 14 500, projected with the based data of the 2011 census (NSA, 2011); and smaller users such as the Namibia Wildlife Resort (Hardap Resort) and an aquaculture farm (Hardap Inland Aquaculture Center).

Like the Hardap Dam, Neckartal Dam constructed at about 352 km downstream in the Fish River, between 2015 and 2019, also impounds the Fish River. Water supply during the construction of Neckartal Dam was a challenge. Coetzee (2017) stated that alternative water supply sources were investigated and identified, including the releases from Hardap Dam which is located 352 km upstream of the Neckartal Dam site which led to a total of 10.7 Mm^3 of water being discharged from Hardap Dam in 2017, for construction purposes of Neckartal Dam. This high priority ad-hoc demand was not planned for the 2017/2018 hydrological season and instantly became one of the highest consumers of the Hardap Dam.

1.2 Statement of the Problem

Management of water supply and demand remains a major challenge in most developing countries including Namibia. Namibia is a semi-arid country and surface water supplies are limited mostly during drought periods. Given the extremities the Hardap catchment is exposed to, water supply and demand management is a challenge. This results in water resource allocation problems, which threaten the sustainable management of water resources in the Hardap Catchment. Therefore, there is a need to carry out a baseline study through modelling to assess the operation of the Hardap Dam and water resource management strategies for the Hardap Catchment.

1.3 Objectives of the Study

1.3.1 Main Objective

To develop and assess a WEAP model for the Hardap Dam operation and water resource management strategies in the Hardap Catchment.

1.3.2 Specific objectives

a. To develop a calibrated water resource management model using historical data for the Hardap Dam Catchment.

b. To assess the impacts of water supply and demand management strategy scenarios on historical data (implementing demand-side management for Mariental Town, improved irrigation efficiency, increased irrigation schemes area, and hydrological seasons for high flows and low flows).

c. To evaluate the impact of the discharge of water made for the construction of Neckartal Dam from the Hardap Dam in 2017 in terms of demand and supply.

1.4 Research Questions

a. What will be the impact of water releases on water supply security to current and new users downstream of Hardap Dam?

b. Which water resource management strategies will best improve water resource availability for all users?

c. Did historical operations of the Hardap Dam affect water supply security?

1.5 Ethical Issue

This research is a desk study; hence, it will not tamper with environmental and ecological processes within the catchment. Data sourced from the organizations will be strictly used for this study. Therefore, ethical integrity will be maintained by the researcher.

1.6 Limitations of the Study

The limitations of the study would be the availability and accuracy of data. Time and finance are also limited hence WEAP version 21 for students was used.

1.7 Significance of the Study

The information generated from the study will assist decision-makers and stakeholders within the Hardap Catchment to mitigate water crises by implementing water resource management strategies based on a planning tool. This study will also create awareness of the importance of water management as we face water crisis and drought in Namibia. The use of the WEAP tool in WRM is limited in Namibia, therefore, it will contribute to the studies of using WEAP in the country, benefiting the national and international communities and academic scholars. The results will be useful to the Ministry of Agriculture, Water and Land Reform, NamWater, decision-makers, policymakers, irrigation farmers and Namibia at large.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides an outline of previous research on water resource modelling and management strategies. It introduces the structure for the study that includes the main focus of the research described in this thesis.

2.2 Water Supply and Demand

The supply and provision of adequate water is already a common problem in many river catchments as water demand already outstrips supply and many more are projected to experience the same (UN- WATER, 2012). Water resource management has been done based on the social criteria whereby government invests in supplying infrastructure to ensure continuous water availability for various demands and uses (Bangash et al., 2012). However, this has since changed because of the increasing water demands and the implementation of ineffective water allocation systems (GWP, 2000). Water resource management, therefore, becomes a structured medium meant to manage and allocate the available water resources fairly, equitably and sustainably to different consumers to avoid scarcity and conflicts (Bangash et al., 2012).

Traditionally, demands are mostly calculated using the activity level multiplied by the water use rate. For domestic demands, this is the population size multiplied by the demand rate based on the theoretically derived demand norms for that specific area. CSIR, (2000) stipulated a typical consumption rate of 250 litres per capita per day (l/c/d) for the high-income population. While Planning Division, (1992) recommended a rate of 200 l/c/d for the high-income population. This method takes into account the population growth if there is a need for population projection and estimation when the census data are not current. The population projects are estimated using the arithmetic growth method in **Equation 1** based on the current 2011 census data (NSA, 2011). NSA, (2011) indicated that Mariental has a total population of 12 473 people and a growth rate of 1.5%.

$$P = P_0 \times (1 + r)^{(t - t_0)} \qquad \text{(\textbf{Equation 1})}$$

Where:
P = Projected population in number
Po = Baseline population in number

r = growth rate in percentage
t = Projected year
to = Baseline year

Demand analysis in WEAP is an end-use based approach for modelling the requirements for water consumption for a specific area. It provides a lot of flexibility in how you structure your data, ranging from highly disaggregated end-use oriented structures to highly aggregate analyses (WEAP21, 2020). WEAP has two optional methods to input and calculates demand. The Monthly demand method allows you to input month by month demand values for the demand site, or you may use the read from file function to read in monthly demands of the actual observed demands, which can then be varied with the time series wizard if need be (WEAP21, 2020). While the Annual demand with monthly variation allows you to express demands on an annual level which requires the input of an activity level (e.g., population size) and a water use rate associated with that activity level (e.g., an annual volume used per person) (Sieber & Purkey, 2015). This method was used with the demands of the projected population of 2021.

The supply of resources in WEAP is based on rivers, dams, and other sources (WEAP21, 2020). For the dams, the input required are the inflows, storage levels, volume-elevation relationships, net monthly evaporation rates, operating rules, and any other conservation purposes (Sieber & Purkey, 2015). Month inflows into the dam must be defined as a starting point of the source. The net evaporation is required as a monthly evaporation rate that can be positive or negative to account for the difference between evaporation and rainfall surface area of the dam (WEAP21, 2020).

2.3 Water Resource Management

Water resource management is becoming increasingly difficult due to the complex issues that water resource professionals and resource management agencies must address (Alfarra, 2004). There have been significant changes in the water utility industry over the past 20 years (Savenije, 2000). One major change is that there is now intense competition between water used for domestic, versus other uses such as recreation, agriculture, and industry and hydroelectricity generation. WRM involves the process of planning, decision making and implementation (Alfarra, 2004). It comprises the full range of activities, from demand analysis through planning, design and construction to operation and monitoring. According to Savenije (2000), WRM is a highly dynamic process, covering a wide spectrum of activities in the fields of assessment, planning and operation.

The current approach to water resource management for the Hardap Dam includes but are not limited to water demand saving for Mariental Town, reduction of water use on irrigation scheme and fish farm. These management plans are generally applied during the period of droughts when the dam levels are getting critically low.

As the global water demand is increasing, pressure on the available water resources also increase and this has had major implications and challenges on water resources management (Sungu, 2018). Some of the challenges, particularly on the Hardap Dam water have been aggravated by changes in the patterns of water utilisation. These changes are brought about by rural/urban migration and rising standards of living, changing of socio-economic situations, hydrological and hydraulic conditions, and the application of inefficient irrigation systems. The fact that the irrigation scheme is being supplied via a reticulation network of concrete- lined open canal coupled with a high level of evaporation in this region (3 389 mm/a), generally reduces water use efficiency as well (Lange et al., 2007).

The concept of integrated water resource management (IWRM) helps with water allocation between different sectors (Leong & Lai, 2017). According to GWP (2000); (Haigh, Fox, & Davies-Coleman, 2010); and (Sungu, 2018), "IWRM is a process that enhances the coordinated development and management of water, land and related resources, to maximise the economic and social welfare equitably without compromising the sustainability of vital ecosystems". One of the aims of IWRM is to improve all aspects of water resource management progressively (Haigh, Fox, & Davies-Coleman, 2010). Hence, the study assessed scenarios of WRM strategies to coordinate the management of water resources.

2.4 Water Policies and Laws

The Namibian water sector is governed by policies and legislation for the management of water resources and proper utilization. Soon after independence, the existing apartheid-era policies that governed the water sector were severely outdated and did not conform to the new political order which explicitly emphasized human rights and equitable access to resources and opportunities for all citizens (Remmert, 2016). The adoption of integrated approaches for the management of water resources has required reforms for many countries with adjustments to water policy, water legislation and water resources planning (UNEP, 2012). The Namibian nation has seen several reform processes and fundamental changes to legislation and regulation of the water sector.

There are two main suppliers of water in Namibia: the national Namibian government and the Namibia Water Corporation (Braga, Castiglione & Higgins, 2004). Within the government, the Department of Water Affairs has two Directorates that are responsible for the water supply of Namibia: the Directorate of Resource Management and the Directorate of Water Supply and Sanitation Coordination (DWSSC). The Namibia Water Corporation, also known as NamWater, was established by the NamWater Act (12 of 1997) and is the only commercialized company authorized to supply bulk water in Namibia, especially in urban and selected rural areas i.e. in high population areas, with a larger portion of rural water supply falling directly under the DWSSC. The entity (NamWater) is owned by the government (Parastatal) for the efficient supply of both raw and potable water to consumers based on a cost-recovery model, hence they are in charge of surface water dams that are linked to water supply (Pazvakawambwa, 2018).

Water supplied from Hardap Dam is managed and operated by NamWater, which includes monitoring of the upstream river and streams within the catchment, gauging stations, water treatment, bulk supply, and flood control of the Hardap Dam. NamWater sells the Hardap Dam water to the Mariental municipality for domestic and industrial use and the Ministry of Agriculture, Water and Land Reform for distribution to the irrigation scheme (Lange et al., 2007).

Various water policies and laws that govern the Namibian water sector are briefly described here. The Water Act (Act 54 of 1956) was adopted in Namibia, based on the South African regime and the Act was selectively applied to Namibia whereby some sections did not apply. The law disregards the ecological reality of Namibia and emphasizes the use and control of water in a centralized essence, discriminating against the majority of citizens (Remmert, 2016). Unfortunately, the Act remains in force since the Water Resource Management Act (WRMA) of 2013 has not been enacted. The Water Resources Management Act No. 11 of 2013 was introduced by the Namibian government in December 2013. The act gives rights for water resources management to be developed to ensure the sustainable use of water in Namibia by maintaining the integrity of water supply and the sources from which supply is derived in the long term.

Two of the main important policies in the sector are the National Water Policy White Paper of 2000 as well as the Water Supply and Sanitation Policy 2008. The National Water Policy White Paper of 2000 provides for a policy framework for equitable access to water resources and sustainable water resources management and water services to support integrated management of Namibia’s water resources. The policy states that water must be recognised as a finite resource and every effort should be made to control utilization. This policy stipulates approaches emphasising the water assessment and demand management of water resources. The demand management should use a range of effective measures to achieve its objective of more efficient water utilisation, including the demand water savings and improved water efficiency in irrigation techniques which this study intended to assess and implement (MAWRD, 2000). Furthermore, the policy continues to state that water resources assessments are needed, which will require commitments to ensuring that information is accessible for use by the technical, scientific community and scientific research to generate reliable and appropriate information needed for proper management (MAWRD, 2000). Of particular importance to this section is that this study aimed to assess and implement strategies for the management of water from Hardap Dam in terms of scientific research.

The Water Supply and Sanitation Policy 2008 (WASP) is to ensure the availability of essential water supply and sanitation services to all citizens at affordable costs. The WASP (2008) provides a priority ranking that should be applied in the case of water shortages, with the first priority being for the provision of water for domestic use and the second priority being the provision of water for economic activities. This policy will ensure that the demand and supply priorities are determined and set out in the WEAP model for this study. The priority modelling assumptions of economic activities which include irrigation will be determined as per WASP policy of 2008.

Another important planning tool sufficiently used by the sector is the Integrated Water Resources Management Plan (IWRMP) of 2010, which has a long term objective to enable Namibia to achieve a sustainable water resource management regime contributing to social equity, economic efficiency and environmental sustainability in the country (IWRMP, 2010). This is based on the optimisation of water supply, allocation and reduction of water demand to realistic levels and efficiency improvement throughout the water sector, taking sustainable development into account. As the WEAP model is an IWRM tool, it will ensure that the allocation and utilisation of water are implemented in an integrated manner. The IWRM plan allows for potential water resources to be realised, used effectively and allocated accordingly (GWP, 2009). The IWRMP of 2010 stated six approaches for enhancing the ability to sustain and manage water resources. One of these approaches is water demand management to be implemented with changes in water use practices for contributing to improved water resource management as a necessity to ensure continued water provision (MAWF, 2010). This study will implement water demand management strategies as part of water resources management strategies in a wide stream of IWRM, specifically with changes of water use practices such as; demand savings for Mariental Town and for the Hardap Irrigation Scheme to improve water use efficiency.

The dam operating rules play a major role as the operation criteria of a dam determine how much water is available in the current time step to be released for downstream demand (Yates et al., 2005). The following **Table 1** represents the hydrological data and operating rules for the Hardap Dam (Hydrology Division, 1994; NamWater, 2009).

Table 1: Hydrological data and operating rules of Hardap Dam (adapted from Hydrology Division, 1994; NamWater, 2009)

Description	**Level**
High flood level H.F.L. (m)	1138.2
Full supply level F.S.L. (m)	1135.0
Capacity at F.S.L. (Mm^3)	294.590
Surface area at F.S.L. (km^2)	28.77
Annual gross evapo. Loss from F.S.L. (Mm^3)	64.56
95% assured yield at 100% FSL (Mm^3)	58
95% assured yield (Mm^3) at 70% FSL	46
Dead storage (Mm^3)	4.299
Lowest abstraction level (Mm^3)	19
Reliability of domestic water supply (%)	95
Reliability of irrigation water supply (%)	80
Flood safety control level (%)	80 - 100

Hardap Dam has a 95% assured safe yield and the reliability of water supply for domestic demands is 95% and that of irrigation demand is 80%. According to NamWater (2009), the dead storage capacity is taken at 4.229 Mm^3 and at 19.0 Mm^3 for domestic and irrigation demands. Once the dam reached a capacity of 19 Mm^3, the irrigation supply is cut off but there will be sufficient water for domestic demands up to 12 months for the Mariental Town. For flood absorption and control the targeted full supply level varies between 80% beginning of the rainy season to 100% at the end of the rainy season to maximise yield and minimise flood risk (Hydrology Division, 1994). The priority and assurance of supply for the demands are further classified in **Table 2**.

Table 2: Hardap Dam supply assurance (adapted from Mare, 2007)

Demand category	Priority classification & assurance of supply		
	Low **80%** **1 in 5 year**	**Medium** **90%** **1 in 10 year**	**High** **95%** **1 in 20 year**
Urban/Industrial	0%	0%	100%
Irrigation	83%	17%	0%

Restrictions in the water supply are first applied to the water use assigned with a low assurance level (once in 5 years possibility of shortage in the water supply) (Mare, 2007). Thus, the curtailments are imposed on the higher assurance of 95%, if all the water assigned to the lower assurance users, had been restricted in full. The supply priorities and assurances consider the 95% safe yield for the Hardap Dam of 46 Mm^3/a at 70% operational capacity and the lowest irrigation abstraction level of $19Mm^3$. Hence total months of supply are determined using **Equation 2**, assuming a constant distribution of demands (NamWater, 2014).

$$\text{Total supply months} = \frac{\text{Residual storage}-\text{Buffer zone level}}{\text{Monthly max abstraction}} \qquad (\textbf{Equation 2})$$

According to the user guide for WEAP 2015, the operation rules divide the reservoirs into water level-related zones. Hardap Dam has four zones as illustrated in **Figure 1**. The water in the Flood control zone cannot be stored and is used for flood control and attenuation. In the next zone, the operational FSC, is a conservation zone and water is used as required to meet all demands. In the Buffer zone, restrictions are applied so that the water is not used too quickly. The top of the buffer zone is also the lowest abstraction level for the Hardap irrigation scheme (19 Mm^3); when the Hardap Dam reached this zone, supply to the irrigation scheme stopped to cater for domestic demands for a period of two full supply seasons based on the supply assurance (NamWater, 2014). Below the “dead storage level” (4 Mm^3), this is a critical zone and water is still used for domestic demands by imposing demand saving measures.

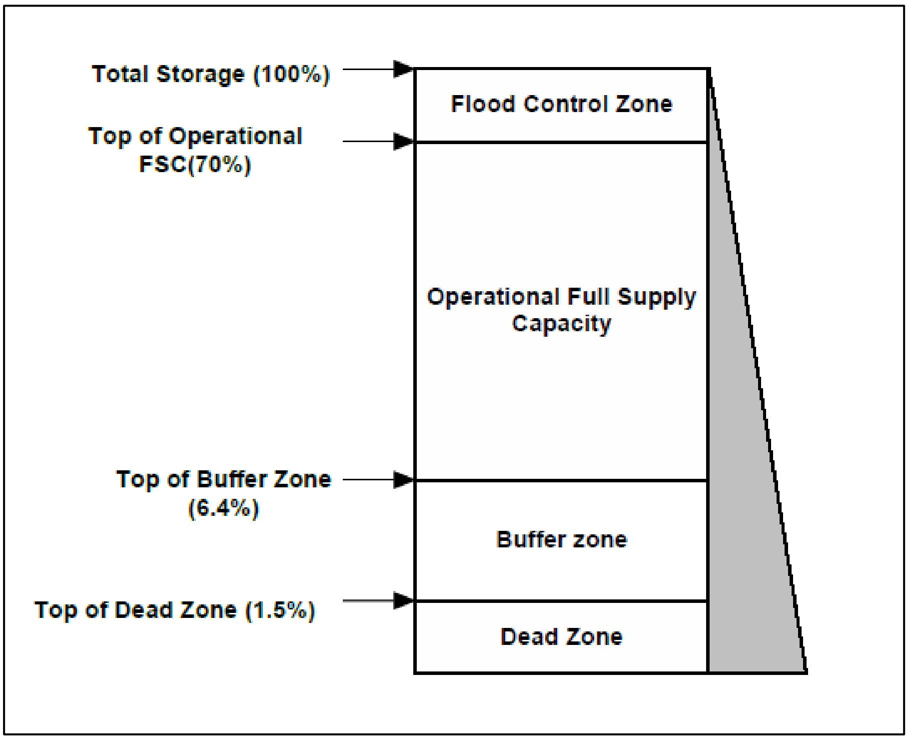

Figure 1: Hardap Dam water level zones (adapted from WEAP, 2015)

To define dam zones in the WEAP model, the volumes corresponding to the top of each zone are entered. The WEAP model uses the buffer coefficient (**Bc**) to slow down releases when the storage level falls into the buffer zone. When this occurs, the monthly release cannot exceed the volume of water in the buffer zone multiplied by this coefficient. In other words, the buffer coefficient is the fraction of the water in the buffer zone available each month for release (Sieber & Purkey, 2015). For the study, a buffer coefficient of 0.5 was used as an average value between 0 and 1, with 0 representing higher extreme restrictions and 1 being less restrictive. Practically for Hardap Dam, there is no inactive zone as there is a floating pump reserved to abstract water from the inactive zone. When this happens, the demand saving managements are also activated for Mariental Town, determined by performing a depletion analysis with the amount of water available. The residual storage volumes are such that the domestic demands will be met for the next two years with restrictions applied to the Hardap Irrigation scheme.

Within the WEAP model, water from these zones is released based on the following: The amount available to be released from the reservoir (***Sr***) is the full amount in the operational FSC zone (conservation) (***Sc***) and flood control zone (**Sf**) and a fraction (defined by ***Bc)*** of the amount in the buffer zone (***Sb***) (Yates et al., 2005). **Equation 3** shows the calculation for the amount of water available that can be released from the Hardap Dam.

$$\boldsymbol{Sr} = \boldsymbol{Sc} + \boldsymbol{Sf} + (\boldsymbol{Bc} \times \boldsymbol{Sb}) \qquad \textbf{(Equation 3)}$$

$\boldsymbol{Sr} = (207\ \mathrm{Mm}^3 - 19\ \mathrm{Mm}^3) + 0 + (0.5 \times (19\ \mathrm{Mm}^3 - 4\ \mathrm{Mm}^3)$

$= 188 + 0 + (0.5 \times 15)$

$= 196\ \mathrm{Mm}^3$

Where:

Sr = total amount for release from reservoir storage

Sc = operation FSC (conservation storage)

Sf = flood storage

Sb = buffer storage

Bc =buffer coefficient

2.5 Water Resource Management Models

Water assessment enables planners to make realistic future water demand estimates against potentially available water resources (Sungu, 2018). This kind of assessment provides boundaries for water allocation between the various sectoral water demands and priority water rights through scenario analysis (Mounir, Ma, & Amadou, 2011). These scenarios were evaluated through modelling by using water resource management models (Mounir, Ma, & Amadou, 2011).

With the water resources virtually being over-exploited over time, these resources will begin to show increasing signs of stress. Thus, decision-makers require reliable models to allocate water resources between various stakeholders effectively and efficiently. As a solution to this problem, researchers and specialists have emphasized on applying different simulation modelling techniques to develop decision support systems for integrated water resource management (IWRM) (Leong & Lai, 2017). Numerical water resource models have been used to assist decision-makers to deal with the complexity of water resource management. In the following sections, several models commonly used for analysing the water assessment and evaluation of river basins and used as decision support tools in water resources planning and management are briefly discussed.

2.5.1 Mike Hydro Basin

MIKE BASIN is a multipurpose, GIS-based river basin simulation package for integrated water resources analysis, planning and management of river basins (DHI, 2019). The MIKE HYDRO BASIN was developed by the Danish Hydraulic Institute (DHI) in 2001. The model is a mathematical representation of the river basin including the configuration of river and dam systems, catchment hydrology and water user schemes (DHI, 2019). MIKE BASIN can be used to determine the quantity and quality of water in a river basin of a slowly changing system and is used as a DSS by analysing water-sharing problems and environmental issues at interstate or international levels (Ayele, 2016). Leriao (2016) used the MIKE HYDRO Basin to carry out a flood and hydrological analysis of the Fish River Catchment considering flood remediation scenarios. Another study was done for Zayandeh Rud catchment using MIKE HYDRO BASIN to simulate the complex water use and management processes in the Zayandeh Rud basin, taking into account the water allocation and water supply availability (Kaltofen,Muller, & Zabel, 2017).

2.5.2 Water Resource Yield Model and Water Resource Planning Model

The Water Resource Yield Model (WRYM) and the Water Resource Planning Model (WRPM) were developed in South Africa by the BKS consulting firm based on the Canadian ACRES Reservoir Simulation Program (Mackenize & Van Rooyen, 2003). The WRYM relies on a solver that optimizes the water allocation in a river system based on a set of penalties for storage, channels and demands at various nodes and links within the catchment (Juizo & Liden, 2010). The network in WRYM is analysed for each period and solved with the selected penalty structures. This network solver will minimize the penalties for each time step by choosing the best allocation of water to the different users (Juizo & Liden, 2010). The WRYM is widely used in Southern Africa and is the preferred tool by the South African Department of Water Affairs or system analysis of all the river basins in South Africa (Carmo Vaz & Van der Zaag, 2019). The WRPM is designed for projection analysis of operational and development planning decision support, considering the dynamic changing water use, new infrastructure, maintenance schedule and project the risk of drought curtailments (Juizo & Liden,2010). The two models were applied on the Orange–Senqu River basin through the Commission for assessing the risk of water availability of the catchment and how it compares against specific risk criteria (WRP, 2014). The models were also used to assess the Hardap flooding situation and to provide a mechanism to decide on the minimum operating level of the Hardap Dam, without negatively affecting the agreed assurance of supply to the various consumer groups (Mare, 2007).

2.5.3 Water Evaluation And Planning (WEAP)

Water Evaluation And Planning system (WEAP) is a user-friendly software tool for an integrated approach to water resources planning that provides a comprehensive, flexible framework for the development of water assessment, scenario generation, planning and policy analyses (Sieber & Purkey, 2015). WEAP can simulate a broad range of natural and engineered components of these systems, including sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; vulnerability assessments; and ecosystem requirements (WEAP21, 2020). WEAP operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems (WEAP21, 2020).

The latest version (WEAP21) extends the previous WEAP model by introducing the concept of demand priorities and supply preferences, which are used in linear programming to solve the water allocation problem as an alternative to the multi-criteria weighting or rule-based logic approaches (Yates at el., 2009). The application involves defining the problem, setting a time frame and areal boundary, and identifying and configuring the system components; creating the 'current accounts', which show the actual water resources, supplies for the system; demands and future trends (Sungu, 2018).

The WEAP model simulates water system operations in a river system on a monthly time step, under varying conditions both in current state and future scenarios. WEAP21 incorporates water supply in the context of demand-side management and ecosystem preservation and protection into a practical tool for water resources planning and policy analysis. The model places demand-side issues such as water use patterns, equipment efficiencies, reuse strategies, costs, and water allocation schemes on equal footing with supply-side themes such as streamflow, reservoirs and water transfers (Ayele, 2016). This gives the water planner a more comprehensive view of the broad range of factors that must be considered in managing water resources for present and future uses.

The capabilities of WEAP include; Geographical Information System (GIS) based interface, a model building tool with physical simulations of demands and supplies, scenario management with priorities of allocation and dynamic links to spreadsheets (Ayele, 2016). In addition to that, the WEAP model licences and acquisitions are available for academic use and to non-profit organisations at no cost. Models like MIKE HYDRO BASIN, also have the capabilities to carry out the assessment but require extensive training and high cost is involved in the software licence acquisition. In light of this background, the researcher sees the necessity to use WEAP21 as a tool of assessment, for the operation of the Hardap Dam and water resource management strategies for the Hardap catchment.

The WEAP model further analyses the consequences of mutual-conflicting interests and divergent water allocation in management options (Nyika, Karuku, & Onwonga, 2017), something which has been identified as a huge challenge as well when it comes to the sharing of the water from Hardap Dam. It provides an integrated assessment of the land use, hydrology, climate, water allocation, and water management of catchments (Amin et al., 2018), necessary for the sustainable use and management of water from Hardap Dam.

WEAP was successfully used in the Okavango Basin whereby the application was developed for the Transboundary Diagnostic Assessment (TDA) of the Okavango basin. This was done to derive scenarios of impacts on environmental flow and to estimate the impact of different scenarios on stream flows at eight different Ecological Flow Assessment (EFA) sites (FAO, 2016).

A similar study carried out in Kenya, to assess the influence of water allocation on water resources management for the Nyando Basin using WEAP, proposed increased efficiency in the use of natural resources and integration of water and land in the national policy agenda for natural resource conservation and management (Sungu, 2018).

2.5.4 RiverWare

RiverWare is a reservoir and river basin modelling tool that allows the user to model and analyze a variety of basin operations in both simulation and forecast modes for more effective decision-making and long-term water resource planning (Johnson, 2014). The RiverWare model was developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado in Boulder (Asmaa, Doaa, & Mohamed, 2019). The RiverWare model relies on logic within complex algorithms rules that drive the simulation and express multifaceted operational policy that can be prioritized (Johnson, 2014). Asmaa, Doaa &Mohamed (2014) carried out a study to update the existing water allocation, the Eastern Nile model using RiverWare. The evaluation was performed by simulating the historical conditions and updating the hydrologic data up to 2014. This study was able to define a well-designed operation policy and modelling framework that provides accuracy, transparency, and flexibility to develop and test innovative solutions and explore several alternative solutions (Asmaa, Doaa, & Mohamed, 2019). **Table 3** summarises the models in terms of advantages and disadvantages.

Table 3: Water Resources Management Models advantages and disadvantages (adapted from WRP, 2014)

Name of Model	Description	Advantage	Disadvantage
Mike Hydro Basin	A GIS-based decision support tool for integrated water resources analysis, planning and management of river basins. Designed for analysing water sharing issues at an international, national or local river basin scale.	Provides an easy-to-use, map-based modelling framework. Fast and flexible simulation engine. Detailed outputs from model features provide an easy overview of scenario results.	There is a high-cost implication for obtaining software licenses. Extensive training is required for new users.
WRYM and WRPM	Constant development simulations that perform risk-based yield analysis. Design for projection analysis of operational and development planning decision support.	Specifically developed for arid regions such as Namibia. Software is available at no cost. Configured for future management and scenario analyses.	New users require to learn both two models as the WRPM requires inputs from WRYM.
WEAP21	Provides an integrated & comprehensive framework for the development of water assessment, allocation, scenario generation, and planning and policy analyses. WEAP21 operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, and river basin systems.	Model scenarios and user-friendly software tool. License acquisition is free to academics and non-profit organizations. Integration with other tools for detailed outputs visualisation.	High cost for license acquisition to profitable organizations. Training required for new users.
RiverWare	Operations in both simulation and forecast modes for more effective decision-making and long-term water resource planning.	Provide long-term forecasting model. Provide several alternatives scenarios.	Use complex algorithms rules that drive the simulations. Extensive training is required for new users. Lack of integration with other tools for detailed outputs overview.

Details on model selection criteria and how appropriate models should be selected and outlined are based mainly on the project objectives and goals (Engel et al., 2007). Once the aim is defined, other criteria should follow for downscaling such as; appropriate level of detail required, calibration requirements, data requirements and availability, previous applications of the model and its acceptance, ease of use, how the model results will be used and availability of resources and time (Engel et al., 2007).

The catchment does not have an established water resource management model but there are existing operational rules for the Hardap Dam. Therefore, there is a need to set up and build a water resource management model that helps to simulate available water resources effectively and reliably. WEAP model was used in this research study because it has the integrated scenario analysis approach, an easy-to-use model, freely available for academic use and allows decision-makers to understand the physical dimension of allocating water and the technical significances so that it is easy to see the implications of any decisions to be made.

2.6 WEAP Modelling

2.6.1 Model Calibration and Validation

Calibration is the adjustment of model parameters that the model reproduces the observed prototype data at an acceptable accuracy (Brunner, 2008). Validation of the model is done to check the accuracy and outcome of the model basis on the observed data. The performance of the model was evaluated by comparison of the simulation results with the observed data using indicators; the Nash Sutcliffe Efficiency (NSE), which ranges from -∞ to 1, where 1 indicates the perfect score of the simulation (Krause, Boyle, & Bäse, 2005). A scaled version of the Root Mean Square Error (RMSE) was also used to evaluate the performance of the model where a smaller value represents a good model (Brunner, 2008). The NSE and RMSE are defined by **Equation 4** and **Equation 5**.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O}_i)^2} \qquad \textbf{(Equation 4)}$$

$$\mathrm{RMSE} = \sum_{i=1}^{n} \sqrt{\frac{(O_i - S_i)^2}{n}} \qquad \textbf{(Equation 5)}$$

Where

O_i = observed values

S_i = simulated values

$\bar{O}_i$ = Mean of observation values

n = number of months

2.6.2 Study Modelling

The modelling was done using the WEAP model version 21. The WEAP21 version is structured as a set of five different "views": Schematic, Data, Results, Scenario Explorer and Notes (Sieber & Purkey, 2015). According to Sieber & Purkey (2015), schematic is a GIS tool for configuring the system by dragging and dropping to create and position the map. The data view is used to build the model with collected data as it creates variables and relationships. Users can also enter assumptions and projections using mathematical expressions and dynamically link to Excel files. Results view displays detailed model outputs in the form of charts, tables and maps. Scenario explorer is a high- level view and split between a Data view and a Results view, with each section displaying information from their respective views (the Data view and the Results view). With the result view, the explorer is used to group multiple charts and tables created in the results view into "Overviews". This enables one to simultaneously examine different important aspects of your system, such as demands, coverage, flows and storage levels, environmental impacts and costs and within the Data section, it can display selected data across many scenarios. The slider moves to change the value of the associated scenario data variable and WEAP recalculates so that the impact on user-selected key results are displayed as preferred. The process of modelling and simulation using WEAP in the catchment makes use of the following steps (Sieber & Purkey, 2015):

1. Problem definition including a time frame, spatial boundary, system components and configuration. This step involves siting of the catchment area, delineation and the collection of data. The required data was collected such as dam inflows, storage levels, population, rainfall, evaporation, catchment characteristics, and standards and guidelines.

2. Establishing current accounts. The current accounts are viewed as a calibration step in the development of an application and they provide a snapshot of the actual water demand, resources and supplies for the system.

3. Building scenarios based on different sets of future trends based on policies, technological development, and other factors that affect demand, supply and hydrology. The scenarios are used to address “what if” questions such as: What if the demand saving management is implemented, what if the irrigation efficient systems is improved and increased in irrigation size?

4. Evaluating the scenarios concerning the criteria of water resources management. The results generated from running the model are used as a DSS for decision-makers. **Figure 2** illustrates the WEAP model framework for the simulation of water supply and utilisation of the Hardap Dam water.

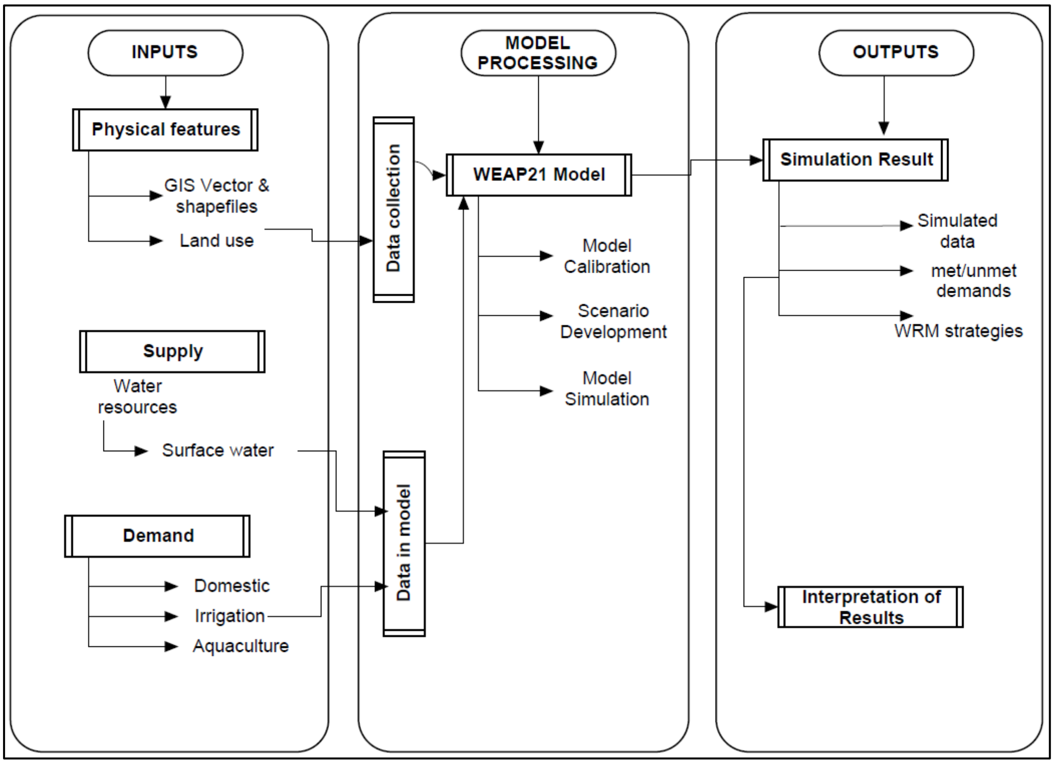

Figure 2: WEAP model framework

2.6.3 Model Processing

WEAP calculates a water mass balance for every node and link in the system on a monthly time step. Water is supplied to meet demand requirements, subject to demand priorities and supply preferences. WEAP operates on a monthly time step, from the first month of the current accounts year through the last month of the last scenario year (Sieber & Purkey, 2015). Thus, all of the water entering the system in a month is stored in a dam and leaves the system by the end of the month (outflow from the dam, demand site consumption, evaporation, leakage, transmission and return flow link losses). All flows occur instantaneously because the time scale is relatively long (monthly). The mass balance equations and calculations happen within WEAP and they are the foundation of WEAP's monthly water accounting: total inflows equal total outflows, net of any change in dam storage. Every node and link in WEAP has a mass balance equation (Sieber & Purkey, 2015). Each mass balance equation becomes a constraint in linear programming (LP). **Equation 6** presents a mass balance equation that was used in WEAP.

$$\sum \text{Inflow} - \sum \text{outflow} - \sum \text{addition to Storage} = 0 \qquad \text{(\textbf{Equation 6})}$$

Addition to Storage is positive for an increase in storage and negative for a decrease in the storage of the Hardap Dam. Outflow includes consumption and losses. Every flow from one point to another is represented by a variable in the LP.

2.6.4 Demand Priorities and Supply Preferences

In WEAP21, priority values (1 to 99) are used to classify demands, with 1 being the highest priority value and 99 the lowest (Arranz & McCartney, 2007). Many demand sites can share the same priority. If priorities are the same, shortages will be shared equally (Arranz & McCartney, 2007). The domestic demand are given a priority value of one (1). Irrigation and aquaculture demands are given a priority value of two (2). Using supply preferences, WEAP determines the allocation order to follow when assigning the water supply (Sieber & Purkey, 2015). The Hardap Dam is given a supply preference of one (1) to supply for all the demands.

2.7 Climate Change Implications

Climate change trends that were observed in Namibia, particularly in Southern Regions showed that; there is an increase of inter-annual variability in rainfall since 1970 with higher rainfall anomalies and more intense and widespread droughts reported (Turpie et al., 2010). Hence Namibia's volumetric rainfall has steadily declined as the area experiences high dry spell frequencies linked to El Niño events (Turpie et al., 2010). These phenomena have become more frequent and intense over the years with low flow regimes in major river basins in Namibia. Water scarcity is increasingly becoming a problem in many river catchments.

The Hardap catchment is mostly prone to drought conditions with the most recent drought leading to a declaration of a state of emergency on 6 May 2019 (UNICEF, 2019). This drought had major impacts on the Hardap Dam storage, bringing down the water level to 24% of full supply capacity (MAWF, 2019), subsequently resulting in little to no allocation for the irrigation scheme, or for the provisions of local water supply to Mariental Town, which could have had higher economic impacts on the Hardap region. The droughts put the catchment in a challenging state, and therefore, water resource allocation, regulation and policies on water, require priority in terms of management particularly as far as droughts and eventually, water scarcity are concerned.

2.8 Summary

Water scarcity is increasingly becoming a problem in many river catchments, especially in Southern Africa, hence various studies were discussed on water resource management, water law, and policies and modelling tools. Studies show that water resource management is a crucial process that involves, planning, assessment and operation to ensure water availability for all users. The existing Namibian water law and policies were also discussed on how they apply to the Hardap Dam in terms of management and fairly allocation. There was also a discussion on different types of water resource management models and their advantages and disadvantages outlined to find the best model for this study. WEAP version 21 was one of the models discussed and details were given on how it is applicable for this research study as a modelling tool. The next chapter will look into the research methodology and approaches for this study.

CHAPTER 3: CATCHMENT BASELINE

3.1 Introduction

This chapter presents the catchment characteristics that have affected the operation of the dam. It is the historical dynamics and events observed for the study period.

3.2 Pre-analysis of Data

3.2.1 Rainfall

Rainfall data recorded at Hardap Dam, available from 2003 to 2021. **Figure 3** presents the monthly rainfall.

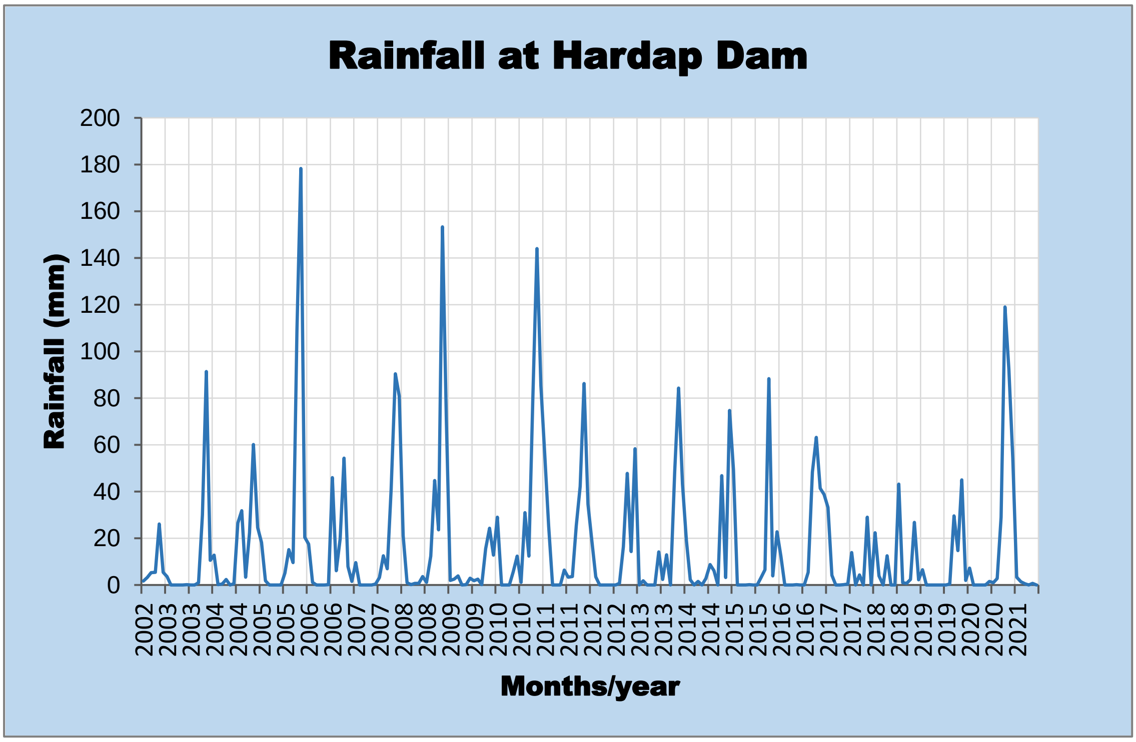

Figure 3: Monthly Rainfall recorded at Hardap Dam from 2003 to 2021

The highest rainfall was recorded in February 2006 with a total of 178 mm; it was one of the wettest seasons recorded in Namibia. The year 2009 and 2011 also recorded higher rainfall with 153 mm/month and 144 mm/month respectively. **Figure 4** presents the annual rainfall at Hardap Dam.

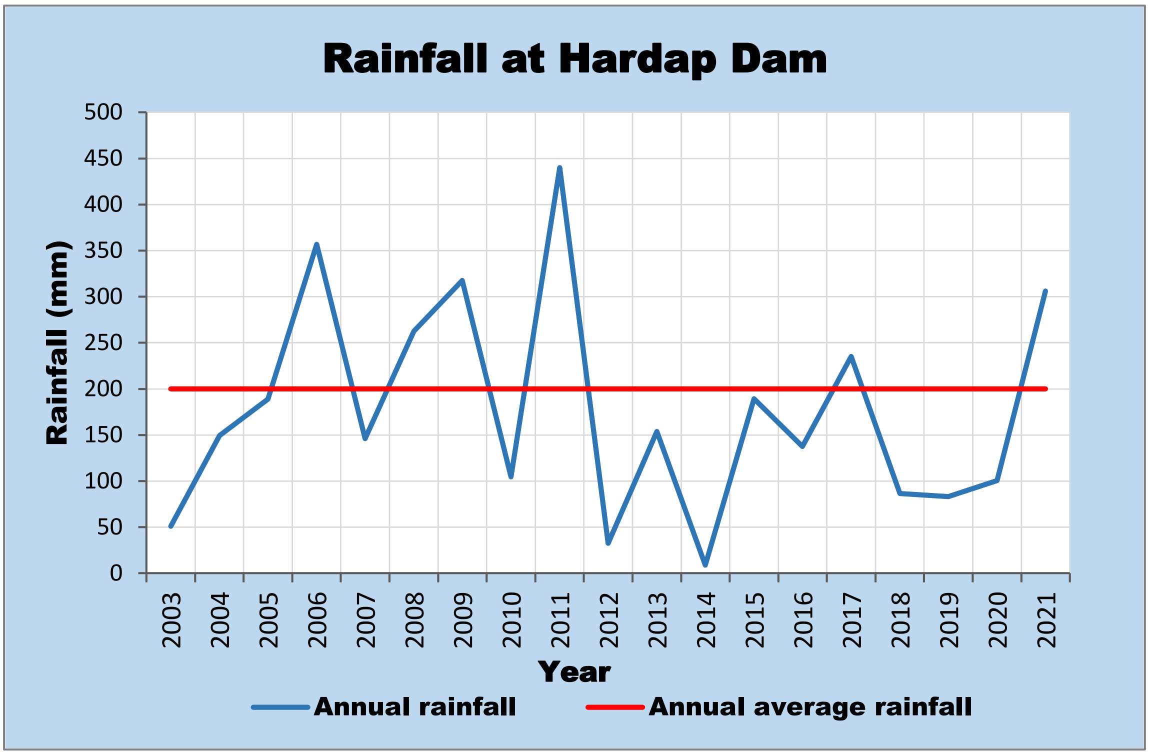

Figure 4: **Annual rainfall at Hardap Dam**

There are high peaks in rainfall for the years 2006, 2009, 2011 and 2017, which indicate wet years. During the years 2006 and 2011, the Hardap Dam rainfall station recorded 357 and 440 mm/a respectively against its annual average of 100 -200 mm/a.

3.2.2 Inflows

Major inflows were observed through the years with the 2006 inflows being the highest recorded. **Figure 5** represents the total inflows recorded for the study period of 1999 to 2021.

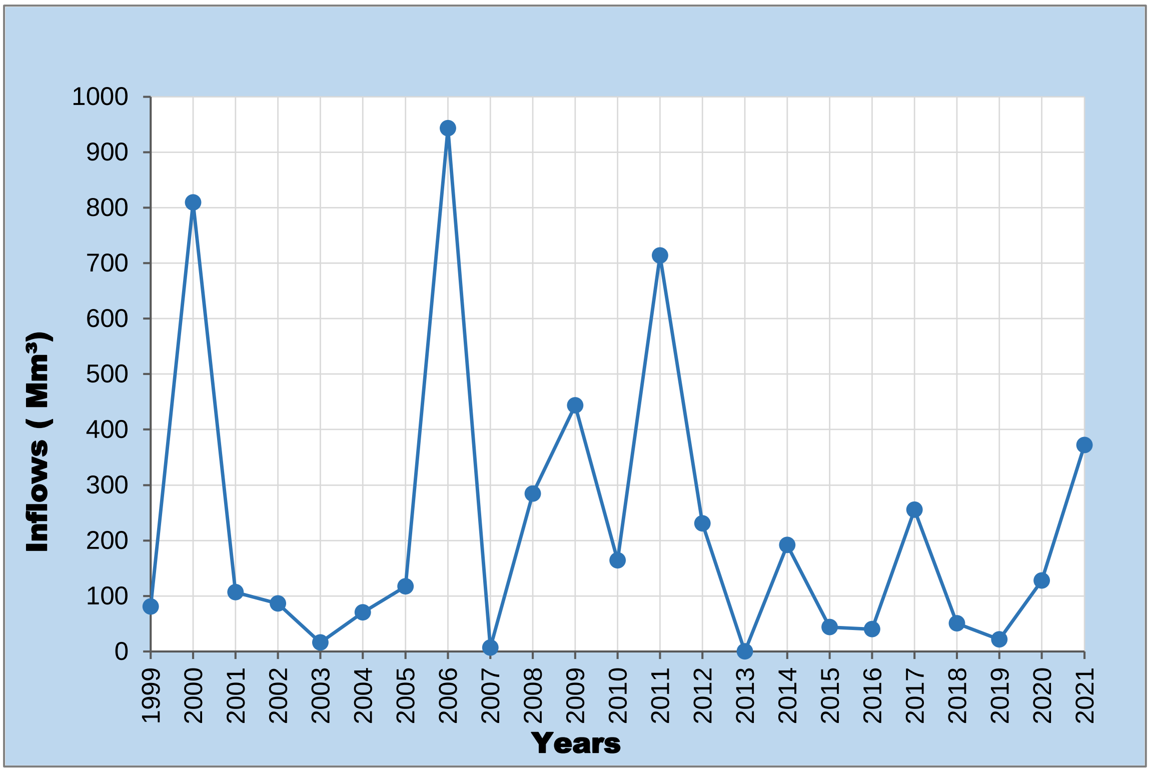

Figure 5: **Annual Inflows for Hardap Dam**

The wettest years have higher inflows which are greater than the Hardap Dam capacity and total annual demand, hence water flows further downstream as it gets released via the Hardap Dam gates. The 2006 inflows, being the highest recorded between 1999 and 2021 was 943 million cubic meters (Mm^3), which was three times greater than the full supply capacity (FSC) of 294.6 Mm^3. Moreover, occasional high inflows are observed within the years. The inflows only happen during the rainy season and are typical as flash floods due to the characteristic of the catchment which results in high runoff. The storage volumes change and fluctuate within a short period as inflows and outflows happen simultaneously. There is a consecutive dry period of three years from 2002 to the year 2004. The accumulative total flow is low compared to other years with a total of 168.9 Mm^3. Hence, this period will be used as a reference dry year for the hydrological season scenario. **Figure 6** represents the ratio of inflows as a proportion to the full supply capacity of the Hardap Dam.

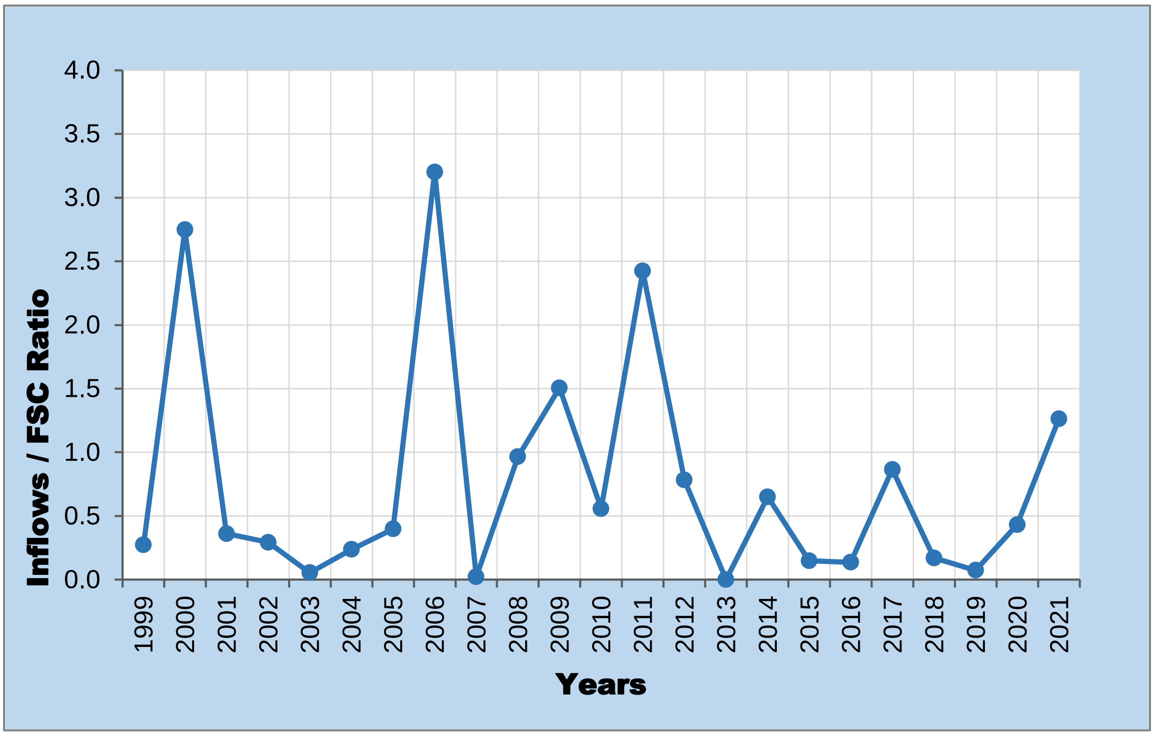

Figure 6: Inflows as a proportional to fully supply capacity of Hardap Dam

The inflows of 2000, 2006 and 2011 exceeded the FSC two to three times, indicating extreme flood events.

3.2.3 Evaporation

The mean monthly net evaporation for Hardap Dam was used in the WEAP model. This was obtained by using the actual measured gross mean monthly evaporation less the mean monthly rainfall as shown in **Table 4**. The WEAP model requires input data of net evaporation.

Table 4: Monthly net evaporation for Hardap Dam

MONTH	ACTUAL MEAN MONTHLY GROSS EVAPORATION (mm)	ACTUAL MEAN MONTHLY RAINFALL (mm)	MONTHLY NET EVAPORATION (mm)
October	299	8.4	291
November	340	7.3	333
December	352	13.9	338
January	336	45.0	291
February	278	59.0	219
March	252	37.0	215
April	216	16.0	200
May	174	3.1	171
June	137	0.3	137
July	147	0.9	146
August	194	0.4	194
September	**257**	**2.9**	**254**

The actual mean monthly gross evaporation was obtained by taking an average of the 20 years for gross evaporation data. The same method was used to determine the actual mean monthly rainfall. The mean monthly rainfall for Namibia varies greatly and the net evaporation could have an impact of a 1% variance chance that can be negligible. **Figure 7** shows the actual mean monthly net evaporation for the Hardap Dam.

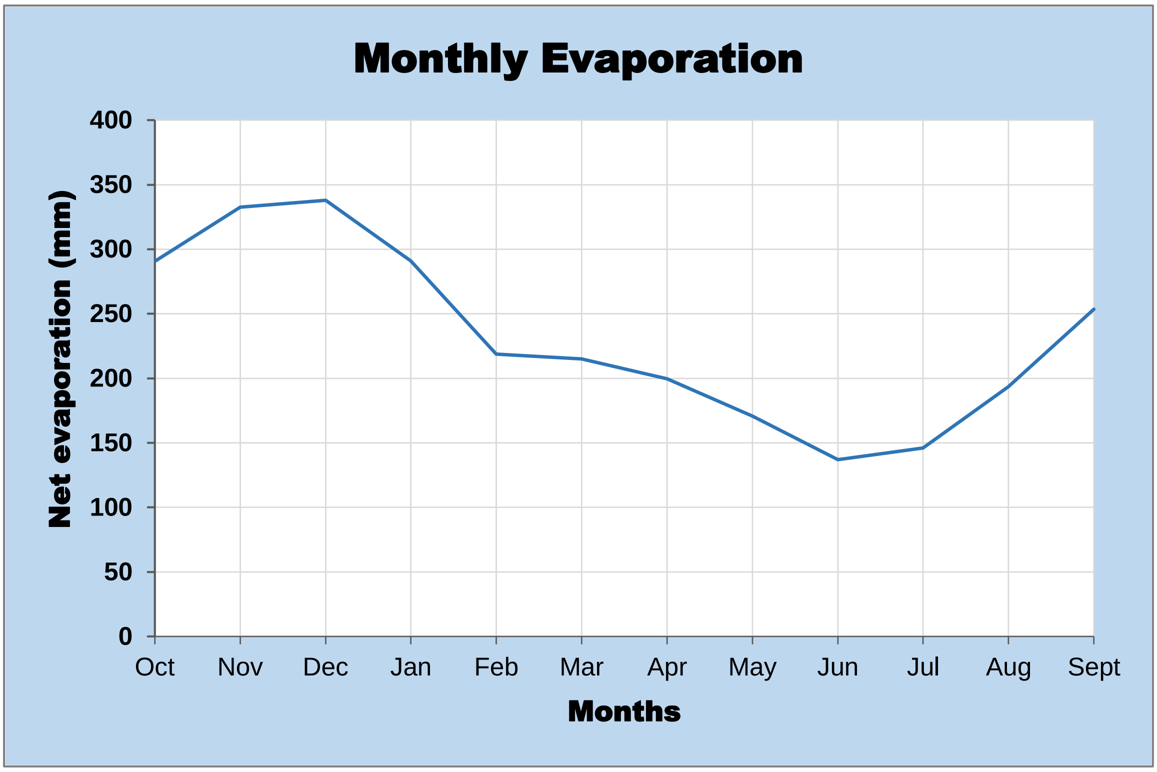

Figure 7: Monthly net evaporation

The monthly evaporation is higher during the summer months and lower during winter. The highest evaporation is in December with a total of 338 mm, while the lowest is in June with a total of 137 mm. This indicates that the area is exposed to a higher evaporation rate which could have a negative impact on the availability of water resources.

3.2.4 Abstractions and Demands

Total annual abstraction is dominated by three main demands, Mariental Town, Hardap Irrigation Scheme and the Hardap Inland Aquaculture Center. The highest total abstraction was recorded for the year 2019 with a total of 54.9 Mm^3 and the lowest in 2020 with an amount of 34.4Mm^3. The result shows that irrigation is the largest water use sector, which comprises 96% of total water demands (48.4 Mm^3 per month). The annual domestic water demand was the second largest with 1.5 Mm^3, which represents 3% of total annual water demands. Aquaculture was accounted and the annual water demand is 0.5 Mm^3, which comprises 1% of total water demands. This indicates that any changes to the irrigation will have an impact to the water supply. **Figure 9** presents the graphical total annual abstraction demands for the current year, 1999.

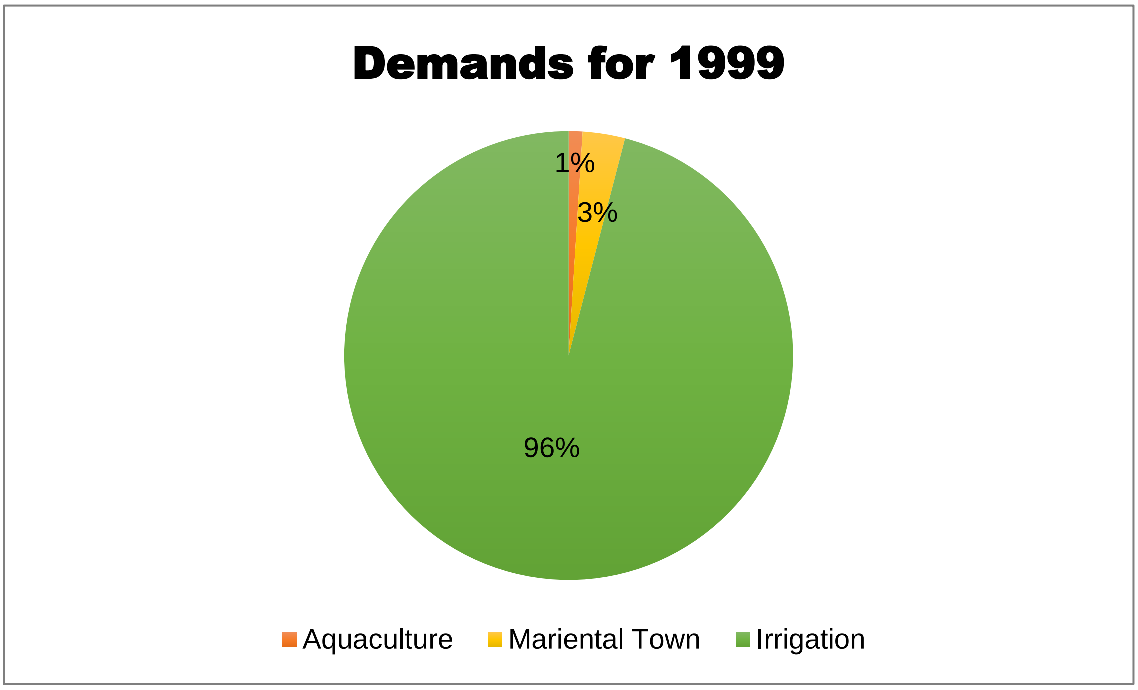

Figure 8: Annual demands for 1999

The total allocation for the Irrigation Scheme is 18 000 m^3/ha/a, which amounts to 40 Mm^3/a but fluctuates throughout the years. Hence, **Figure 9** presents the annual abstraction demands for irrigation.

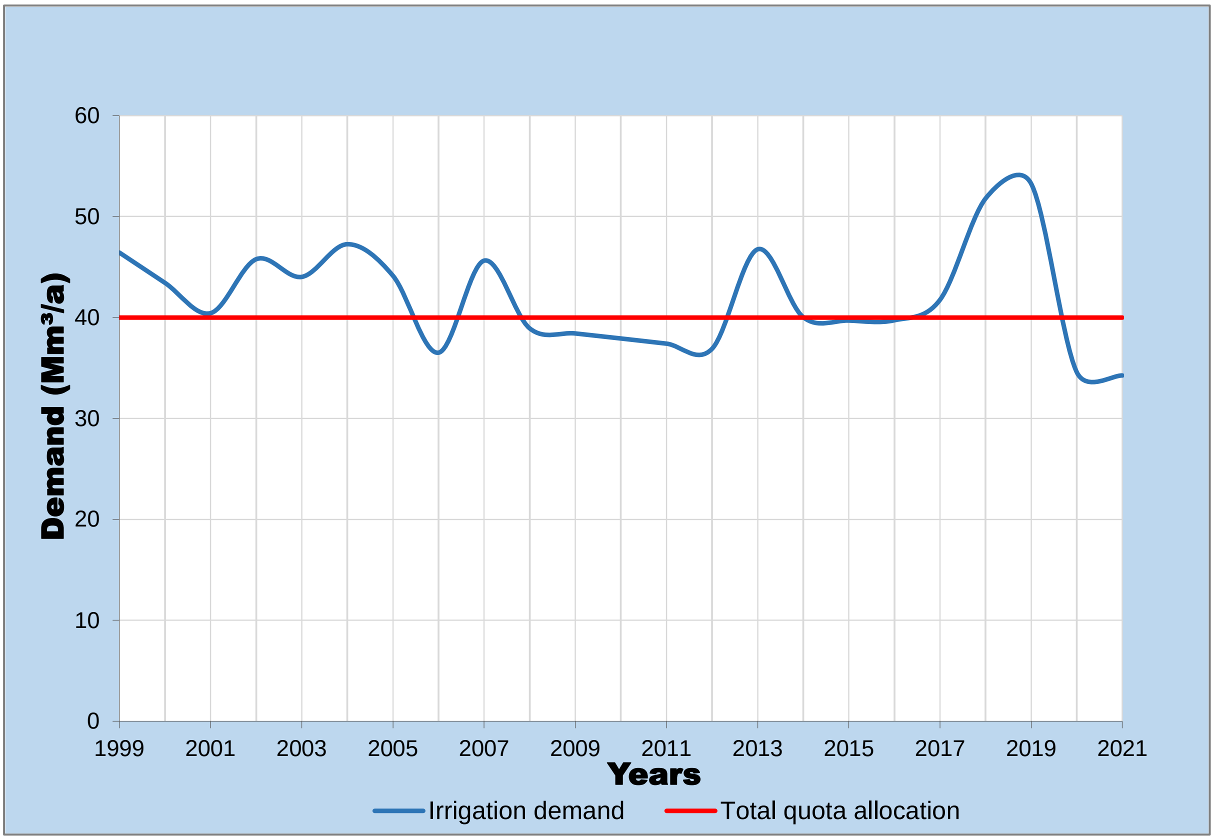

Figure 9: Annual irrigation demands 1999 to 2021

The annual demand for irrigation water varied between 36 and 53 Mm^3/a over the last 22 years. The maximum abstraction of 53 Mm^3/a was observed in the year 2019, which is above the allocated quota of 40 Mm^3/a. It is not clear why the demands for 2019 were higher, but below annual average rainfall was observed for the catchment and it was one of the dry years. The lowest abstraction of 36 Mm^3/a was for the year 2020 which is below the allocated quota, which may be due to drought-enforced reduction in the water supply**.** **Figure 10** indicates years of demands being above and below the allocated quota.

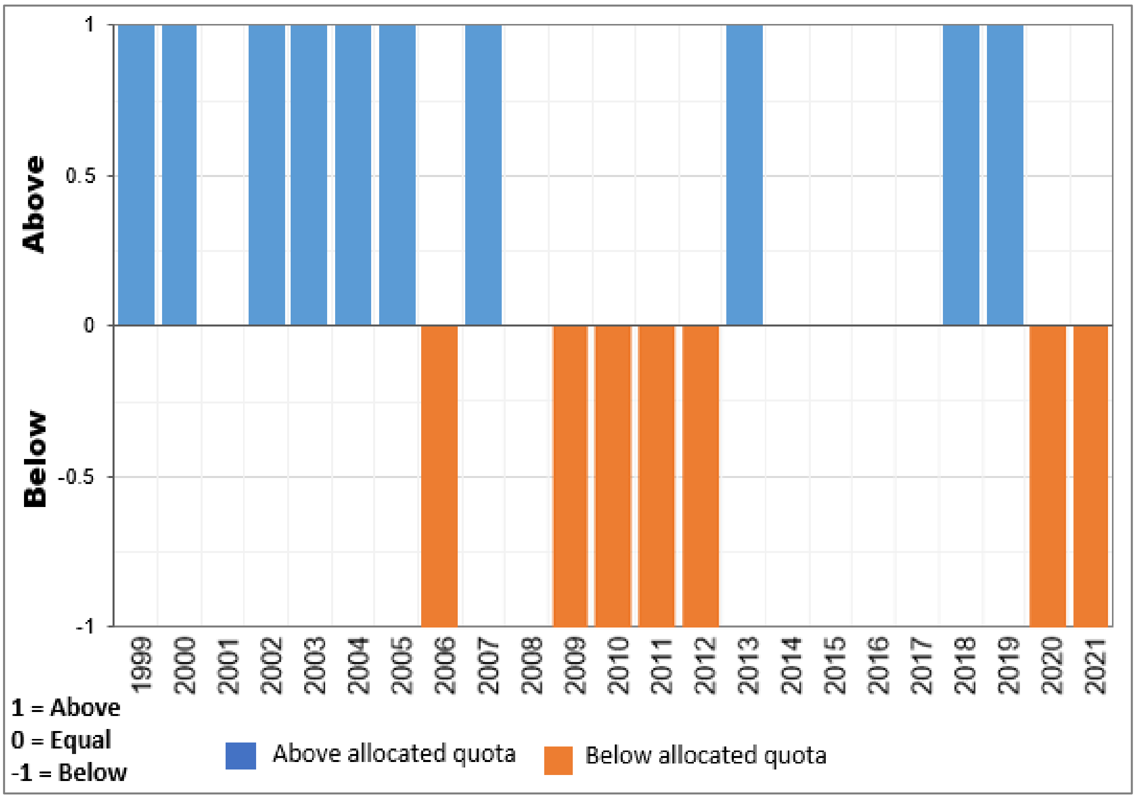

Figure 10: Irrigation demands years above and below the allocated quota

From **Figure 10**, there are more years where the demand exceeded the allocated quota as compared to below and the actual quota allocated. From the historical record, the observed data indicated that during the critical low dam levels of 2019/20, irrigation demands were restricted for about two weeks during January 2020 and there were major complaints from the community. This restriction was implemented when the dam reached the lowest irrigation abstraction level (buffer zone) as based on the operation rule of the Hardap Dam. **Figure 11** presents the annual demands for Mariental Town and Hardap Inland Aquaculture.

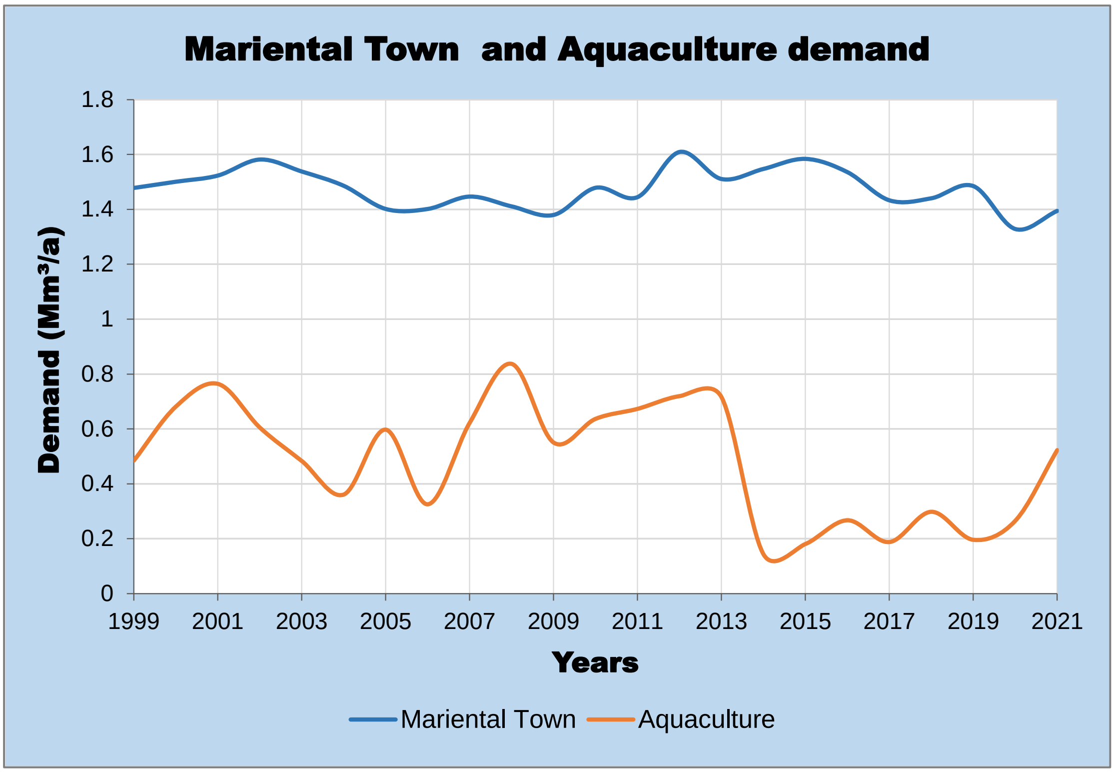

Figure 11: Annual demand for Mariental and Aquaculture

The Mariental Town demand was relatively constant, varying between 1.3 to 1.6 Mm^3/a from 1999 to 2021. The lowest demand was recorded in 2020 with a total demand of 1.3 Mm^3/a and the highest demand was in 2012 with a total of 1.6 Mm^3/a. The Hardap Inland Aquaculture total annual demands are the lowest demands ranging from 0.1 to 0.6 Mm^3/a. The annual demand varies differently throughout the years. The highest demand of 0.84 Mm^3/a was in 2008. The lowest was in 2014 with an amount of 0.1 Mm^3/a. The water demand for aquaculture has declined by approximately 50 000 m^3/a from 2013 to 2014 and has slowly increased onwards in recent years. The reduction could be related to drought-enforced reductions of water supply as there were no inflows during the hydrological year 2012/13.

3.2.5 Dam Operation

The operation of Hardap Dam has changed which was specifically influenced by the flooding event of 2006, hence an assessment was carried out to determine the minimum operating rule that will sufficiently protect the resource and prevent future flood disasters. The 70% of FSC operational level was found to be sufficient to supply all the demands and maintain an acceptable assurance of supply to the users. The operating rule has changed from 100% of FSC to 70% of FSC with a 2% variance. **Figure 12** indicated the inflows and dam content during the 2006 hydrological season.

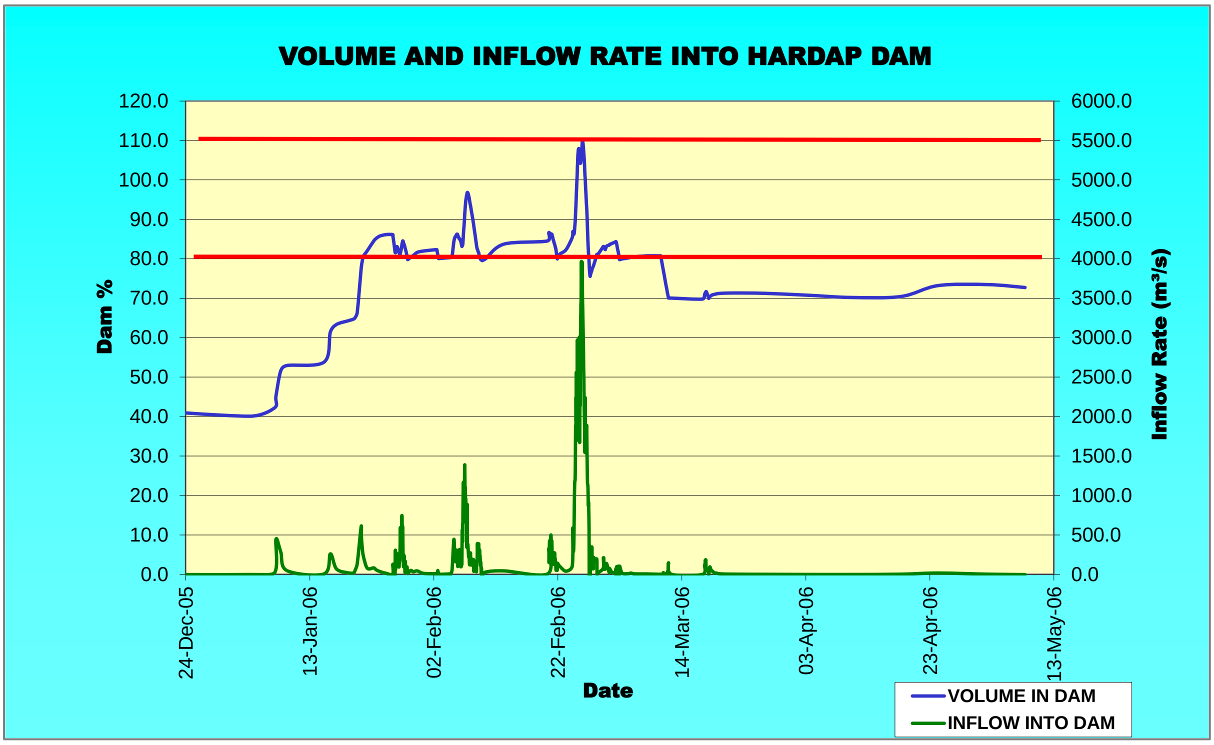

Figure 12: Storage Volumes and inflows into Hardap Dam 2006 (adapted from NamWater, 2006)

The 2006 inflows rate were higher with a maximum rate of 4000 m^3/s and the operation of the dam was challenging, as more outflows were being released from the dam. During February 2006, the dam content went beyond 100% of FSC and controlled releases were made to rapidly decrease this capacity for flood mitigation purpose. A total of 805.7 Mm^3 was released from the Hardap Dam during the 2006 hydrological season. It is evident that the operational capacity changed from 100% of FSC in February to 90-80% of FSC in March and from April between 70-72% of FSC. The maximum storage volumes observed for this period was 110% of FSC with 80% for flood absorptions.

3.2.6 Storage Volumes

The Hardap Dam storage volumes are based on dam levels recorded weekly. These levels were then converted to mean monthly volumes for the study period. During the rainy months (January to April), the storage volumes vary greatly due to the inflows and outflows of the dam. **Figure 13** presents the storage volumes from October 1998 to June 2021.

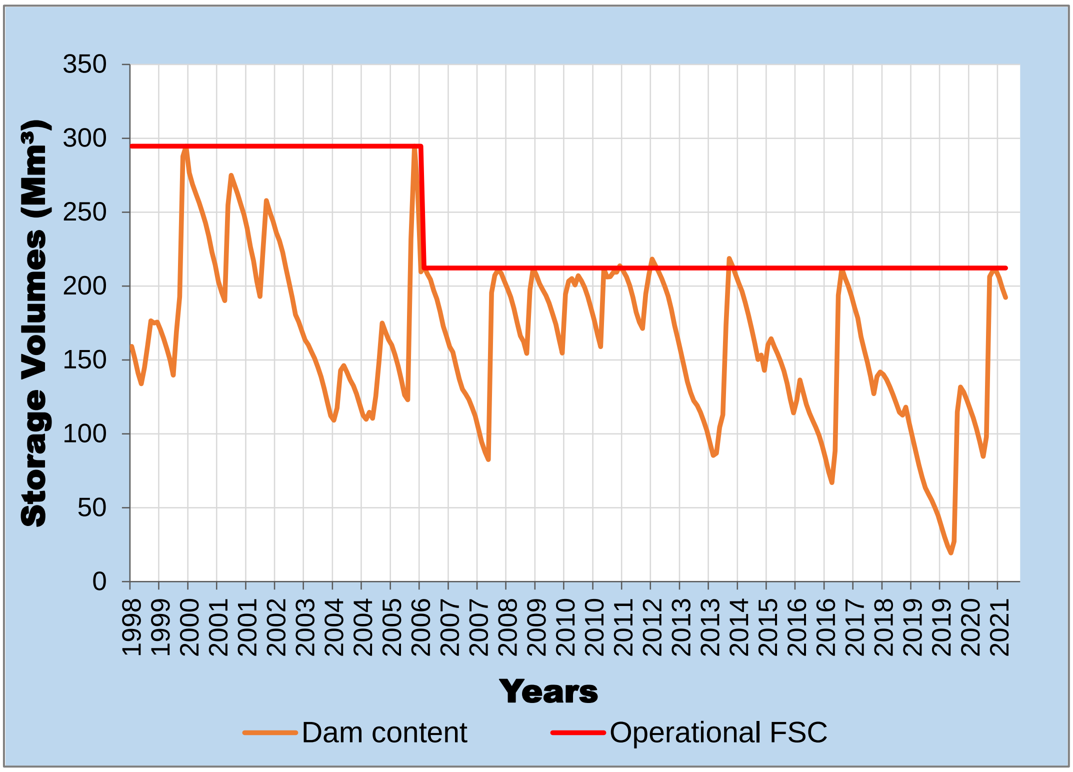

Figure 13: Storage Volumes for Hardap Dam 1999 to 2021

The Hardap Dam reached its full supply capacity (FSC) of 294.6 Mm^3 during the year 2000 and 2006 respectively as high inflows were received into the dam. High peak levels were observed as the dam was receiving inflows, and then reduced immediately by releasing water (outflows) as a measure of flood control and attenuation. The critical low dam levels of 2019/20 as observed from **Figure 13**, it could be due to low inflows received for the season and high irrigation demands that were above the annually allocated quota for that period as an indication that the water supply for irrigation was not well managed.

3.2.7 Outflows

The outflows are recorded once the dam reaches its full supply capacity and the water is released out of the dam and flows downstream. **Figure 14** presents the annual outflows volumes from 1999 to 2021 as obtained from the water balance.

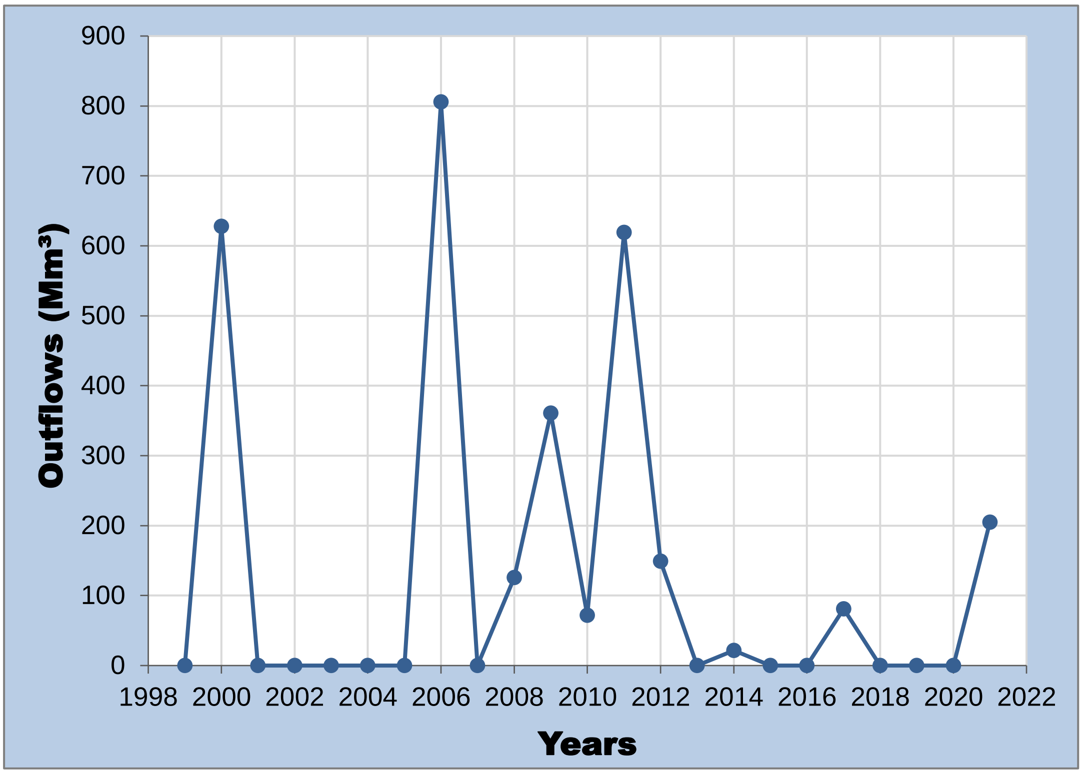

Figure 14: Annual Outflows from Hardap Dam 1999 to 2021

From the **Figure 14**, from 2001 to 2004 no outflows were recorded as an indication that there were no releases made. This indicates a period of three conservative dry years and fewer inflows into the dam. Less outflows were also observed in recent years from 2013 to 2020 and this is same the period where low dam levels were experienced as an indication of drought conditions.

3.2.8 Summary

Pre-analysis of data was done to illustrate the general state of data used in the study. The annual inflow data show extreme flooding events that are two to three times higher than the Hardap Dam capacity. This shows that on average, about 600 Mm^3 is released and flows downstream of Hardap Dam. These flooding events have made the operations of the Hardap Dam challenging specifically after the 2006 massive flooding event that lowered the operational FSC to 70% of FSC.

CHAPTER 4: METHODOLODY

4.1 Introduction

This chapter explains various methodologies that were used in achieving the objectives of the study. The methodologies include study area, types of data and the methods used to analyse the data.

4.2 Study Area

4.2.1 Location

Hardap Dam Catchment is located in the southern-central parts of Namibia across the Hardap Region and a small portion of the Khomas Region. The catchment lies within the latitude of 23° 28' 0'' S - 24° 49' 0'' S and longitude of 16° 32' 00'' E - 17° 32' 50'' E. The Hardap Dam, emanating its headwaters on the Rehoboth Plateau and east of the Naukluft mountains, forms tributaries to the ephemeral Fish River. It is the second-largest dam in Namibia, located on the Fish River, about 17 km northwest of the town of Mariental. The Hardap Dam catchment is approximately 13 550 km^2 in area. **Figure 15** shows the study area in relation to the Namibian location.

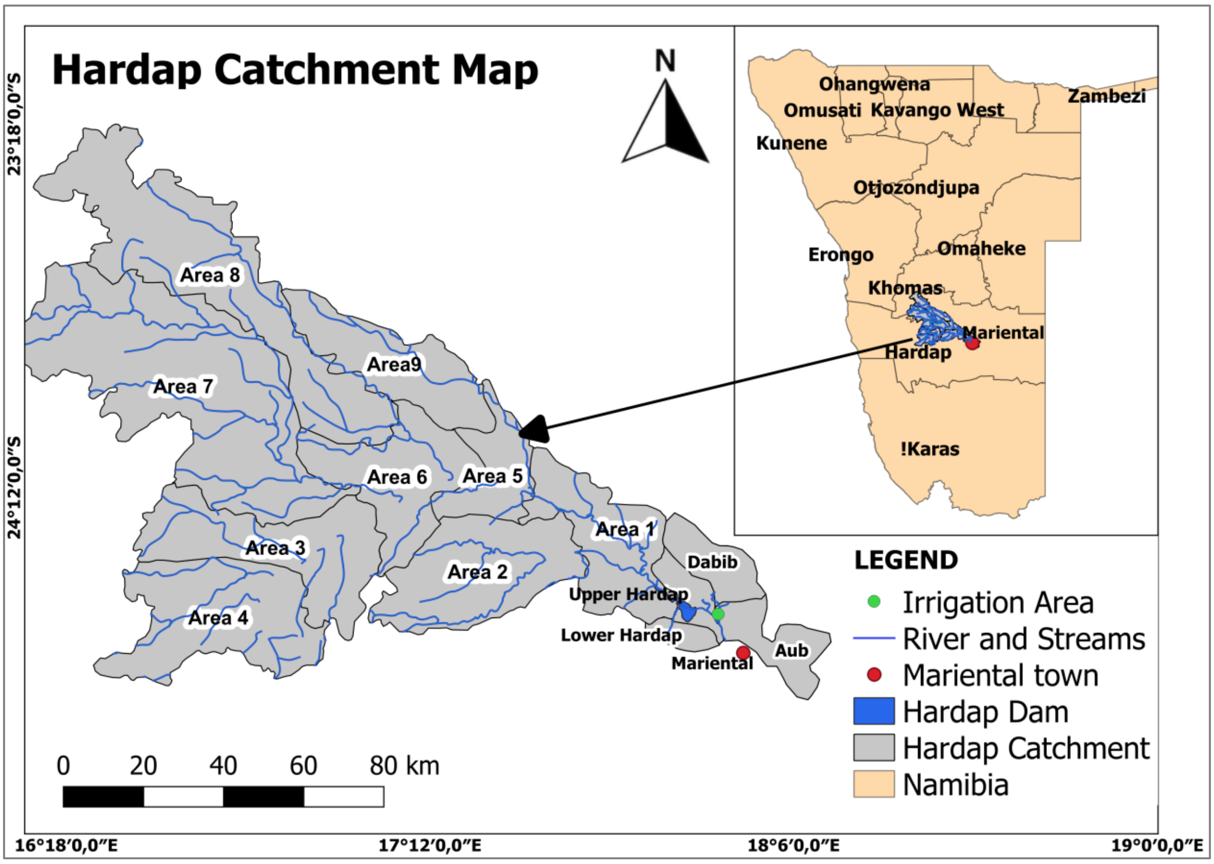

Figure 15: Hardap Dam Catchment

4.2.2 Hardap Dam

The Hardap Dam was designed and built by Dyckerhoff & Widmann (dam structures) and Strabag (asphalt concrete lining) and was completed in 1963 (Hattingh et al., 2010). The dam has a 35.9 m high dam wall with a composite structure consisting of a centrally located, controlled ogee concrete gravity spillway, with four radial gates (Hattingh, 2007b). The main and secondary embankments are lined by asphalt concrete-faced rock fill. On the right bank of the dam towards the main embankment, there are two saddle structures. An auxiliary spillway is located on the outside of the secondary embankment on the left bank and a concrete apron is provided on the downstream toe of the spillway (Hattingh et al., 2010). According to the South African Dam Safety Regulations (DWAF: 1986), the dam can be classified as category three with a high potential of hazard (Hattingh, 2007b).

The dam has a total storage capacity of 294.6 Mm³ and it functions primarily as storage of water for irrigation, domestic and industrial use (Hattingh et al., 2010). Currently, it is also being used to attenuate flood peaks originating from the upper Orange-Fish basin. Hardap Dam must be operated in such a manner that the dam structure is protected, flood damage by releases is minimised while storing the maximum amount of water possible for water supply (AURECON, 2014). Several principal rules have been established in the Hardap Dam. Flood Control Plan (2014) stated that, the dam must be operated at 70% of full supply capacity (FSC) to increase the flood absorption capacity, water must be released in anticipation of a flood where necessary and to the maximum flow rate of the Fish River flow capacity to minimize inundation. It is not possible to safely route the Safety Evaluation Flood (SEF) flow of 11 640 m^3/s in any occurrence and regardless of the operational rule of the dam (NamWater, 2014). **Table 5** summarise the main characteristics of the Hardap Dam.

Table 5: Main characteristics of Hardap Dam (adapted from AURECON , 2014)

Dam type	Composite asphalt-concrete faced rock fill embankment and concrete gravity spillway with a secondary embankment and two saddle embankments (rock fill)
Purpose	Storage of raw water for irrigation and municipal use. Flood attenuation
Gross storage capacity	294 593 000 m^3
Dead storage capacity	4 299 000 m^3
Operational storage capacity	70%
Safe yield	95% (46 Mm^3/a) at 70% operational storage capacity
Surface area at full supply level (FSL)	28.7 km^2
Spillway type	Controlled ogee with 4 radial gates in addition to an uncontrolled auxiliary by-wash section

4.2.3 Climate and Geology

The estimated Mean Annual Rainfall (MAR) in the Hardap Dam catchment ranges from 100 - 300 mm per annum (mm/a) (Du Plessis, 2020). This is classified as a semi-arid environment in Southern Africa with low and unpredictable rainfall and high evaporation rates. The rainfall occurs from October to February with an average maximum temperature above 36°C (Mendelsohn et al., 2002). Evaporation rates are higher during the summer months and the average annual evaporation is estimated at around 2 300 to 3 900 mm (Mendelsohn et al., 2002).

The elevation ranges from 2 054 m AMSL (above mean sea level) in the northwest, down to 1 120 m AMSL at the dam site (Hattingh, 2007a). The area is mountainous to hilly and much of the catchment surface is impermeable, which enhances the runoff potential. According to NASA (2020), the Hardap Dam catchment consists mainly of the Central Plateau geologic with a convergence of the Kalahari

Desert around the dam and Mariental Town. The catchment comprises of sandstones, conglomerates and basalt rock types (Mendelsohn et al., 2002).

4.2.4 Population

The Hardap region is sparsely populated with about 0.7 people per square kilometre (km^2) (NSA, 2011). The Hardap dam catchment is about 13 550 km^2 in area. It is approximated that about 14 500 (estimated using the arithmetic growth **Section 2.1**) people live in Mariental Town, which is downstream of Hardap Dam (NSA, 2011). The population in the town has increased due to urbanisation and migration for job opportunities and better service infrastructure. The rural areas are densely populated at locations with shallow groundwater sources that can be utilised for livestock farming and less populated areas are faced with either water shortages or unfit groundwater. The actual observed water demands were used in WEAP as the model makes provision for the usage of actual data without taking into account the population (see **Section 4.2.3**). However, a comparison between the projected demands was also carried out. According to the Namibian Livestock Identification and Traceability System [NamLITS] (2021), about 1 070 cattle have been registered within the Mariental surroundings.

4.2.5 Land use and Socio-economic activities

People in the Hardap region rely on water stored in the dam, boreholes and shallow wells for domestic uses and livestock farming. The Hardap Dam possesses several activities of economic advantage to the communities. Since the Hardap Dam hosts some human activities ranging from intensive agricultural practice, domestic activities and small-scale businesses, it is essential to assess the operation of the dam in terms of water resources management. The Mariental Town uses water from the dam for domestic and industrial purposes. The minority of the population practice mainly communal farming with herds of cattle, sheep and goats.

MFMR (2004) reports that Hardap Inland Aquaculture Centre is a government fish farm project developed to enhance food security, reduce poverty, generate employment, improve livelihoods and increase investments in reaching the National Development Plan Five (NDP5) and Vision 2030. The centre was established in 1968 and in 2003, a private aquaculture company, Eco-Fish Farm*,* joined the public sector in a Public-Private Partnership (PPP) to operate the fish culture component of the centre on a commercial basis (Rana & Abban, 2012). The project utilises water from the Hardap Dam for the production of Tilapia, Catfish and common carp in tanks, ponds and flow-through systems. An average amount of about 40 000 m^3 per month is abstracted for this production and approximately 70% is returned downstream of the dam.

4.3 Data and Methods

4.3.1 Hydro-meteorological Data

The rainfall and monthly gross evaporation data at Hardap Dam station were obtained from NamWater, ranging from 1999 to 2021 (see **Table 6**). Rainfall is recorded and measured daily at the dam site with a 0.2 mm tipping bucket rain gauge. While the evaporation data is measured on hourly basis with an evaporation pan and recorded via an electronic analog logger. The converted hourly data to monthly gross mean evaporation data were then calculated to monthly net evaporation. This was obtained by using the gross mean monthly evaporation less the mean monthly rainfall as the WEAP model requires input data of net evaporation.

4.3.2 Storage Volumes and Water Level Data

MAWLR through the Department of Water Affairs (DWA) availed the dam levels from 1999 to 2021 (see **Table 6**), while the capacity table was obtained from NamWater. The storage volumes were also taken from the weekly water levels and converted to mean monthly volumes. The inflows and outflows were taken from the water balance calculated based on the change in weekly water levels, less the abstractions and evaporation. According to NamWater (2014), during the 2012/13 hydrological year, the water balance on the pond downstream of Hardap Dam did not yield satisfactory results and could not be used to determine the seepage and leakage from the Hardap Dam. The available data is therefore not sufficient to be used for seepage determination for this study.

Table 6: Available observed data for the study

Variable	Period range	Source
Rainfall	2003-2021	NamWater
Evaporation	1999-2021	NamWater
Inflows & Outflows	1999-2021	DWA/ NamWater
Storage dam levels	1999-2021	DWA/ NamWater
Abstraction volumes (demands)	1999-2021	NamWater

4.3.3 Water Demands

The demand data for the study will be the actual observed data. According to Sieber and Purkey (2015), demand analysis in WEAP is also the starting point for conducting integrated water planning analysis since all supply and resource calculations in WEAP are driven by the levels of final demand calculated in the demand analysis. The monthly method for demand was used for this study which makes use of the observed consumption data hence no population data were used. The upstream demands are nominal as they consist of rural farmers and do not abstract directly from the Hardap Dam. For this research study, the upstream catchment demands are assumed to be negligible and will not be considered.

Domestic Water Demands

Hardap Water Treatment Plant supplies potable water to Mariental Town. The abstraction data from Hardap Dam for 1999 to 2021 were obtained from NamWater. The annual domestic water demand was the second largest with 1.5 Mm^3, which represents 3% of total annual water demands. This is an indication that the domestic demands have a small ratio contributing to the annual abstraction and the impacts would be minimal as compared to the demand with a higher ratio. The input data used in the model are the actual observed demands from 1999 to 2021.

The domestic demand was further analysed with population projection using the 2011 base year census data and a consumption rate of 250 l/c/d for high-income population was adapted for the study which represents a recent rate and pattern for the Mariental urban area in terms of average consumption. In WEAP the annual demand method was used to make use of the population data as an activity level and annual water use as a consumption rate.

Livestock Water Demands

The Namibia census of agriculture provides information on the population figures of livestock in Namibia (NSA, 2015). However, these census data do not match any other regional breakdowns used in Namibia, such as the regions or towns and these census figures do not state how many livestock are supplied with water by NamWater. The NamLITS system has recorded a few cattle, about 1 070, which are registered within the vicinity of Mariental and the surroundings of the Hardap Dam. The estimated water consumption for livestock is minimal, which is based on an annual demand for livestock of 40 l/day of the demand norms. The livestock water consumption is low compared to urban, irrigation and evaporation demands. For this research study, the livestock demands are assumed to be inclusive of the domestic demands and will not be considered as a separate demand.

Irrigation Water Demands

Irrigation abstraction data were also obtained from NamWater. Irrigation water supply is mainly influenced by the availability of water and the management of water resources, which will determine the total demands and abstraction. A theoretical irrigation requirement of 48 Mm^3 was determined for the Hardap Irrigation Scheme using the SAPWAT model based on the current combination of crops. However, it was reduced to 40 Mm^3 as only 80% of the area is irrigated annually (Mare, 2007). LCE- SCE (2017) indicated that the water allocation for the Hardap Irrigation Scheme is 18 000 cubic meters per hectare per year (m^3/ha/a). The actual observed demand data for irrigation was used for this study. The irrigation demands may vary from month to month which represents the monthly water shares (Sieber & Purkey, 2015). The percentage of monthly water used in each month was determined as a percentage share of annual totals.

Aquaculture Water Demands

The aquaculture abstraction data were obtained from NamWater for the period 1999 to 2019. The Hardap Inland Aquaculture Centre produces tilapia among other fishes in ponds and tanks. The Centre is located approximately at 24° 29' 42'' S and 17° 51' 47'' E. The Hardap Inland Aquaculture Centre has different components of an indoor breeding greenhouse recirculation system and an indoor hatchery. There are 18 breeding tanks with a total surface area of 162 m^2 and 24 hatcheries with a total volume of 36 m^3 (MAWF, 2006). Furthermore, there are 18 nursery ponds and 20 grow-out ponds with a total surface area of 1 196 m^2. There is no water use for the established ponds on the northeast side; hence, it is not clear if all ponds are being utilized. The water demands vary from 8 000 m^3/month to 10 000 m^3/month and the effluent is discharged behind the Hardap Dam wall. The actual observed demands data was used. The percentage of monthly water used in each month will be determined as a percentage share of annual totals.

Tourism Water Demands

The Hardap Resort demand is abstracted together with Mariental domestic demands from the Hardap Dam and purified at the Hardap Water Treatment Plant then transferred to the resort via pipeline.

The study assumed that the tourism demand is already incorporated within the domestic demand above.

4.3.4 Demand Sites and Schematic Map development

Demand sites were identified based on their significant water withdrawal quantities. GIS- based vector boundary, rivers, dam and town shape files for the Hardap Dam catchment were imported into the study area to configure the area and improve the area boundaries. Digitisation was carried out to demarcate all the sites to be entered on the schematic within WEAP.

4.3.5 Calibration and Validation process

The input parameters for calibration are the demands, storage volume and inflows which are assumed to be measured, calculated and recorded accurately. The actual observed data were used for the study. The data trend is monthly with October being the start of the season and annually with the year 1999 as the base year. The calibration was carried out using iteration; where it was first carried out for one year, then two years and so forth until the modeller gains confidence with the result from the model. This means that at the beginning, the model was set up and run with the 1999 year (base year) data; results were compared and adjustments were made where necessary. The full model calibration was done using data for the period 1999 to 2009 for all parameters.

The validation procedure was undertaken by using the calibrated model of up to 2009 and forecasting it from 2010 up to the year 2021. The simulated results from the model were then compared with the observed data. The model performance was evaluated using the statistical analysis of efficiency, root mean square error, and coefficient of determination.

4.3.6 Scenarios and WRM Strategies

In the WEAP model, scenarios were built and then compared to assess water requirements, management strategies and reliability of supply. This study developed scenarios based on the assumptions that they have an impact on the water supply, water demands and water allocation. These scenarios are demand-saving measures and improved irrigation efficiency. The demand-saving measures are to enable consumers to use water wisely, to lengthen the period of supplies. The expansion of irrigation activities by increasing the area has a great impact on the water supply as well. To address a broad range of "what if" questions, four scenarios were created and their possible impacts on water utilisation were evaluated. These scenarios were chosen to assess if implementing the demand management strategies had a positive effect on the water availability to improve some of the observed critical water- stressed periods of the Hardap Dam catchment, specifically the dry period of 2001 to 2004 and 2019 to 2020.

4.3.6.1 Scenario 1: Demand-side management of Mariental Town and irrigation efficiency of the Hardap Irrigation Scheme

According to LCE-SCE (2017), the non-revenue water (losses; being the difference between abstraction and sales) in Mariental is approximately 12%, which is within acceptable limits. These losses occur for several reasons such as; leakages within the system, water lost during treatment, poor monitoring and inaccurate meter reading. Population growth, urbanisation and the rising of industries can lead to greater water demand which can potentially put pressure on the water supply. This scenario has addressed the impact of reducing the consumption of Mariental Town and assessing any significant improvement of the available storage volumes. It is not certain what percentage values of the demands management were implemented previously for the Mariental Town. For this study, an assumption of 10% demand saving was used. The 10% was assumed as the average value to reduce the demands irrespective of the system losses and population growth. The 10 % was input into WEAP under the demand-side management.

Improved irrigation efficiency implies that the irrigation methods to be used are water-saving techniques such as sprinkler and drip irrigations, which improve the irrigation efficiency. Irrigation efficiency is defined as the ratio between the amount of water used to meet the consumptive use requirement of crop and the total volume of water diverted or pumped for irrigation. Irrigation efficiency is reduced when the water supplied by the irrigation system and not made available (wasted) to be taken up by plant roots. This means that water use reduces significantly as the efficiency of the irrigation system increases. Flood irrigation is much less water-efficient than drip irrigation. This scenario was chosen to assess the current irrigation method; if it will have a major impact on the availability of water to improve the low dam levels of drought conditions when demands are reduced. The current irrigation efficiency of the flood irrigation method at Hardap Irrigation Scheme is not specific, as the researcher could not avail any recent data based on literature review and limitations to carrying out field measurements due to time constraints. An assumption of 50 % efficiency for flood irrigation and 85 % efficiency for drip irrigation that save about 30% of water use was adopted as recommended by Nilsson, Sahlen & Stage, (2003). Drip irrigation was adopted as a way to improve irrigation efficiency and assess the impact on the storage volumes of Hardap Dam.

4.3.6.2 Scenario 2: Increase in the irrigation area

The irrigation capacity of the Hardap Irrigation Scheme is almost fully utilised. As the population is bound to increase, this will demand more food production hence more irrigation areas will be required to cater for the increased demand. The Department of Agriculture within the Ministry of Agriculture Water and Land Reform has also foreseen the future development of a small irrigation area of approximately 100 hectares (ha) for disadvantaged farmers (LCE-SCE, 2017) as a governmental practice to include particular groups that have been underrepresented to promote the right of equality within the development of the Green schemes. The estimated water demand for this additional irrigation area amounts to 1.8 Mm^3/a at a rate of 18 000 m^3/ha/a, considering the same irrigation method and growing the same crops as existing farmers. For the study, the current irrigation area will be increased by 5% as an assumption to cater for future demand increased be either new users or expansion of current users with an additional 100 ha for the disadvantaged farmers. Hence, the irrigation area was increased to a total of 213 ha. The allocated quota of 18 000 m^3/ha/a was used for the additional area and considering the same types of crops and irrigation methods for existing farmers. The model was also used to forecast the critical and extreme threshold areas that could affect the water supply for the current demand.

4.3.6.3 Scenario 3: Hydrological seasons for high/low flows

This will be implemented with the water year method in WEAP. The water year method will allow the use of historical data in a simplified form and to easily explore the effects of changes in hydrological patterns (Sieber & Purkey, 2015). Hydrologic fluctuations will be entered as variations from a normal water year by defining standard types of water years and characterising the hydrological conditions. WEAP uses the five types of water years namely; normal, very wet, wet, dry, and very dry, which are based on relative amounts of surface water inflows. A reference dry year was outlined by identifying three conservative years of low flows, adding the total flows together and obtaining a low cumulative flow. The inflow data were then arranged in descending order and the five bin percentage was calculated (20, 40, 60, 80 &100 %) limits. This allows for defining the water year type and sequence for the years. This scenario was used to assess the change in the hydrological regime of the Hardap Dam Catchment and how it will affect the availability of water.

The scenario was explored further to forecast the expected inflows based on the rainfall forecast of the Southern Africa Development Community Climate Services Centre (SADC CSC). There is good quality data availability of the rainfall forecast for the years 2014 and 2015, hence the year 2013 was used as the base year to make the forecast for the hydrological year 2014/15 and 2015/16.

For the year 2014 SADC CSC, (2015) stated that according to the Global climate and prediction centres, the El Niño conditions were present during most of the Southern Hemisphere summer of 2014, hence normal to below-normal rainfall conditions were experienced in the continental SADC. The region also experienced a long dry period from October 2014 to January 2015 with suppressed rainfall conditions, which predominate over parts of Namibia (SADC CSC, 2015). The rainfall forecast for 2015 was forecasted to be an El Niño event, with below-normal rainfall conditions. The rainfall performance analysis shows that October 2014 to March 2015 period, was drier in most southern parts of the region with less rainfall up to 30 % of the long-term average (SADC CSC, 2015). These drought conditions prevailed and mostly affected Namibia for the 2015/16 hydrological year. With dry conditions and below-normal rainfall conditions, low inflows are expected into the Hardap Dam with very dry to dry years.

4.3.6.4 Scenario 4: Historical water discharged from Hardap Dam for the Neckartal Dam construction

A total of 10.7 Mm^3 was discharged downstream of Hardap Dam in 2017. The total discharged was done in 3 sequences and it was only a once-off to cater for the Neckartal Dam construction demand. Within WEAP a new demand of 10.7 Mm^3 under scenario management “Neckartal Dam” was added downstream of Hardap Dam. The scenario assessed if there will be any impact in terms of water availability and how it affects other demands.

The scenario was then explored to determine if the residual storage volumes (carryover storage volumes) for 2017/18, 2018/19 and 2019/20 were affected. The residual storage volumes for the 1st of October for each hydrological year from the model, 95% safe yield of 46 Mm^3/a (Annual maximum abstraction and net evaporation) assuming a monthly constant share and a buffer zone level of 19 Mm^3 (lowest irrigation abstraction level) were used to determine total months of supply. The formula in **Section 2.4** was used to determine the total months of supply.

The Neckartal Dam scenario was further evaluated to assess what if there were no inflows received into the dam from June 2017 up to September 2021. This will determine the supply run dry date of when the dam will be depleted. In the WEAP model, the 2017 to 2021 inflows were removed from the model and a simulation was carried out.

All scenarios started from a common year for which the data of the current account is established. The current account refers to the base year of the model. A “reference” scenario is established and inherits all activity levels from the current accounts (Sieber & Purkey, 2015). The structure of the scenarios is represented according to the current accounts; for this study, is 1999; the reference scenario is 2000-2021, hence all scenarios will be historically based and no future forecasts will be made.

4.3.7 Summary

In this chapter, the study area has been described by outlining the location and the physical features. The chapter also outlined the types of data used in the study, data sources and the methods used for analysing the collected data. The researcher has also described the model calibration and validation and the scenarios developments of the study area. The next chapter will be the presentation of results and discussion of the analysis carried out on the data collected.

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1 Introduction

The WEAP model was set up with the baseline year of 1999 and a reference year of 2000 to 2021. The model performance was evaluated by comparing the observed data with the simulated data. The scenario analysis approach was used to assess the operation of Hardap Dam and WRM strategies. The analysis was based on four main scenarios. Under each scenario, the water demands and supply were computed and analysed.

5.2 Domestic Demands

The domestic demand was analysed with population projection and compared with actual observed consumption. **Figure 16** represents the observed consumption vs projection of the Mariental Town.

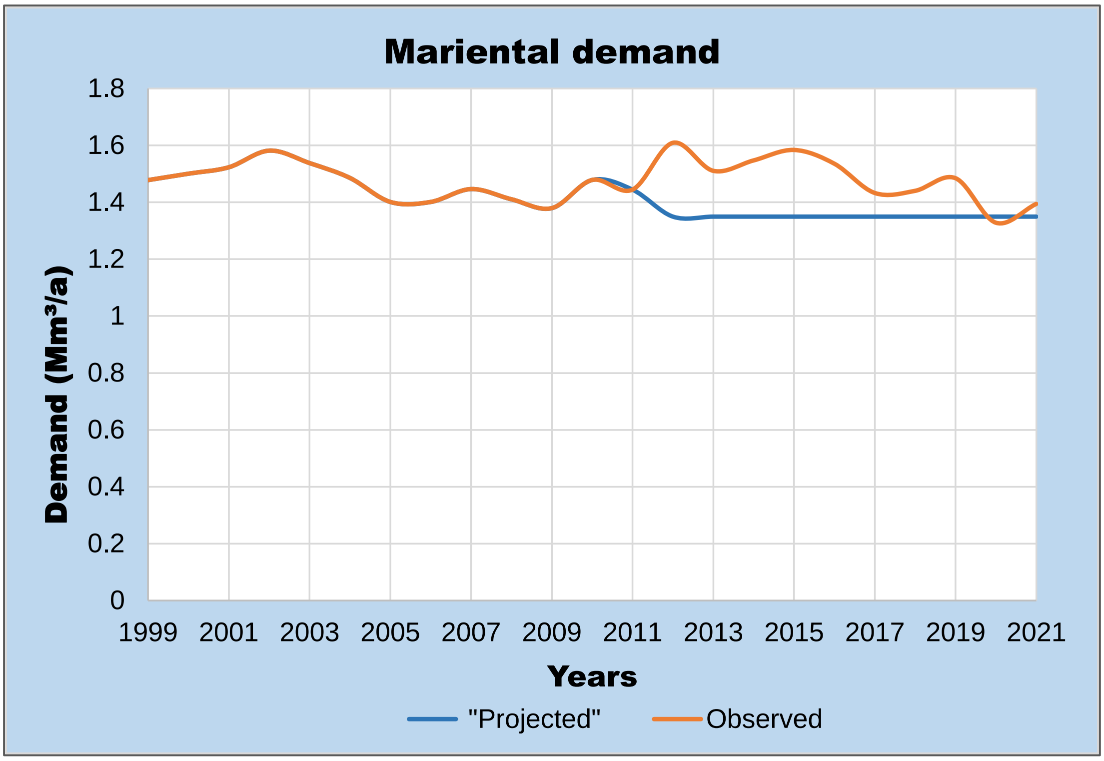

Figure 16: Mariental demand of observed compared with projection

The projected demands were projected with the 2011 census data and a consumption rate of 250 l/c/d as indicated in **Section 4.3.3**. The results show that the projected demands are lower than the observed demands, except for the year 2020. The dry period for 2019 to 2020 was critical such that less inflows were received into the dam which may have caused less demand. The consumption rate is underestimating the current demands, this could be attributed to the theoretical derivation of the consumption rate that is being used as an estimation. Overall the projected demands show a reduction of a ratio toward the total demand contribution of the Hadrap Dam. The observed demands were used and adopted for this study.

5.3 WEAP Model performance

The WEAP model performs a mass balance of flow sequentially, making allowance for abstractions and inflows within a dam system. The WEAP model was tested on a monthly and annual time step basis for the period of 1999 to 2021. It was calibrated using the observed 10-year data set period from 1999 to 2009 and validated with 12-year data set of 2010 to 2021. The model performance was evaluated using statistical parameters such as Root Mean Square Error (RMSE) and model Nash Sutcliffe Efficiency (NSE), as described in **Section 2.6.1**. The model compares storage volumes, observed and simulated to assess if the model is representing the system accurately. **Figure 17** presents the model calibration between observed and simulated storage volumes.

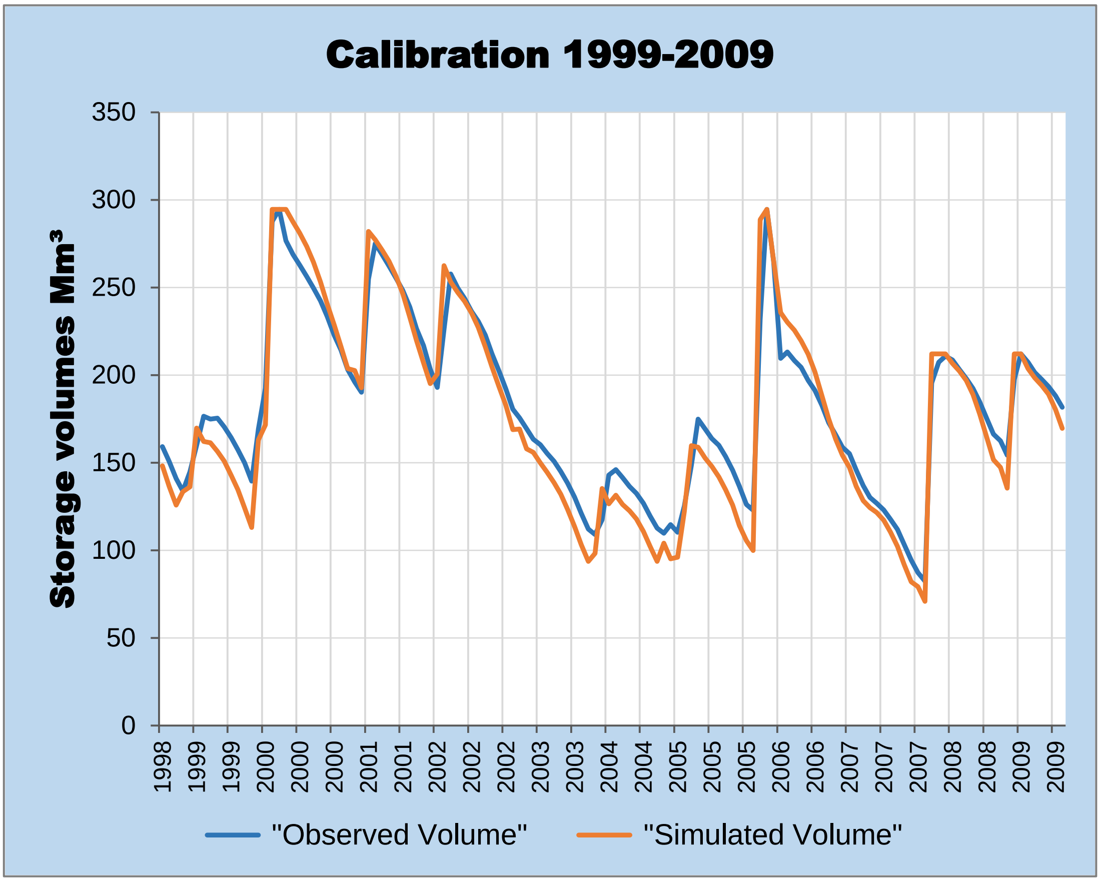

Figure 17: Calibration of storage Volumes of Hardap Dam for 1999 to 2009

The above time series figure shows that the trend in the simulated monthly storage volumes closely follows the measured observed data. During periods with inflows into the dam, the model is overestimating the storage volumes and underestimates during low dam levels. This can be associated with the calibration period that may be insufficient and the operation of the dam during wet seasons, when the dam is receiving high rate of inflows and controlled releases are made. From 2007 to 2009 with an operating rule of 72% of FSC, the model gave a better fit with less deviation from the observed data. Overall, there is an average best fit observed throughout. **Table 7** presents the statistical analysis for calibration.

Table 7: Calibration statistical analysis results

Storage Volumes	**Mean (Mm^3)**	**Standard Deviation (Mm^3)**	**Root Mean Square Error (RMSE) (Mm^3)**	**Coefficient of Efficiency (NSE)**	**R^2**
Calibration	163.4	54.4	13.9	0.92	0.96

The results show that the simulated storage volumes match the observed values with an NSE value of 0.92, which is within the acceptable ranges. The NSE determines the goodness of fit between observed and simulated values. **Figure 18** presents a correlation between observed and simulated storage volumes data.

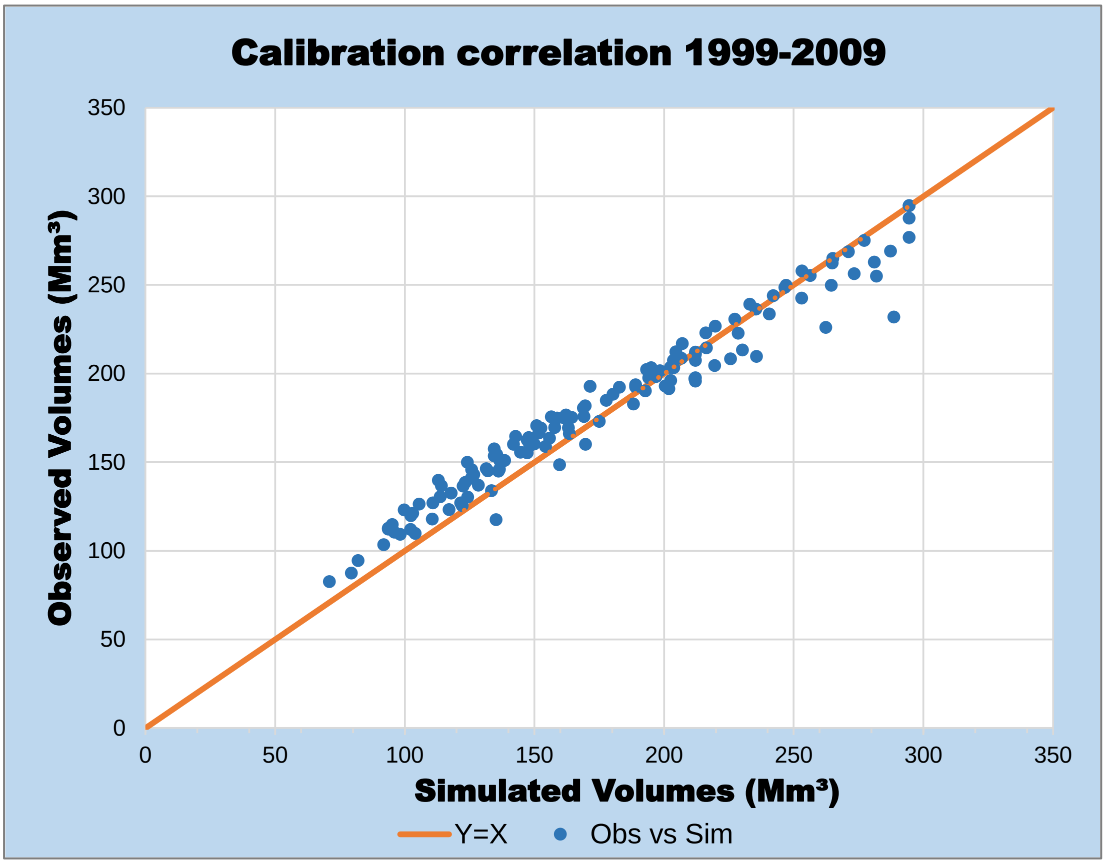

Figure 18: Calibration correlation between Observed and Simulated storage volumes

In this figure, the simulated and observed storage volumes values demonstrate a near tendency to the best fit line. The coefficient of determination R^2 value is 0.96, which falls within the acceptable ranges of a good model. Hence, the overall calibration is deemed good and the model is giving an accurate presentation of the observed data.

Validation of the model was done to ensure the true presentation of the model. The calibration data of up to the year 2009 was used to simulate the storage volumes from 2010 to 2021 and then compared with the existing observed storage volumes. **Figure 19** presents the validation with the observed demands, period from 2010 to 2021 between observed and simulated storage volumes data.

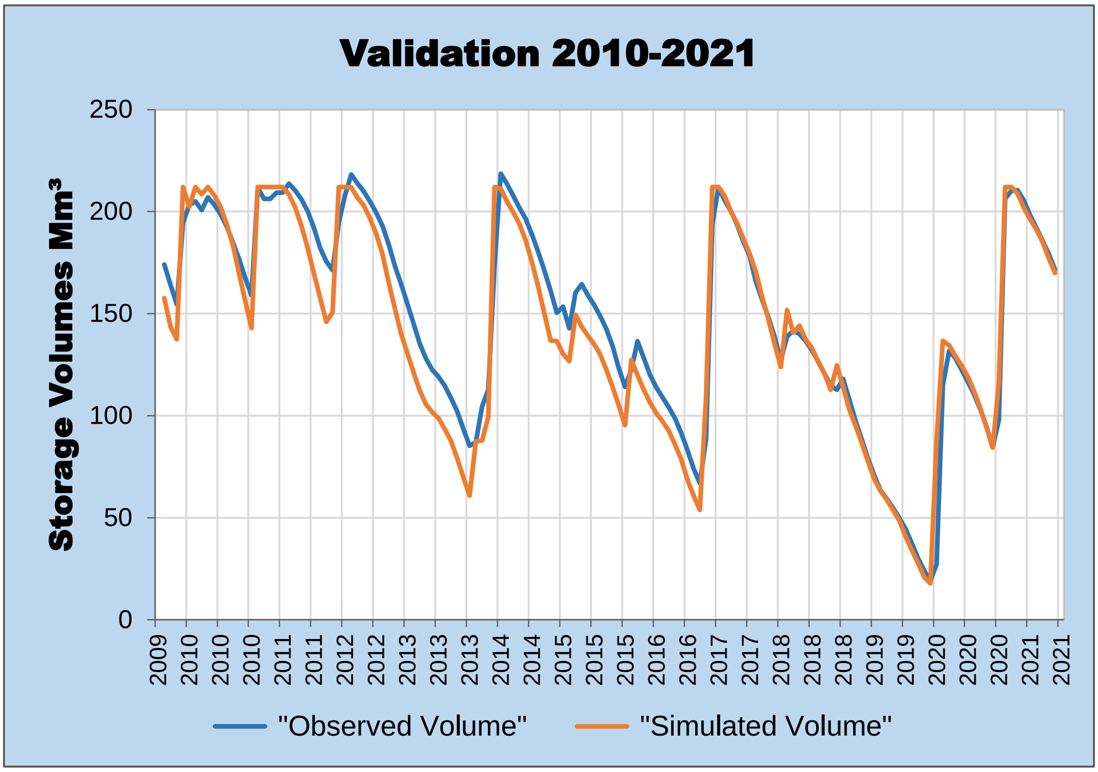

Figure 19: Validation with observed demands

The model is underestimating the storage volumes in 2011, 2013, 2015 and 2016 with a slight deviation from the observed data when compared to the simulated data. This can be attributed to the operation of the dam that ranges between 70 -72% of operational capacity which makes it challenging to maintain a constant level, mostly during the period when the dam is receiving inflows and releases are made at the same time. From 2017 onwards, the simulated data is giving a better fit with the observed storage volumes.

The validation process was also carried out using the projected demand data from 2011 to 2021. **Figure 20** represents the validation with projected demands.

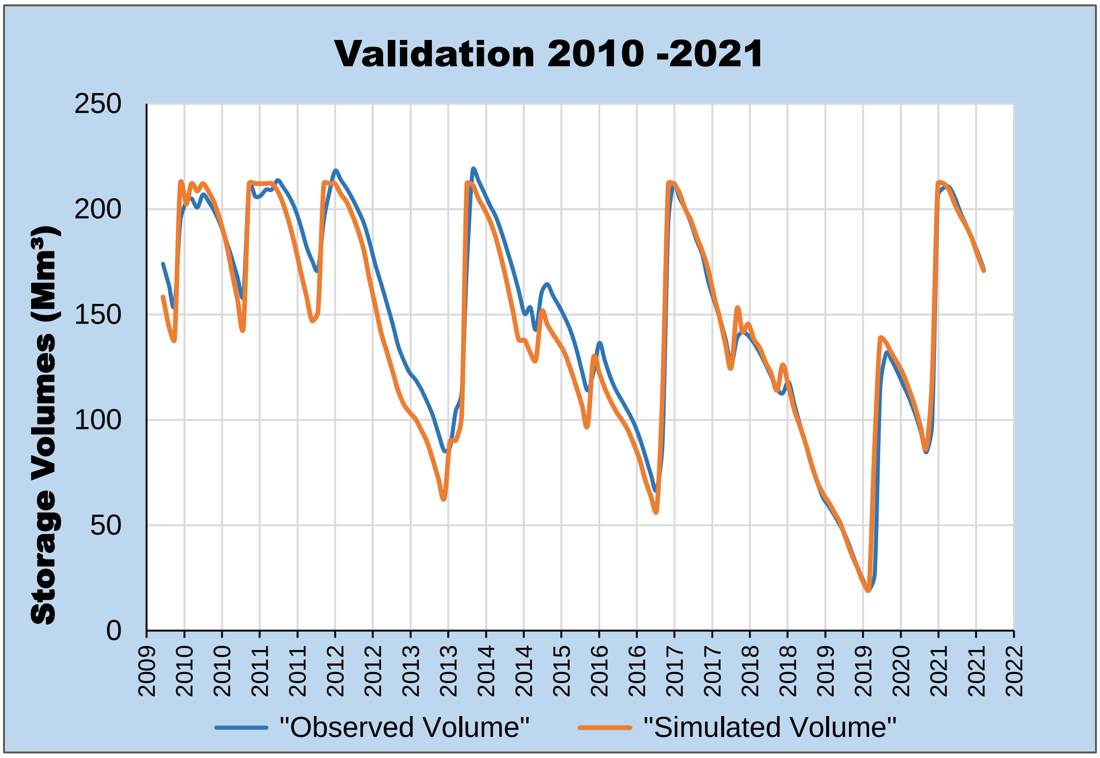

Figure 20: Validation with projected demands compared with observed demands

The validation figures have a similar trend, except with the projected demands the model is slightly underestimating the observed volumes as compared to the validation with observed demands. This could be attributed to low projected demands which lead to a reduction in abstraction volumes from the dam. **Table 8** presents the statistical analysis for validation of the model.

Table 8: Validation of statistical analysis

Storage Volumes	Mean (Mm³)	Standard Deviation	Root Mean Square Error (RMSE) Mm³	Coefficient of Efficiency (NSE)	R²
Validation (actual)	158.2	51.1	14.1	0.93	0.94
Validation (projection)	143.1	50.6	13.5	0.93	0.94

The models show satisfactory results for NSE of 0.93, which is within acceptable ranges. However, the difference between the models is only observed in the root mean square error. This could be associated with the percentage shares that the domestic demands contribute a minimal outflow from the dam as compared to the irrigation demands. The impact of projected demands is quite low, hence the actual observed demands were used for the study. **Figure 21** presents a correlation between observed and simulated storage data.

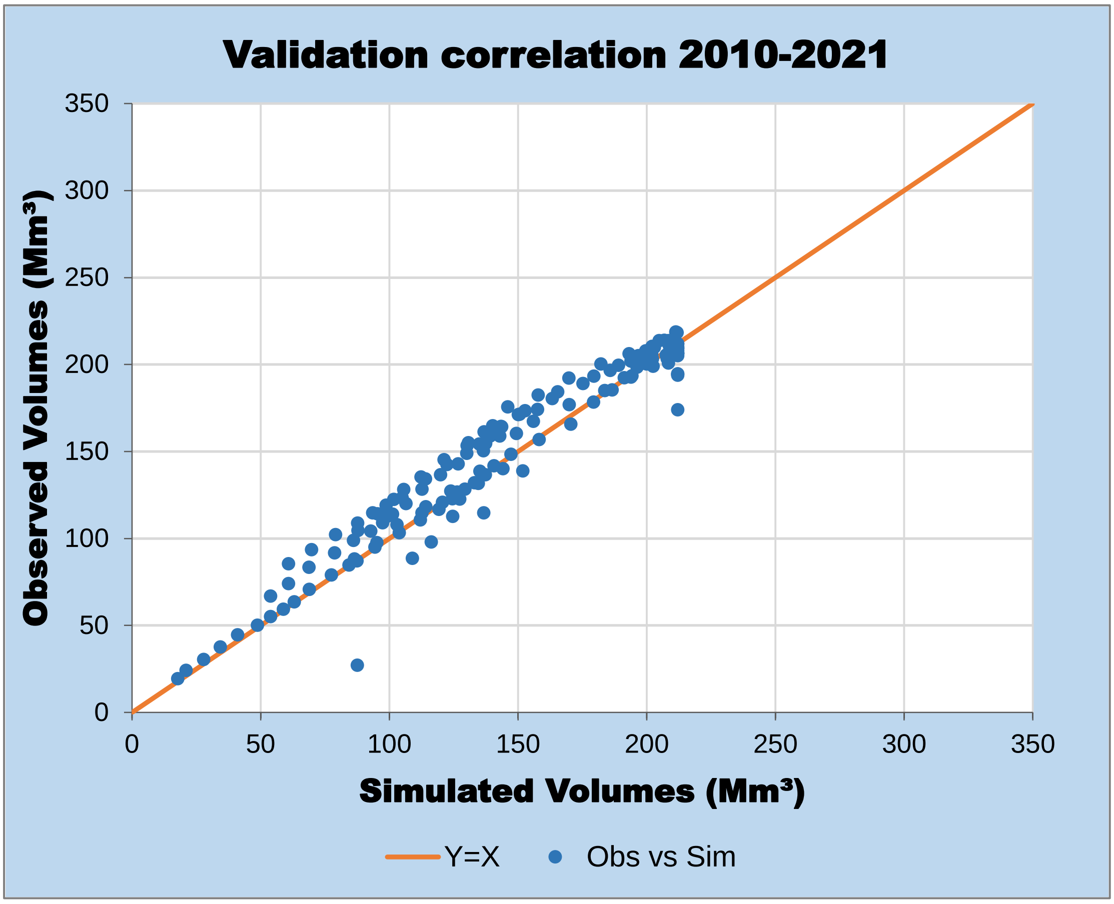

Figure 21: Validation correlation between Observed and Simulated storage

In the scatter plot diagram provided in **Figure 21**, the simulated and observed storage volumes values demonstrate a very close tendency to the best fit line. The coefficient of determination R^2 value is 0.94 which falls within acceptable ranges of a good model. Hence the overall validation is deemed good and the model is giving a good presentation.

5.2 Scenario Management Analysis

Scenario analysis enables the answering of 'what if' questions in a water system. Five scenarios were set up for the study including the reference scenario.

5.2.1 Reference Scenario

The reference scenario is the base scenario, which uses the actual data in which the current situation, of the current account year 1999 is extended to the 'future' (2000-2021). The objective of a reference scenario is to bring an understanding of the current historical trend. Other scenarios are built on this reference scenario with variations on the demand or supply side. Thus, the reference scenario is the results presented above.

5.2.2 Demand Management and Irrigation Efficiency Scenario

A 10% demand-side management (DSM) was imposed for Mariental Town and improved irrigation efficiency. By imposing the DSM to Mariental Town, the demands for Mariental Town decreased as indicated in **Figure 22**.

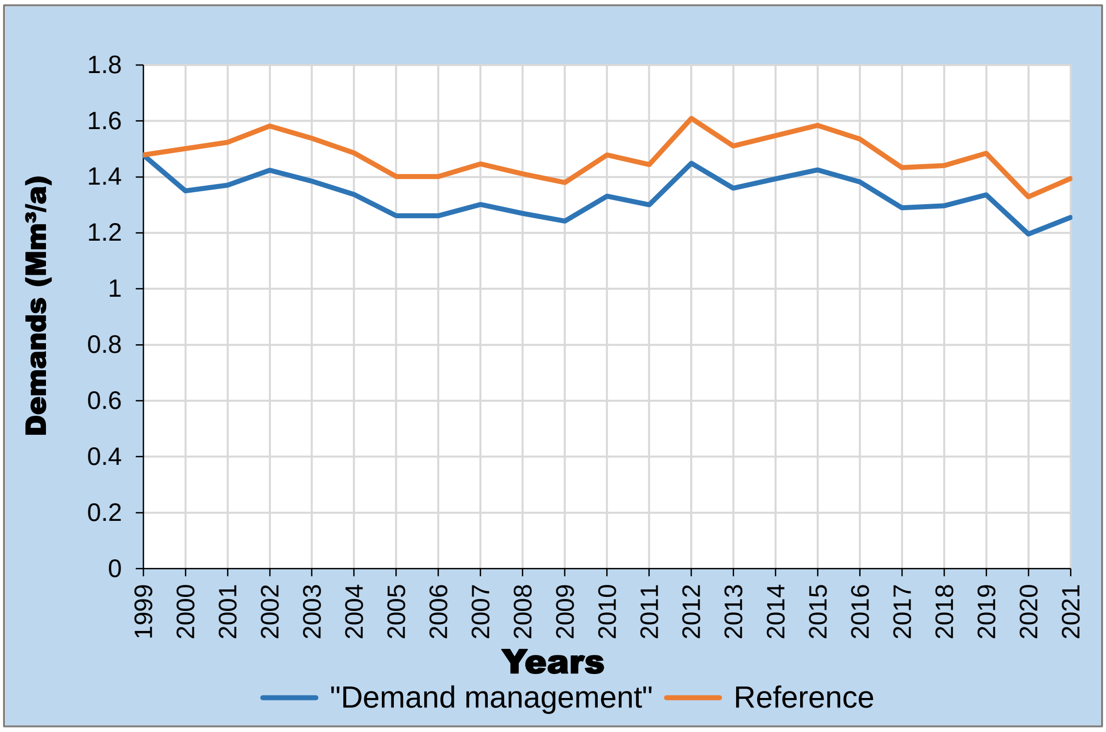

Figure 22: Demand saving implementations for Mariental Town

The storage volumes of Hardap Dam, before and after the demand saving was implemented were compared and the results show no change as shown in **Figure 23**. The effect is not significant as the Mariental Town demand represents a small share of the total demands being supplied from the Hardap Dam.

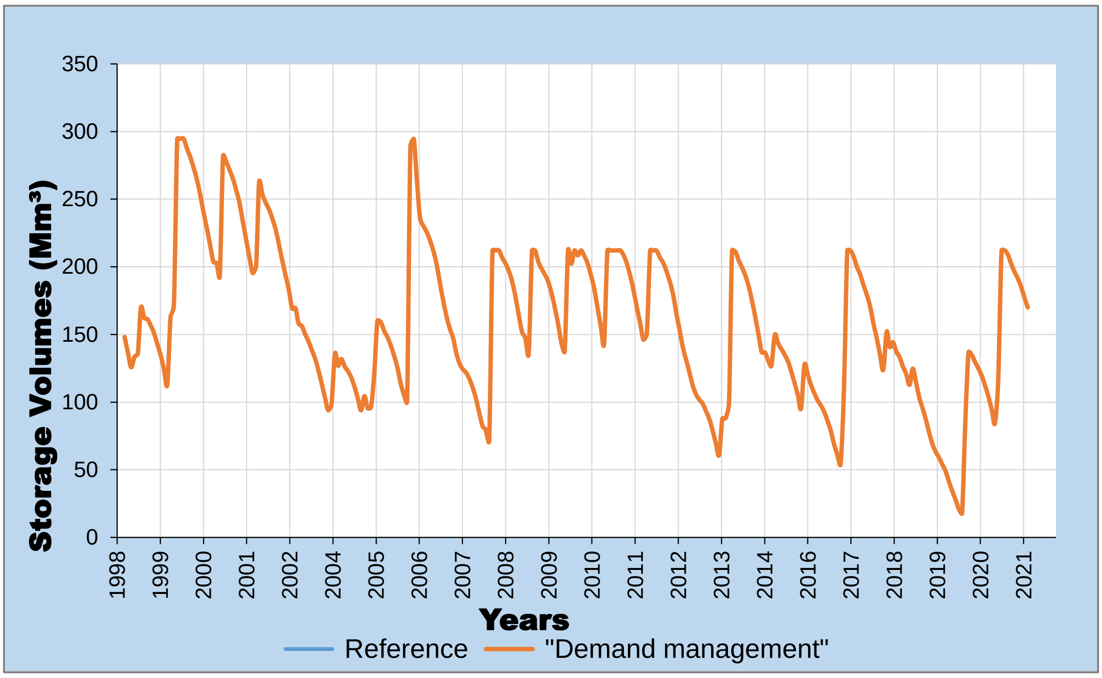

Figure 23: Storage volumes of Mariental Town demand management compared with reference

The irrigation efficiency is based on the change of irrigation methods from flood irrigation to drip irrigation method. Drip irrigation efficiency was assumed and estimated to be 85%. **Figure 24** presents the change in demand after irrigation efficiency was implemented for the Hardap Irrigation Scheme.

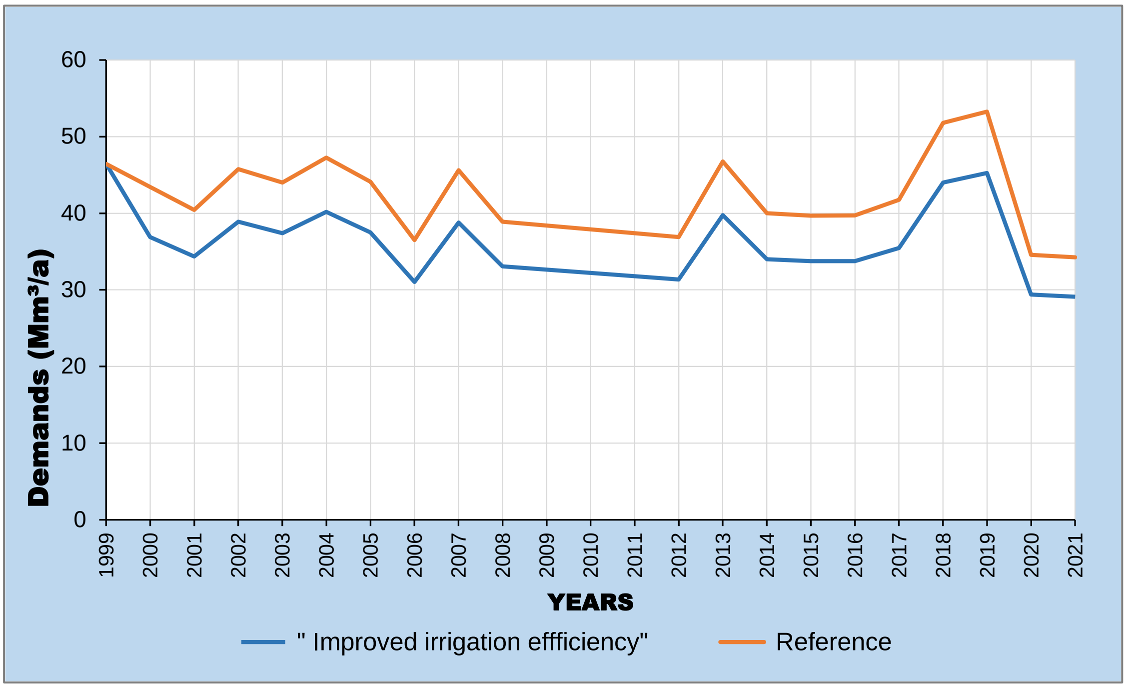

Figure 24: Irrigation demands with improved irrigation efficiency

This scenario indicates that improving the irrigation efficiency will significantly reduce water demands by at least 30%, which will then improve the storage volume and carry over levels of the dam as shown in **Figure 25**.

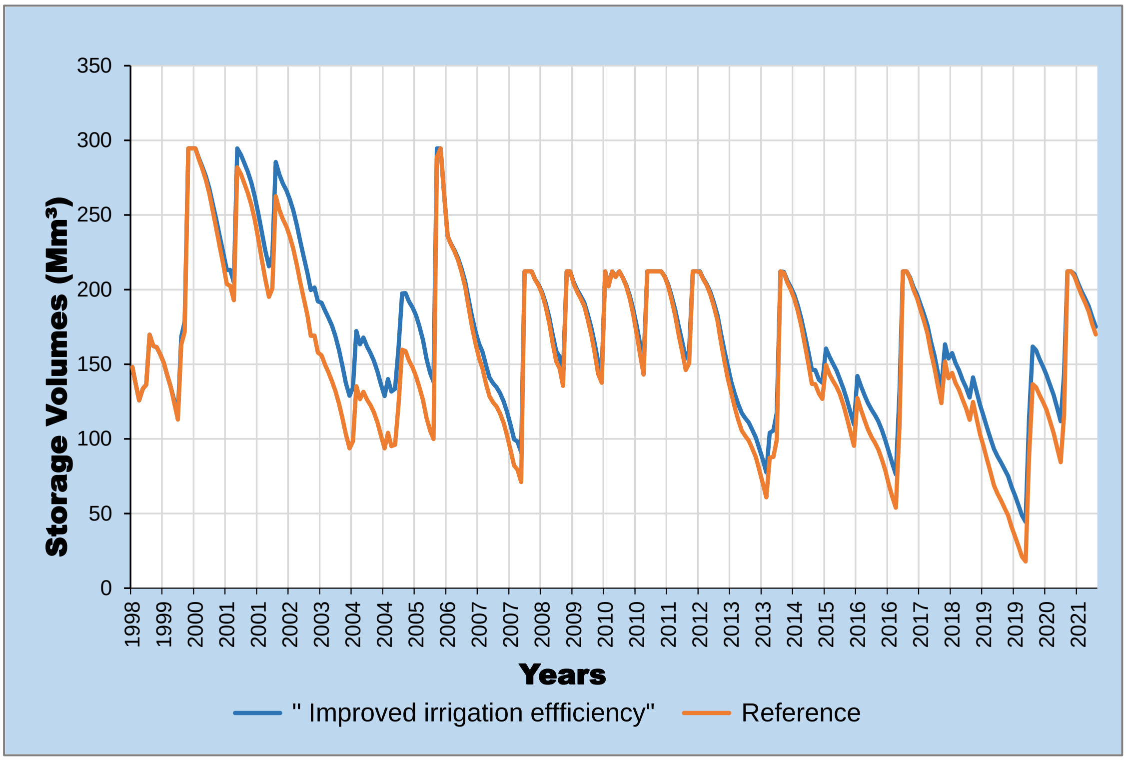

Figure 25: Storage volumes for improved irrigation efficiency compared with reference

The increase in storage volume with an average of 13% emphasizes that the supply period has been extended further to cater for the demand required for longer periods if no inflows are received into the dam. The impact of this scenario is evident during periods of low storage volume levels which indicate water is saved for the critical droughts periods and extreme low dam levels are prevented.

5.2.3 Increased Irrigation Area Scenario

This scenario was used to analyze the effect of expanding the irrigation area. The irrigation area was increased to a total of 213 ha, which consists of 100 ha for the disadvantaged farmers and 5% of the current existing irrigation area. The allocated quota of 18 000 Mm^3/ha/a was used for the additional area. **Figure 26** presents the total demand for an increased irrigation area scenario.

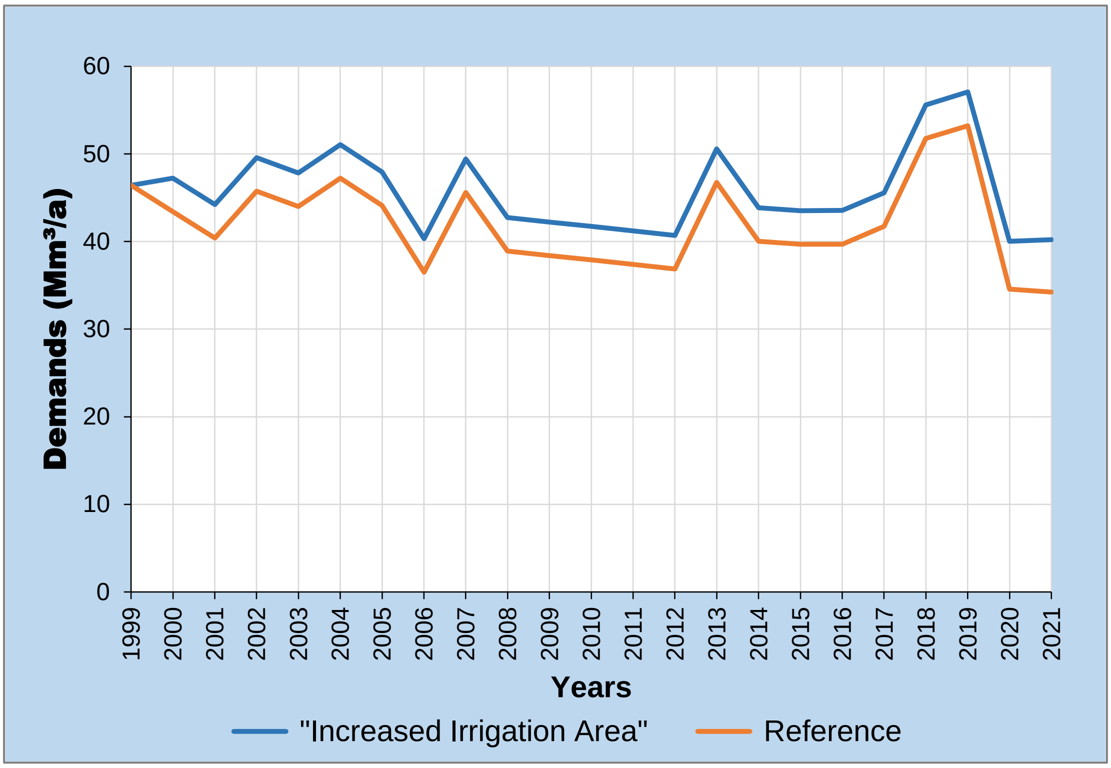

Figure 26: Increased irrigation area demands compared with reference

These results showed that by increasing the irrigation area, the water demand for irrigation will increase by 3.8 Mm^3/month; notably, there are no demands downstream of the dam which are not met. Based on the historical data, this indicates that the demand coverages will be fully utilized if the irrigation area is expanded. This scenario has an impact of about 4% on the reduction of storage volumes of the Hardap Dam as indicated in **Figure 27**.

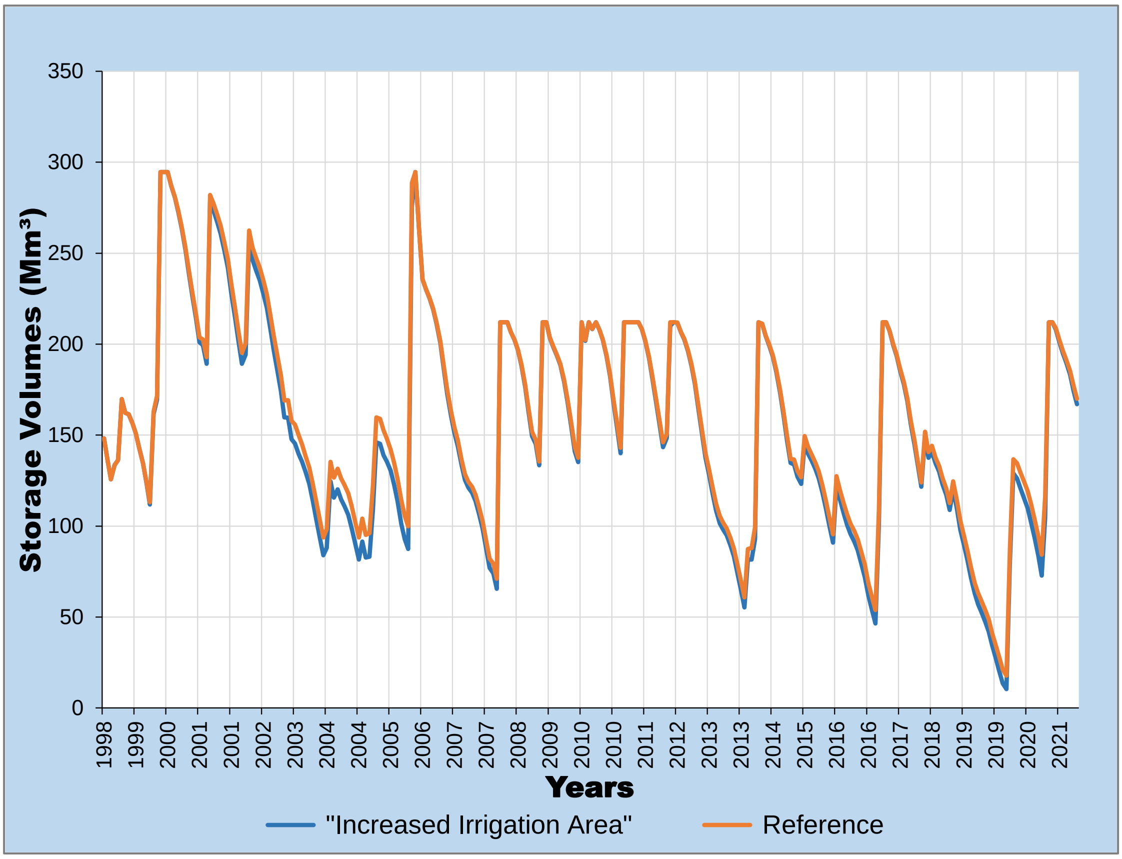

Figure 27: Hardap Dam storage volume with increased irrigation area compared with the reference

It is observed that the dam levels have reduced during periods of droughts by 4%, the year 2000 to 2005 and 2013 to 2020 which could be critical as the supply periods are shortened. However, the expansion of the irrigated area would have no impact on demands if alternative irrigation methods are used, such as drip irrigation.

The model forecasted a critical threshold in terms of increased irrigation area to a maximum of 300 ha which represents an additional 87 ha to the 213 ha which was simulated above. The 300 ha has an impact on the demand coverage for the extremely dry months of December 2019 and January 2020. Whereby the demand coverage was reduced by 10%, and only 90% of demand was covered for Mariental Town, aquaculture, and irrigation demands. This represents an amount of 0.61 Mm^3 of unmet total demands for the year 2020.

A reduction in the storage volumes is observed for the dry years with low dam levels. The critical period is December 2019 to January 2020 when the dam level reached a level of 7.4 Mm^3 as compared to the observed of 18 Mm^3 which is below the lowest irrigation abstraction level. On average, the dam levels were reduced by at least 6% as represented in **Figure 28**.

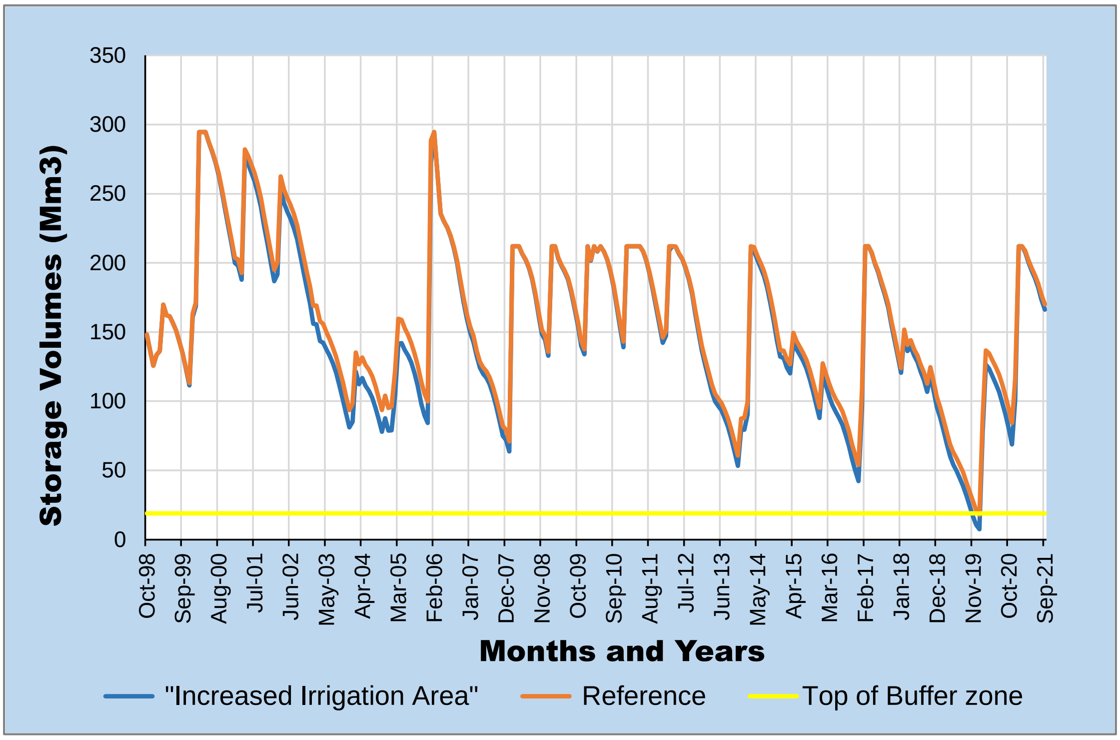

Figure 28: Hardap Dam storage volumes with the critical irrigation area compared with reference

Furthermore, the model also forecasted a worst-case scenario for the extreme threshold in the irrigation area. A total of 1000 ha was forecasted as it deplete the Hardap Dam beyond the dead zone as shown in **Figure 29**.

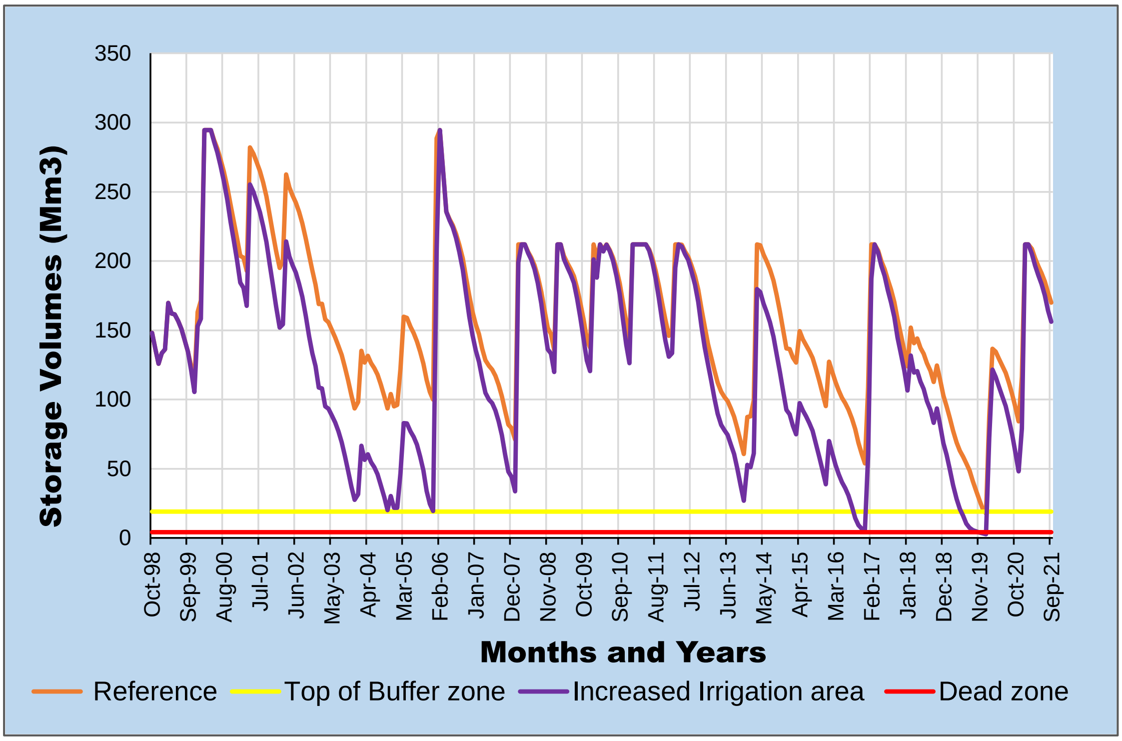

Figure 29: Increased irrigation area (worst-case scenario) compared with reference

The increased irrigation area shows a highly significant impact mostly during the dry years. The critical dry years are 2016 and 2019 to the beginning of 2020. For this period the demands are higher such that they deplete the water supply up to the dead zone and slightly beyond for the year 2020. For the wet years, the impact is experienced in the year 2001 to 2003, 2014, and 2018 as compared to the maximum area of 300 ha which didn't depict any significant impact for this period. With the extreme threshold area, the demand coverage has been reduced to 5% for 2016 and to 1% for 2019 and 2020. This represents a high amount of unmet demands with a total of 25 Mm^3 for 2020. The extreme period where the dam level breach the buffer zone indicates that the supply to the irrigation is curtailed in full to make provision for the domestic supply.

5.2.4 Hydrological seasons/ Water Year Method Scenario

The water year method was used to represent a variation of the supply, the natural variation in climate data of inflow data. With this method, the different climate regimes were defined as, very dry, dry, very wet, wet and compared relative to a normal year, which is given a value of 1. A period of low inflows was determined to be used as a dry reference year for the study. The dry reference years were determined by taking three consecutive low flow years to find their cumulative total inflows. The year 2001 to 2004 was selected to be the reference dry years for the study as their accumulative total inflows was the lowest compared to other conservative years with a total inflow of 170 Mm^3 as shown in **Table 9**.

Table 9: Reference dry years

Reference dry years		
Year	**Inflows Mm^3**	**Cumulative inflows Mm^3**
2002	90	90
2003	10	100
2004	70	***170***

The years with total annual inflows of up to 90 Mm^3 are considered to be dry years. The definitions of the wet and dry years were determined by arranging the inflows data into descending order and calculating the five bin percentage (20, 40, 60, 80 &100 %) limits, which were then used to find the ratio relative to the normal water year type. Dry years have a value less than 1, and very wet years have a value larger than 1. **Table 10** indicates the water year sequence and definitions as set in the Hydrological season variation scenario under the hydrology water year method within WEAP.

Table 10: Water year definitions

The 5 bins (%)	Limits inflow (Mm³)	Water year type	Average Inflows (Mm³)	Ratio/Water Year Definitions
20	40	Very Dry	20	0.2
40	90	Dry	60	0.5
60	170	Normal	120	1
80	340	Wet	240	2
100	940	Very wet	660	5.5

From **Tabele 10**, the very wet years varies significantly, up to five times compared to the normal years while the very dry years have inflows of 0.8 times less than the normal years.

The definitions of the wet and dry years were determined by arranging the inflows data into descending order and using the inflow limit range from the water year definition above. **Table 11** presents the water year sequence.

Table 11: Water year type and sequence

Year	Inflows (Mm³)	Water year type
2005/06	943.0	very wet
1999/00	809.3	very wet
2010/11	713.7	very wet
2008/09	443.7	very wet
2020/21	372.0	very wet
2007/08	284.3	wet
2016/17	255.0	wet
2011/12	230.3	wet
2013/14	191.6	wet
2009/10	164.1	normal
2019/20	127.3	normal
2004/05	114.3	normal
2000/01	102.0	normal
2001/02	85.6	dry
1998/99	80.7	dry
2003/04	70.1	dry
2017/18	50.3	dry
2014/15	43.6	dry
2015/16	40.2	very dry
2018/19	21.7	very dry
2002/03	13.2	very dry
2006/07	6.4	very dry
2012/13	0.0	very dry

In WEAP the above water year definitions and sequence were entered in which will vary the inflows data as dry or wet as a climatic variation. With the water year methods, the inflows into the Hardap Dam varies as compared to the reference scenario. **Figure 30** represents the varied inflows.

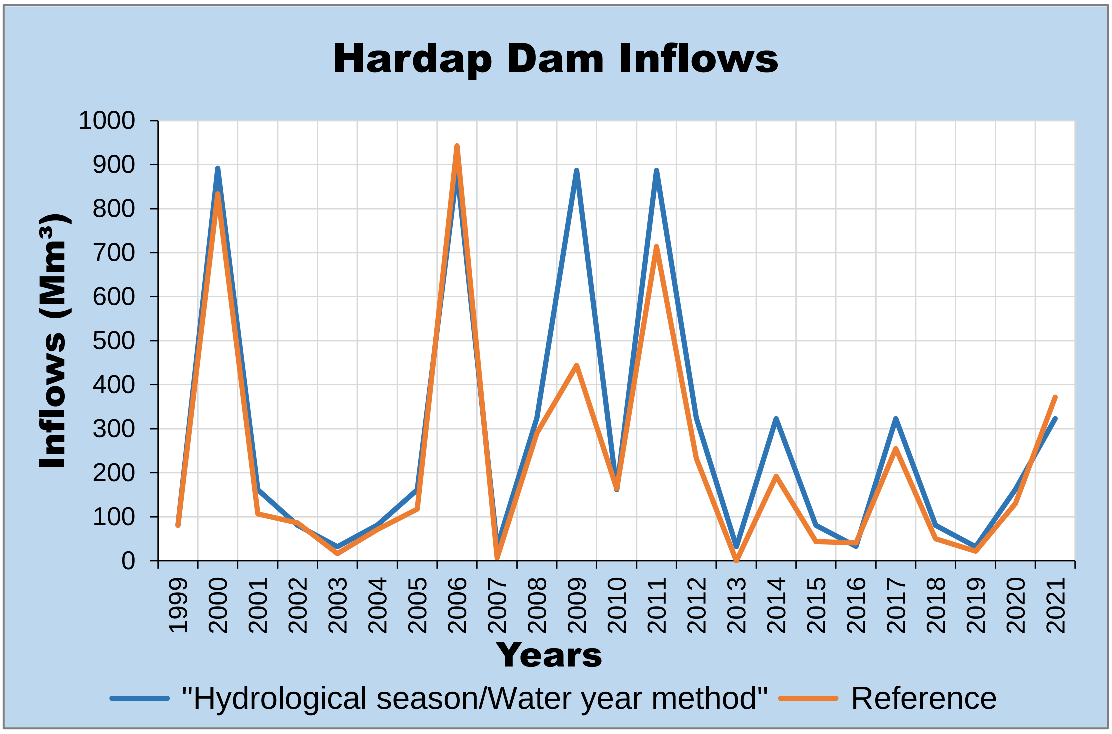

Figure 30: Inflows data for the water year method and reference scenario

The inflows do not vary much for the very wet and wet years as compared to the very dry and dry years. **Figure 31** presents the storage volumes with varied inflow data as compared to the reference scenario.

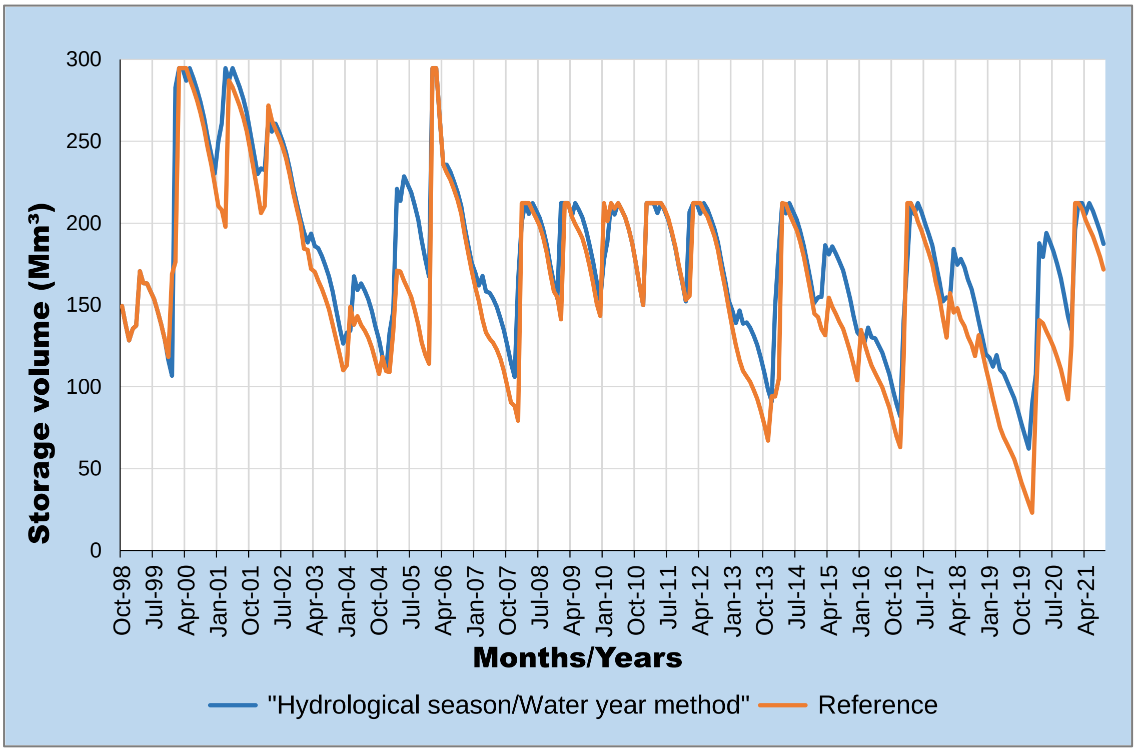

***Figure 31: Hardap dam storage volumes for the water year method compared to the reference scenario**.*

From **Figure 31**, the storage volumes differ mostly for the normal and dry years. During the dry years, the dam levels and storage volumes were increased by an average of 15% as compared to the reference scenario. For the rest of the years, the reference storage volumes are lower; this could be attributed to high ratios of wet years as compared to dry years. The normal year of 2005 in March, has recorded a higher level of storage volume under the water year method with a difference of approximately 60 Mm^3, among others is the year of 2015, 2018 and 2020 respectively. In this scenario, the model is picking up all the dry years as observed historically with an increment that will improve the storage volumes. Hence, extremely low dam levels are prevented and supply periods are further improved. The model depicted a positive storage volume level at the end of the study period of 180 Mm^3 as compared with observed data.

The scenario was explored to forecast the expected inflows for the hydrological year 2014/15 and 2015/16 based on the rainfall forecast of the SADC CSC using the 2013/14 inflows as based data. The inflows for 2013/14 were input into the WEAP model to forecast inflows. The total annual inflows for 2013/14 were 191 Mm^3, which is defined as a wet year as per **Table 10** and **11**.

The results show that the model forecasted dry and very dry for the 2014/15 and 2015/16 hydrological years respectively and accurately as per the SADC CSC forecast. **Figure 32** presents the forecasted inflows results and water year type compared with reference data.

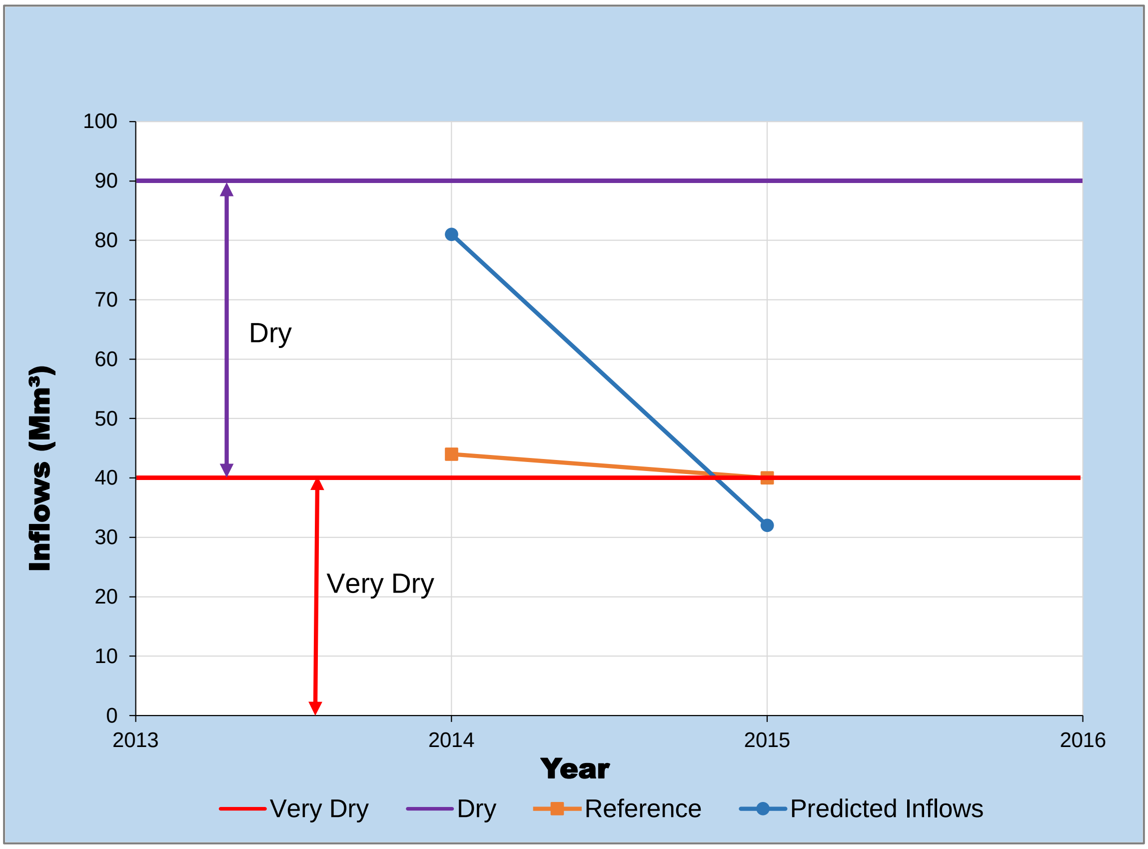

Figure 32: Forecasted inflows and water year type compared with reference for the 2014 to 2015

For 2014/15 the model forecasted a total inflow of 81 Mm^3 which is within the dry year envelope of 40 -90 Mm^3 but higher than the observed data of 44 Mm^3. A good performance was for 2015/16, which forecasted a total annual inflow of 32 Mm^3, which was less with 8 Mm^3 from the reference inflow data of 40 Mm^3 and it is within the very dry year limits of 0- 40 Mm^3.

5.2.5 Neckartal Dam Demand Scenario

A new demand site "Neckartal Dam" was added under this scenario with a demand and supply priority of 1. The scenario looks at a total demand of 10.7 Mm^3 that was discharged from Hardap Dam to Neckartal Dam during the year 2017, which was utilized for the three months, July, August and September. **Figure 33** presents the storage volumes of the Hardap Dam in comparison to the reference scenario.

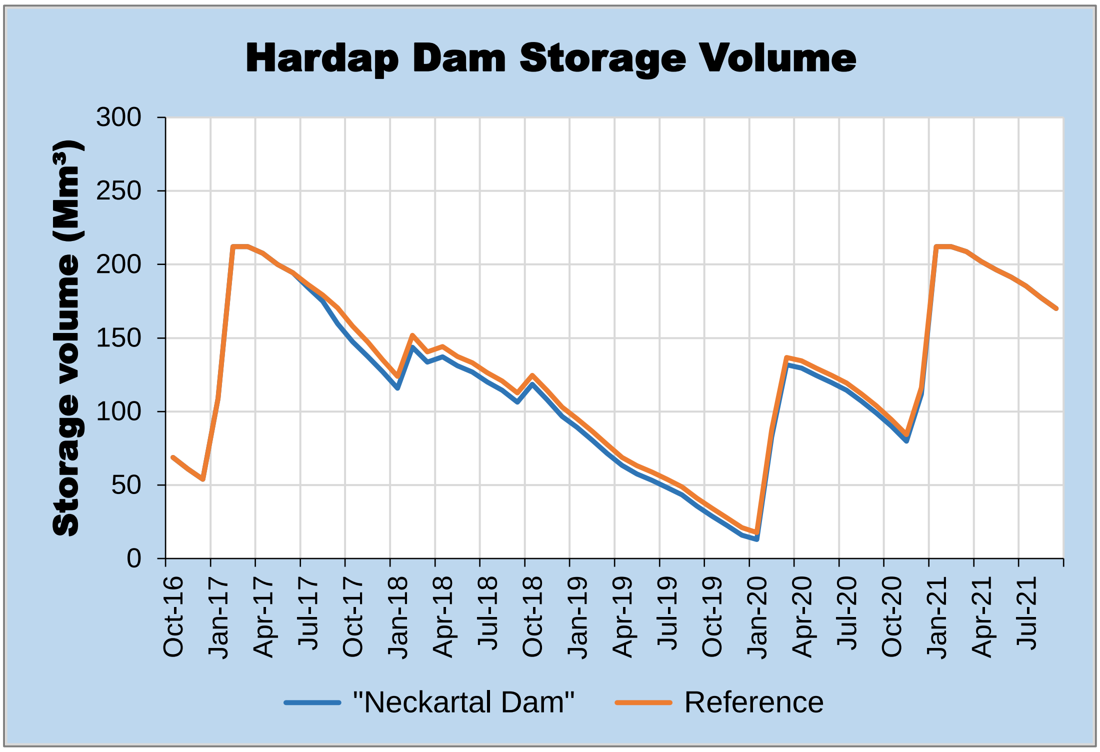

Figure 33: Neckartal Dam demands impacts on Hardap Dam storage volume

The Neckartal Dam demands have increased the total demand by 10.7 Mm^3. From **Figure 33**, the storage volumes have slightly decreased and the impact has been carried over up to December 2020. The difference in storage volume is not significant as the lowest storage level is 4.4% of FSC compared to the initial level (reference scenario) of 6% observed in January 2020, which gave a difference of one-month supply. It is observed that, with the 2021 inflows into the dam, the effect was no more as both scenarios recorded the same storage volumes. **Annexure 1** attached indicates the differences between Neckartal Dam and Reference demands both in volumes and percentages. The scenario was then explored to determine if the residual storage volumes (carryover storage volumes) for 2017/18, 2018/19, and 2019/20 were affected. The residual storage volumes for the 1st of October for each hydrological year from the model, 95% safe yield of 46 Mm^3/a (Annual maximum abstraction and net evaporation) assuming a monthly constant share and a buffer zone level of 19 Mm^3 (lowest irrigation abstraction level) were used to determine total months of supply. The following formula was used to determine the total months of supply for the year 2017/18.

Total Months of Supply = (Residual storage – Buffer zone level)/ Monthly max abstraction

= (156 Mm^3-19Mm^3)/ (46 Mm^3/12 months)

= 35 Months

Table 12 presents the total months of supply for the reference scenario compared with the Neckartal Dam scenario.

Table 12: Residual storage volumes and supply period for Neckartal Dam demand compared with the reference scenario

Scenarios	**2017/18**			**2018/19**			**2019/20**		
	Residual storage volumes (Mm^3)	Annual max abstraction (Mm^3)	Supply period (Months)	Residual storage volumes (Mm^3)	Annual max abstraction (Mm^3)	Supply period (Months)	Residual storage volumes (Mm^3)	Annual max abstraction (Mm^3)	Supply period (Months)
Neckartal Dam	156	46	35	118.4	46	24	29.0	46	**2**
Reference	166	46	38	124.6	46	26	34.4	46	**3**

The residual storage volumes for the first two hydrological years did meet the operation rule of the dam to supply demands for two full seasons. Except for 2019/20, where the supply differed by 1 month, the operation rule was not met. Hence the Neckartal Dam discharge did not affect the water availability and security of the Hardap Dam as a shortage of water was experienced in both scenarios during the 2019/20 hydrological year.

The Neckartal Dam scenario was further explored to assess if there were no inflows received into the dam from June 2017 up to September 2021. In WEAP model, the 2017 to 2021 inflows were removed from the model and an assessment was done to determine the run dry date as indicated in **Figure 34**.

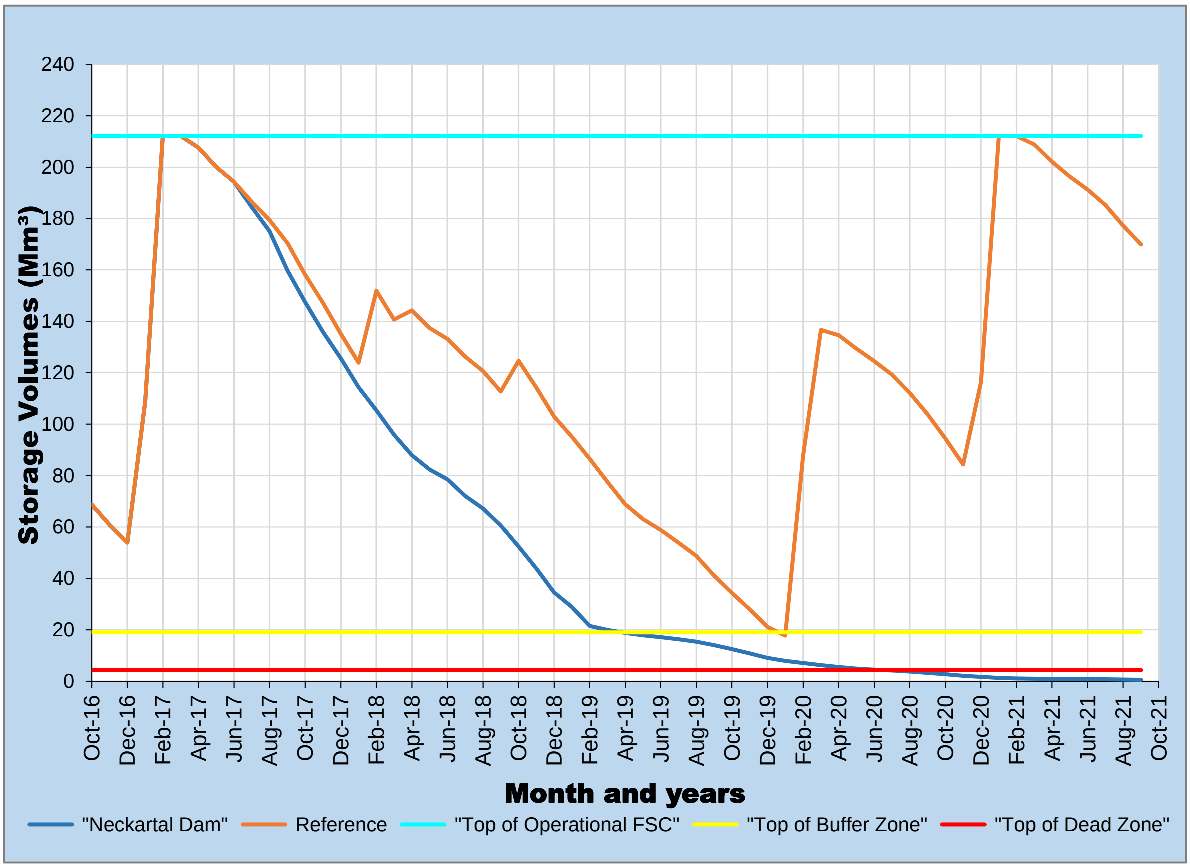

Figure 34: Discharge for Neckartal Dam run dry date

From **Figure 34**, Neckartal Dam demand would deplete the storage volume of Hardap Dam by June 2020 when the dam levels reached the dead zone of 4.3 Mm^3. This represents three full supply seasons for Mariental Town starting from July 2017 when water for the Neckartal Dam was released with restrictions imposed on the low supply assurance level when the dam breached the buffer zone of 19 Mm^3. The supply and abstraction to the Hardap Irrigation Scheme are curtailed in full at the top of the buffer zone in March 2019, representing two full supply seasons for the irrigation demand. Thus, ensuring the supply to the domestic category (Mariental Town) with a higher supply of assurance. The impact of this scenario is not significant as it ensured the residual storage to satisfy the demands with two full supply seasons.

5.2.6 Summary

The calibration and validation of the model show good satisfactory results with acceptable statistical efficiency NSE of 0.92 and 0.93 respectively. The correlation between the simulated and observed indicated the best fit to the line y=x, thus the determination of the model is 0.96 and 0.94, which show the best overall performance of the model. Four scenarios were built on the calibrated and validated model. A comparison was done between the scenarios and the reference scenario to determine the impacts of the scenarios in terms of demands and water supply.

The scenario of demand management and irrigation efficiency shows that there is no change in storage volumes by imposing the 10% demand saving for Mariental Town. The storage volumes of this scenario are increased with the irrigation efficiency of 85% and very notably during the dry periods as an indication that water is saved during the drought seasons, thus supply period and residual storage are increased by approximately 13%. The second scenario of an increased irrigation area of 213 ha indicated that the irrigation demands are increased by 4% in the storage and residual volumes. With this area, the impact is mostly depicted when the dam levels are low but with higher storage volumes, there is no significant impact. All the demands were met with this scenario, but restrictions may be applied during dry years to prevent critical low dam levels. A critical threshold was analysed that determined a maximum area of up to 300 ha had a major impact that reduced demand coverage to 90% and low residual storage volumes were observed. The extreme worst-case scenario was forecasted up to a 1000 ha that breached the dam level up to 1% of FSC and demand coverage was reduced for 2020.

The third scenario looked at the impact of wet and dry seasons by using the water year method. The definitions and sequence of the water year type were identified. The results show that with dry years' improvements by 15% increment of storage volumes are experienced during drought periods and no increment with the wet years. This is mainly associated with the lowered operational capacity of 70%, even with extreme wet seasons, there will be no increase in the availability of water supply as storage volumes remain the same. Furthermore, the forecasted inflows for the hydrological year 2014/15 and 2015/16 were within the dry and very dry years as observed and forecasted by the SADC CSC. The last scenario of Neckartal Dam discharge was analysed with the inflows and with no inflows into the Hardap Dam. The results with inflows into the dam show little impact as the change in storage volumes is very small. This effect is carried along until the year 2020 and the critical stressed period of 2019 on storage volumes was 4.4 % as compared to the observed historical data of 6%. The results also showed that the demand coverage for all the demands was 100%, which implies that all the demands were fully met for 2017/18, 2018/19 years and with restrictions applied to the irrigation demand during the 2019/20 season. The analysis with no inflows into the dam shows that this scenario will deplete the storage volumes to a dead zone within 36 months, which is equivalent to three full supply seasons for domestic demands. For irrigation, the supply is 24 months equivalent to two full supply seasons. Hence, this scenario indicated that the impact is not significant as the Neckartal Dam demands are within the Hardap Dam operations to be able to supply all demands with two full supply seasons.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study developed and assessed a WEAP model for the Hardap Dam operation and water resource management strategies under different scenarios in the Hardap Catchment. The development of the model and the assessment used historical data of 22 years to analyse the hydrology and water management of the Hardap Dam.

1. Calibration and validation efficiency results of 0.93 and 0.92 are within acceptable limits, indicating that the model performed well and that the historical data is being represented accurately. Thus, the model was well adapted for the study, and water management strategy scenarios were analysed.

2. The demand management scenario, which was a combination of demand-side management of Mariental Town and irrigation efficiency, indicates a decrease in total demands while increasing the supply volumes. The implementation of the drip irrigation method shows a great impact of reduction on irrigation demand and a 13% increase in residual storage volumes for dry years.

3. The expansion of the irrigation area increases the irrigation demands by 3.8 Mm^3/month. The other demands of Mariental Town and aquaculture were met at 100% demand coverage. The effect of increased irrigation area on the supply has a reduction of 4% in residual storage and the overall Hardap Dam storage levels. However, the model forecasted a maximum area of 300 ha that could potentially cause unmet demands during critical low dam levels. Furthermore, an extreme threshold of 1000 ha in increased irrigation area was forecast as the worst-case scenario that depleted the Hardap Dam below the dead zone up to 1% of FSC and has a major impact of 25 Mm^3 of unmet demands.

4. The water year method for variations in inflow data showed no impact on the residual storage volumes and available storage volumes during the wet years. However, an increase in storage and residual volumes was observed for the dry years with an average of 15%. The forecasted inflows of 2014 and 2015 show a great outcome of 81 Mm^3 and 32 Mm^3 respectively and within the water year type of dry and very dry as compared to the observed data.

5. For the Neckartal Dam demand scenario simulation results indicated that Neckartal Dam water demands’ impact had no significant impact on the available water of the Hardap Dam. Thus, the impact on the water shortage and supply insecurity for the drought of 2019/20 was purely the effect of low inflows and dry years of 2017 to 2020.

6.2 Recommendations

Based on the results of this study, the following recommendations were made:

1. The 70% operational capacity has greatly reduced the available storage of the dam, which affect the availability of water supply. Alternative ways must be investigated to operate the dam at a higher capacity while ensuring the safety of the dam and the downstream users.

2. The DSM strategy of improved irrigation efficiency showed a positive impact on the availability of water as an increase in storage volumes are observed. It is recommended that more investigation should be done on the drip irrigation method on possible ways to implement it and evaluate the cost implications.

3. This study has established the baseline of operations of Hardap Dam and water resource management in its catchment. Thus, a follow-up study is needed to develop a future forecast analysis of water demands using historical data and projected demands based on planned and possible activities in the catchment area. Including seepage data in the model will improve the accuracy of the model.

4. Future studies of the impacts of climate change on inflow variability must be considered.

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Annexure 1: Hardap Dam storage volumes for Neckartal Dam scenario compared to the reference scenario

Date	Neckartal Dam Mm³	%	Reference Mm³	%	Difference
Oct-16	68.802	23.4	68.802	23.4	0
Nov-16	60.846	20.7	60.846	20.7	0
Dec-16	53.894	18.3	53.894	18.3	0
Jan-17	108.912	37.0	108.912	37.0	0
Feb-17	212.110	72.0	212.110	72.0	0
Mar-17	212.110	72.0	212.110	72.0	0
Apr-17	207.545	70.4	207.545	70.4	0
May-17	200.022	67.9	200.022	67.9	0
Jun-17	194.264	65.9	194.264	65.9	0
Jul-17	184.433	62.6	186.562	63.3	2.129
Aug-17	175.065	59.4	179.322	60.9	4.257
Sep-17	159.787	54.2	170.474	57.9	10.686
Oct-17	155.521	52.8	166.207	56.4	10.686
Nov-17	137.338	46.6	147.244	50.0	9.905
Dec-17	127.084	43.1	135.171	45.9	8.087
Jan-18	115.847	39.3	123.934	42.1	8.087
Feb-18	143.763	48.8	151.850	51.5	8.087
Mar-18	133.649	45.4	140.656	47.7	7.008
Apr-18	137.174	46.6	144.182	48.9	7.008
May-18	131.130	44.5	137.338	46.6	6.208
Jun-18	126.897	43.1	133.105	45.2	6.208
Jul-18	120.123	40.8	126.331	42.9	6.208
Aug-18	114.508	38.9	120.716	41.0	6.208
Sep-18	106.455	36.1	112.663	38.2	6.208
Oct-18	118.418	40.2	124.626	42.3	6.208
Nov-18	107.930	36.6	114.138	38.7	6.208
Dec-18	96.768	32.8	102.976	35.0	6.208
Jan-19	89.176	30.3	95.113	32.3	5.937
Feb-19	80.547	27.3	86.484	29.4	5.937
Mar-19	71.558	24.3	77.496	26.3	5.937
Apr-19	63.387	21.5	68.871	23.4	5.484
May-19	57.610	19.6	63.094	21.4	5.484
Jun-19	53.319	18.1	58.803	20.0	5.484
Jul-19	48.345	16.4	53.829	18.3	5.484
Aug-19	43.279	14.7	48.763	16.6	5.484
Sep-19	35.632	12.1	41.084	13.9	5.452
Oct-19	29.034	9.9	34.351	11.7	5.317
Nov-19	22.546	7.7	27.863	9.5	5.317
Dec-19	15.835	5.4	21.024	7.1	5.189
Jan-20	12.857	4.4	17.797	6.0	4.939

Feb-20	82.653	28.1	87.592	29.7	4.939
Mar-20	131.748	44.7	136.688	46.4	4.939
Apr-20	129.609	44.0	134.548	45.7	4.939
May-20	124.414	42.2	129.353	43.9	4.939
Jun-20	119.619	40.6	124.558	42.3	4.939
Jul-20	114.356	38.8	119.295	40.5	4.939
Aug-20	107.106	36.4	112.045	38.0	4.939
Sep-20	98.928	33.6	103.867	35.3	4.939
Oct-20	89.931	30.5	94.464	32.1	4.533
Nov-20	79.759	27.1	84.292	28.6	4.533
Dec-20	111.776	37.9	116.309	39.5	4.533
Jan-21	212.110	72.0	212.110	72.0	0
Feb-21	212.110	72.0	212.110	72.0	0
Mar-21	208.846	70.9	208.846	70.9	0
Apr-21	202.046	68.6	202.046	68.6	0
May-21	196.298	66.6	196.298	66.6	0
Jun-21	191.304	64.9	191.304	64.9	0
Jul-21	185.267	62.9	185.267	62.9	0
Aug-21	177.189	60.1	177.189	60.1	0
Sep-21	169.958	57.7	169.958	57.7	0