Improving bulk water pump station policies and operations in conditions of uncertain and changing demand

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering (Civil) to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Signed by:

Thendo Mudau

On the **30th** day of **June 2024**

ABSTRACT

South Africa is facing growing and complex changes in water demand; furthermore, acute water scarcity challenges due to drought and degradation of surface water resources threaten its ability to manage the demands. Industrial and power generation sectors in some regions are plagued with water shortages, requiring inter-basin transfer schemes for bulk water transfer to these regions. The complexity in the water demand is further exacerbated when the demand that bulk water transfer systems are designed to manage varies from the demand projections. This has resulted in inefficient pumping operations and unnecessary costs, which are causing great concern as a result of the current water crisis and the increasing cost of electricity in South Africa.

This was an investigation to find out how the increasing energy costs and inefficiencies due to uncertainties in demand could be mitigated in bulk water transfer schemes in South Africa. This was done through determination of the impact demand changes and uncertainties have on bulk water transfer pump stations’ adherence to the operational policy, performance, and costs. Approaches to reduce costs associated with the changes in the demand and improve the operational performance of the pump station were proposed.

The Jericho pump station in the Mpumalanga province, South Africa, was used as a case study to assess the impact demand changes have on the pump station’s operation and control, as well as the operational energy costs. The results of the assessment showed that all these three aspects of the pump station had been negatively affected by the variability in the demand, particularly the energy costs with operational costs due to pumping operations during peak periods contributing to 33% of the estimated energy costs during the study period.

Optimal pump scheduling and a capital investment in the form of a booster pump station to assist the Jericho pumping system and changes to the pump station control policy are proposed, and it is determined that they would ensure a 17.02% saving in annual energy costs. Furthermore, it is shown that operational costs due to pumping operations during peak Time-of-Use (TOU) periods are more than three times the standard and off-peak tariffs, and as such pumping operations during peak periods should be minimized.

This research report showed the significance of optimal pump scheduling and how operational policies of bulk water transfer systems should continuously be reviewed and improved if required, especially with the ever-changing demands.

ACKNOWLEDGEMENTS

I first would like to thank God for the opportunity He granted me on doing this research. I must thank Prof J Ndiritu for his supervision and guidance in this research, and I also express gratitude to the Department of Water and Sanitation for giving me the opportunity to make use of the data from the Jericho pump station and exposing me to operational issues that led me to this research. I would like to thank Jaco Schlebusch for his assistance with regards to operation information and reports from the Jericho Dam office.

I must thank my parents for their continued encouragement and influence. Lastly, to thank my wife, Erica Mudau, I offer appreciation for all her motivation, support, and love.

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Symbols	Description	Unit
$\boldsymbol{P_{Hydraulic}}$	Hydraulic power consumption	kW
$\boldsymbol{\rho}$	Fluid density	kg/m^3
g	Gravitational acceleration	m/s^2
Q	Flow rate	m^3/s
H	Pressure head	m
$\boldsymbol{\eta}$	Pumping efficiency	$\%$
$\boldsymbol{C_{Active}}$	Active energy charges	c/kWh
T	Time	$Seconds$
V	Volume	m^3
P	Performance indicator	-
$\boldsymbol{P_i}$	Electrical power consumed at time *i*	kWh
$\boldsymbol{FV_t}$	Future value of the costs after time *t*	$Rands$
PV	Present valve of cost	$Rands$
r	Average inflation	$\%$
$\boldsymbol{D_t}$	Target demand at time *t*	m^3/s
$\boldsymbol{R_t}$	Maximum allowable release at time *t*	m^3/s
$\boldsymbol{P_t}$	Total pumped flow rate at time *t*	m^3/s
$\boldsymbol{S_t}$	Reservoir storage at time *t*	m^3
K	Reservoir storage capacity	m^3

Chapter 1 : Introduction

1.1 Background

The Constitution of South Africa has several provisions regarding the water and sanitation sector, which when combined with National Water and Sanitation policies, the National Water Act, and the Water Services Act, give the mandate to:

- Provide universal and equitable access to reliable water supply and sanitation services.
- Protect, manage, and develop the nation's water resources in a manner that supports justifiable and ecologically sustainable economic and social development.

South Africa is facing significant challenges in achieving the mandates above and is currently facing a water crisis. Some of the reasons for the water crisis is insufficient water infrastructure maintenance and investment, and the increasing water demands to meet the needs of a rapidly growing, urbanising population, changing lifestyles and economic growth (Department of Water & Sanitation, 2018)

The Department of Water and Sanitation (DWS) has a strategic vision of equitable and sustainable water supply and sanitation service that supports socio-economic growth and development of the well-being of the current and future generations (Department of Water & Sanitation, 2020). DWS uses an integrated approach to managing water resources in South Africa, where water schemes have to comply with the National Water Resource Strategy (NWRS) which places priority on water demand management prior to new infrastructure development (Department of Water & Sanitation, 2015).

DWS makes use of dams, pump stations and bulk pipelines in bulk water transfer schemes. In terms of energy usage worldwide, pumping systems consume 22% of the electrical energy consumed in electric motors, which themselves consume 70% of the electricity consumed (Waide & Brunner, 2011). Pumping of water in the water sector represents the highest portion of energy costs in Water Distribution Systems (WDS) (Sarbu, 2016).

As pumps contribute the most energy usage and considering DWS's mandate of sustainable management of water resources, the efficiency and optimal scheduling of pumps should be a priority in the management of water resources. This is especially because a significant part of the energy consumed by pumps is due to pumps' inefficient operation. Furthermore, although pump performance degrades towards the end of its service life, the rate at which the performance degrades is higher in pumps operating inefficiently (Cardoso, et al., 2017).

There have been several studies on the optimization of pump scheduling and efficient use of pumps in the water sector. However, as the demand that the pumps need to supply changes, the pumps end up being operated not only in an inefficient manner to match the required demand, but also without regard for cost effective operations.

1.2 Aim

Bulk water transfer pump stations are faced with changing demands that they must meet and uncertainties in how the demands will change with time. These have resulted in inefficient operations and additional costs due to operations during peak Time of use (TOU) periods, which are increasingly concerning as a result of the current water crisis in South Africa and the increasing cost of electricity. This study aimed to find out how increasing energy costs and inefficiency due to uncertainties in demand could be mitigated in bulk water transfer schemes.

The aims of this study were:

- Determine the impact demand changes and uncertainties have on bulk water transfer pump stations' adherence to the operational policy, performance, and costs.
- Propose approaches to reduce energy costs associated with the changes in the demand and improve management of existing water resources.

1.3 Scope of the study

The scope of this study only focused on DWS bulk water transfer pumping stations. Furthermore, the pumping stations that utilise Variable speed drives (VSD) for matching the required demand were not considered as a majority of DWS pumping stations do not utilise VSDs.

There are several factors other than demand changes that can affect a pump's operating efficiency, including: delivery valves that are not fully open, obstructions along the pipeline, faulty air valves and pipe leakages. For the purpose of this study, it was assumed that there were no faults or obstructions along the pipelines unless such faults had been reported by the operators. Lastly, DWS bulk water transfer pumping stations usually use centrifugal pumps, consequently, this study only focused on centrifugal pump efficiency dynamics.

1.4 Research Objectives

The objectives of this research were to:

- Determine the level of compliance of bulk water transfer pump stations to the predetermined Control policies specified by the Department of Water and Sanitation bulk water transfer pump stations and find out to what extent they were being followed.
- Determine the effects of changes and uncertainties of demand on the pump station operational and control policies, pump performance and the operational costs.
- Determine operational schedules and propose alternative approaches that minimize operational energy costs and mitigate the effects of demand variations on the operation and control of pump stations, based on the findings of this research.

1.5 Outline of Research Report

The structure of this research report is as follows:

- Chapter 1 provides the background of the problems currently being faced in pump station operation and management by DWS and uses these as the basis for the aim and objectives of this study.
- Chapter 2 consists of a literature review of bulk water pumping schemes, water demand in South Africa, energy costs, pump control policies and optimal scheduling, as well as studies on mitigating the effect of demand changes on pump operations.
- Chapter 3 describes the research strategy and methodology used to meet the objectives as formulated in Chapter 1.
- Chapter 4 presents the data obtained from the case study pump station, the processing of the data and the limitations on the data that was obtained.
- In Chapter 5, the effects of the demand changes are assessed and quantified based on the data from Chapter 4.
- Chapter 6 contains measures that can be implemented to reduce energy costs at the case study pump station.
- Chapter 7 contains the findings and conclusions of the study, and recommendations on pump station operation and design as well as future studies.

Chapter 2 : Management of water demand by bulk water transfer pump stations

In this chapter, the information relating to bulk water pump stations, their operations, and management of varying demands is evaluated. Methods, technologies, and techniques currently used for managing demand in pump stations are explored and assessed as a potential solution to the management of demand by bulk water transfer pump stations. As centrifugal pumps are primarily used in bulk water transfer, their operations, associated costs, and efficiencies are also explored. Lastly, the need for this study based on the unresolved issues is highlighted.

2.1 Water demand in South Africa

2.1.1 Growing population

The water demand in South Africa is increasing at a rapid rate, with a growing population, the water demand in South Africa is expected to grow by a volume of 17.7 billion m^3 in 2030. The water supply is however only projected to amount to 15 billion m^3, which won't be enough to meet the demand (2030 Water Resources Group, 2009).

Figure 2-1 shows the breakdown of water uses in South Africa, with the largest consumer of water being Agriculture with 59%, followed by municipal use in rural and urban areas accounting for 29% (DWAF, 2000).

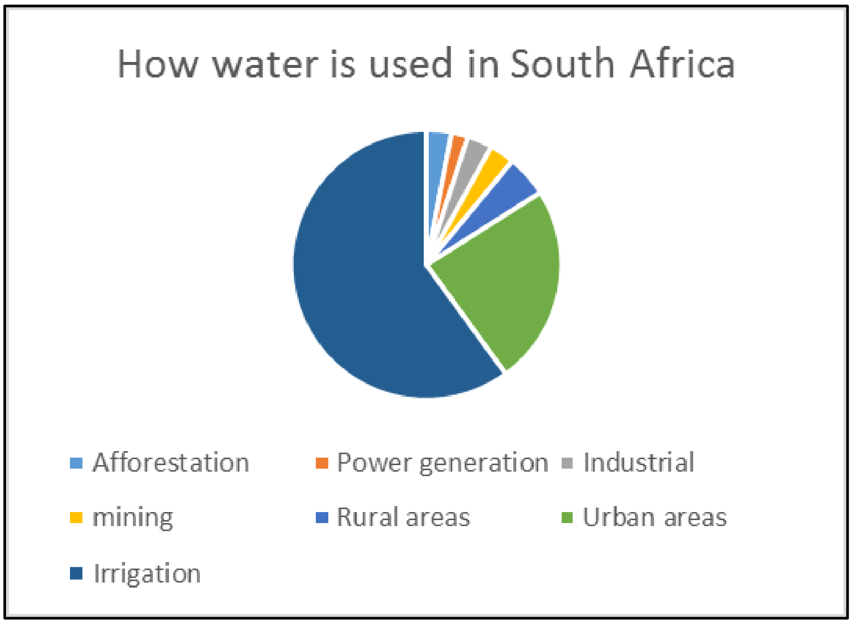


Figure 2-1:Water users in South Africa (Markus, 2018)

The Increasing population leads to increasing demands for food which the Agricultural sector needs to meet. To meet these increasing food demands, the agricultural sector will require substantial water supply and while South Africa faces acute water scarcity challenges due to drought and degradation of surface water resources (Matchaya, et al., 2019), these leave limited options for water supply, one of which is South Africa's dams and the bulk water transfer systems for transporting the water.

2.1.2 Power generation and Industrial uses

Industrial uses and power generation account for 6% and 2% of water users respectively (Pouris & Thopil, 2015), with Eskom being responsible for 1.5 % of South Africa's annual water consumption (Eskom, 2018). Power stations and large industrial areas are located in specific regions of South Africa, with their water requirements managed by the Water management area (WMA) in which they are located. There are 19 WMAs in South Africa, of which 9 have moderate water shortages and 6 have severe water shortages, as shown in Figure 2-2.

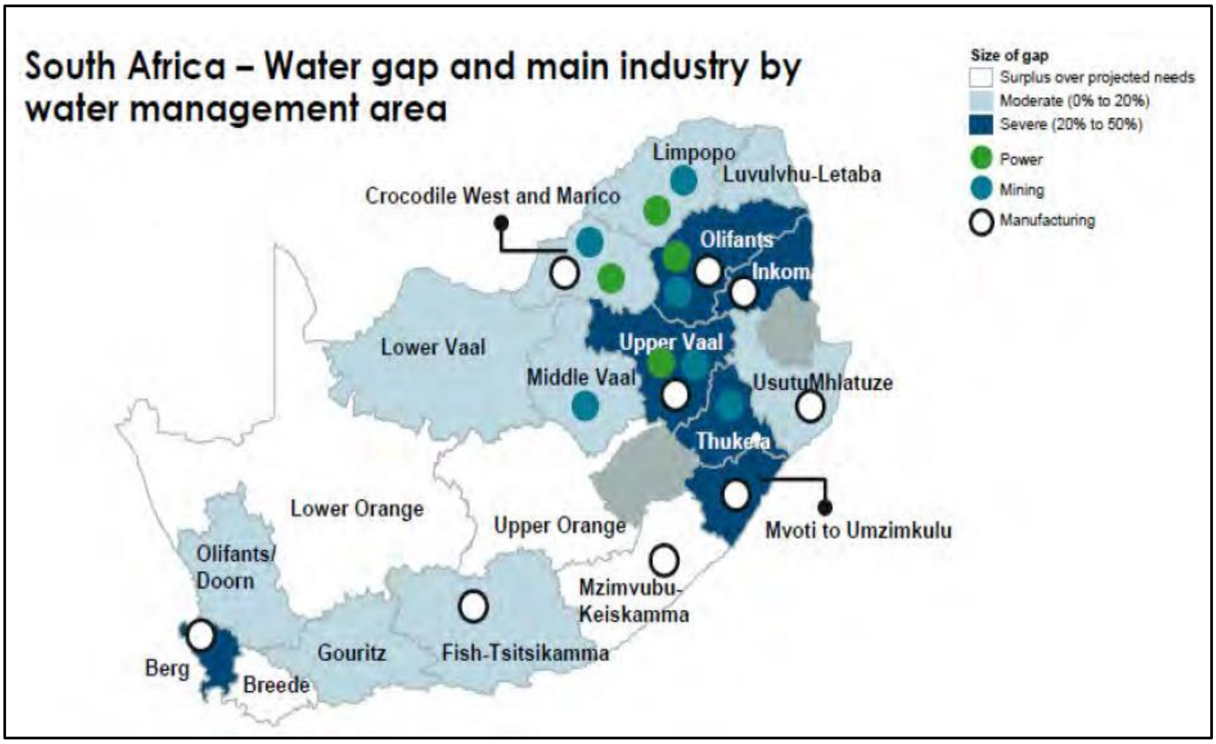


Figure 2-2: Water gaps in South African water management areas (Pouris & Thopil, 2015)

Power generation and industries such as Sasol fall within WMAs with moderate to severe water shortages. Consequently, bulk water transfer systems are required to transport water to these regions. Examples of these in South Africa are the Usutu River Government Water Scheme (GWS) and the Usutu-Vaal GWS which provide water to Eskom power stations and Sasol industries in Secunda respectively.

South Africa is facing difficulties in meeting its electricity demands, and currently relies on periodic power outages across the country to relieve the stresses on primary energy sources and prevent the grid from overloading (Barney, 2023). Additionally, according to the IMF the South African economy is at risk of stagnating due to the negligible growth in the Gross Domestic Product (GDP) and considering that industries such as Sasol contribute a major portion onto the country's GDP, their continued operation is necessary for the country's economy (Africa News, 2023).

These industries rely on bulk water transfer schemes for water supply which are necessary for their operations. As such, management of the bulk water transfer systems to meet the required demand is critical.

2.1.3 Projections of water demand

Each of the 19 WMAs are governed by a Catchment Management Agency (CMA) which uses a catchment management strategy to project and manage the water demand in the WMA. Water demand in influenced by population and developmental trends (DWAF, 2001).

Demographic information on the WMA is used to assess the population trends and determine the projected water demands using population growth rate models which are combined with the demographic trends in rural-urban migration patterns. The demands of existing and planned industrial, commercial, and agricultural developments, combined with population dynamics help each of the CMAs to determine the quantity and distribution of the water demand (DWAF, 2001).

2.2 Bulk water pumping systems

Bulk water transfers are generally described as schemes designed to transport water from water resource regions to other regions or specific locations where water is required (CIWEM, 2023). These transfers occur through mediums such as pipelines, canals, and rivers. In a country like South Africa, where the capital city is over 1000m above sea level and distant from major rivers, complex systems and equipment are required to transport the water (Van Niekerk, 2013).

Pumps are widely used to provide motive force in hydraulic systems, providing the necessary energy to transport water across large distances and elevations. They are widely used in various industries and sectors, such as manufacturing, HVAC, Power stations, water transfer and wastewater treatment, for the transfer of fluids from one location to another (Hydraulic Institute & U.S. Department of Energy, 2006). They require a power source to function through electrical motors powered from electrical grid, generators, or power sources. They consume significantly high amounts of electric energy which leads to considerable operational costs over time, which constitutes approximately 60% of the pump's life cycle cost, whereas maintenance and capital costs constitute 26% and 14% respectively.

Bulk water pumping stations are composed of a single or multiple pumps, along with auxiliary equipment such as motors and valves required to transport a specific volume of water to another location. They are usually located close to reservoirs or dams, from which raw water is pumped to other reservoirs/dams upon which the water is used for either domestic uses, irrigation, industrial uses, or hydro-power production. Figure 2-3 below shows the typical flow of water for domestic uses from raw water dams to clear water reservoirs.

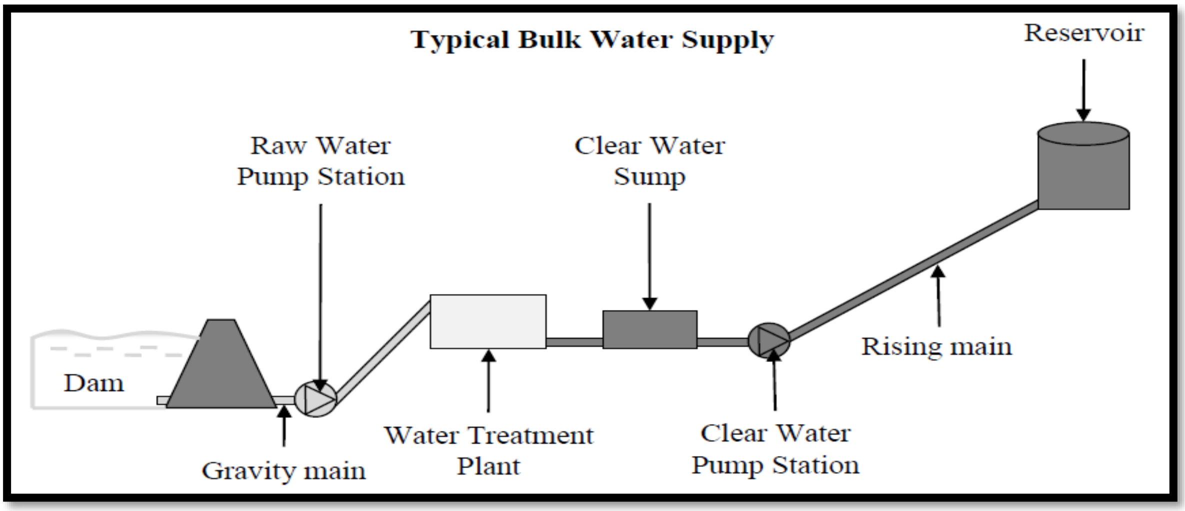


Figure 2-3: Typical bulk water supply (Giliomee, 2016)

2.2.1 Bulk water transfer systems in South Africa

South Africa is classified as a water-scarce country primarily because it has an average annual rainfall of 450 mm, which is considerably less than the global annual average of 860 mm (DWA, 2012). Most of the urban and industrial developments are in water scarce regions, consequently, bulk water transfer is required to transport water to these regions (Van Niekerk, 2013).

Water resources in South Africa are managed on a regional scale in Water Management Areas (WMAs) across the entire country. In the year 2000, the water requirements in 11 of the 19 WMAs exceeded the available water, whereas the water available for the country exceeded the total water requirements for the country (DWA, 2012). In 2012, the Minister of Water Affairs reduced the WMAs from 19 to 9 as strategic intervention on the management of water resources, this are shown in Figure 2-4. Water is not distributed equally across the country and is not always available due to climate variability, furthermore, the water demand is concentrated in certain parts of the country. To ensure the water demand is managed accordingly, bulk water transfer systems for transferring water from regions with surplus water to regions with water deficits are required (DWS, 2015). These transfers are referred to as Inter-basin transfer (IBT).

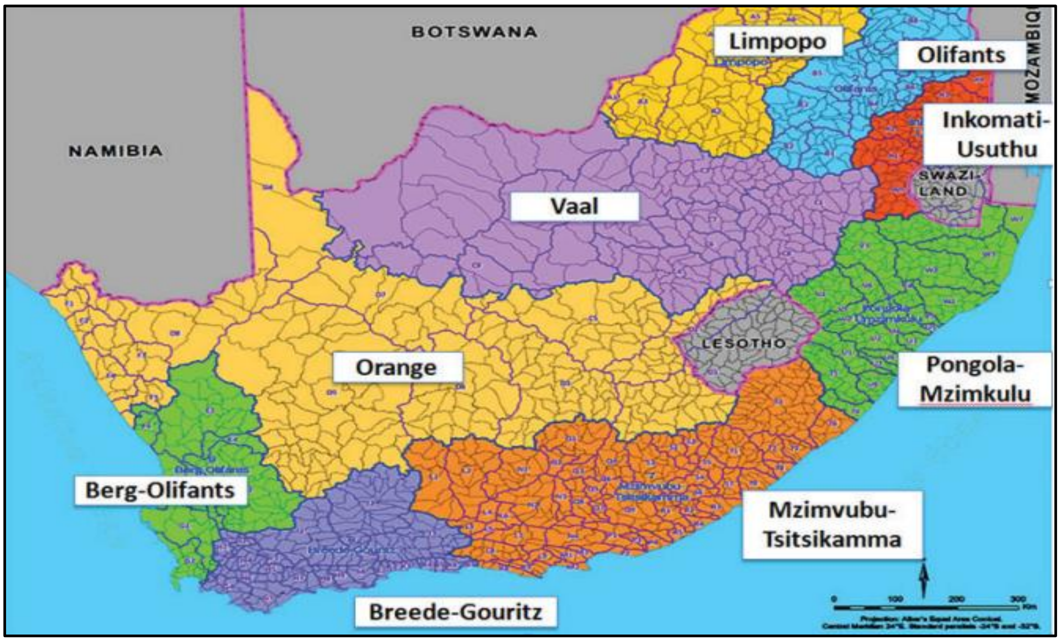


Figure 2-4: Water management areas in South Africa (DWS, 2015)

South Africa has several water schemes responsible for supplying water, some of which transfer water from one basin to another (IBTs). These schemes consist of a network of dams, reservoirs, pump stations, pipelines, and canals.

2.2.2 Inter-basin transfer schemes

In the 1960s, South Africa began constructing more IBTs to meet its growing water demands, and this resulted in sophisticated bulk water infrastructures (WRC, 2013). These include the Usutu-Vaal Government water scheme (GWS) which was built in the early 1980s to supplement the Vaal River system and currently supplies water to SASOL and four ESKOM power stations, namely: Tutuka, Matla, Kriel and Duvha (Scheepers, et al., 2013). Another IBT is the Lesotho highlands water project (LHWP) which supplies to Gauteng's Vaal Water Management Area through transfer from Katse and Mohale dams in located in Lesotho. There are 29 inter-basin and inter-river system transfer schemes in South Africa, which have a combined transfer capacity of 7 billion m^3 / annum (DWS, 2015).

Figure 2-3 illustrates a simplistic view of bulk water transfer systems where water raw water is pumped from the dam to the end user (water treatment plant) without any linkages involved.

However bulk water transfer systems can be more complex, especially in a country like South Africa because of its geographic and climatic characteristics, as well as the concentration of water demand for mining and power generation in certain regions (Van Niekerk & Du Plessis, 2013).

An example of a bulk water transfer system is the Integrated Vaal River System (IVRS), which is depicted in Figure 2-5, and is composed of multiple IBTs. It is considered as the most important bulk water supply system in South Africa, responsible for supplying water to 46% of the country's economy and 33% of the population (DWS, 2023). The IVRS is comprised of various WMAs and GWS, with multiple dams and pump stations involved (Duvenhage, 2015).

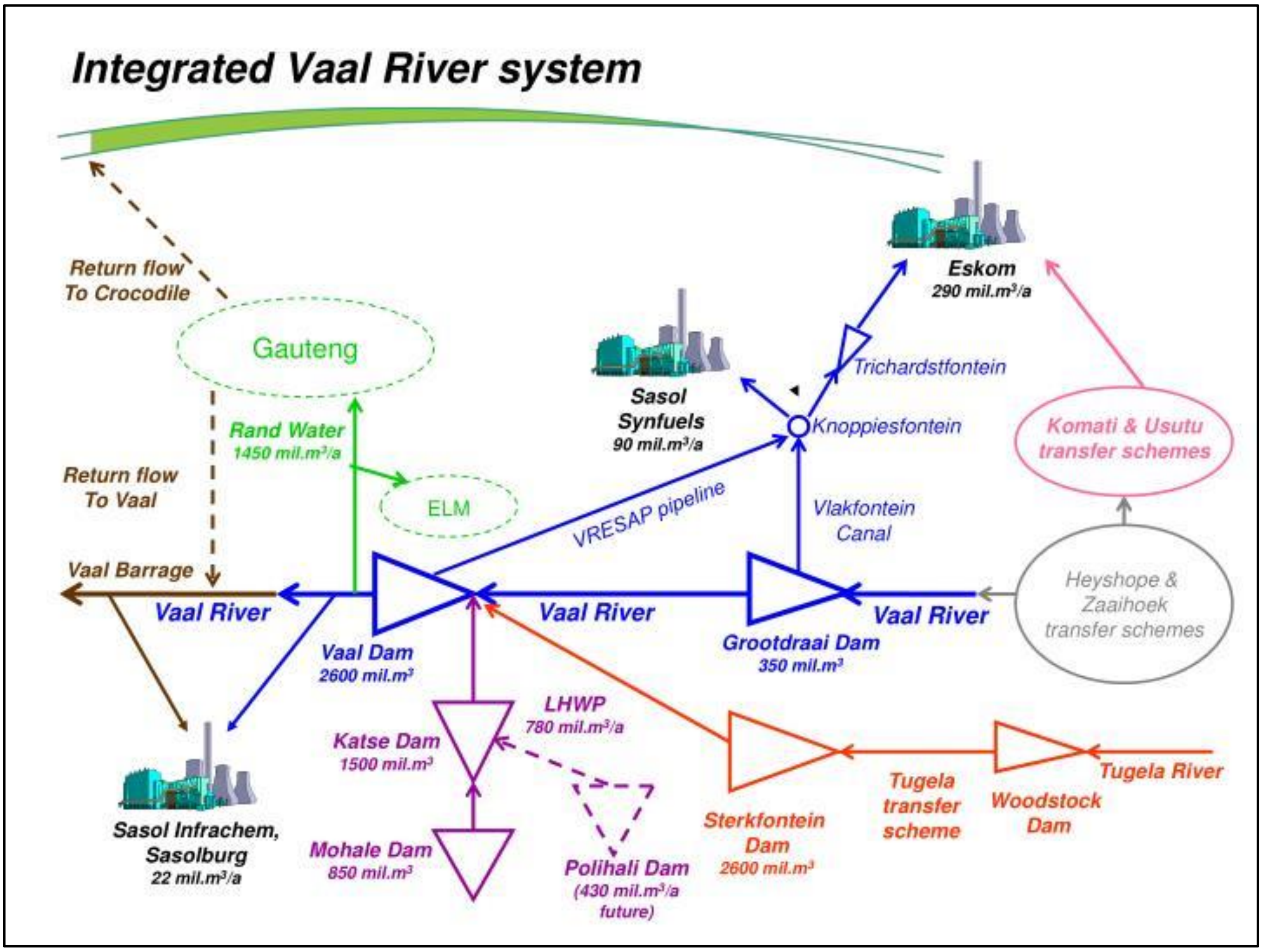


Figure 2-5: Illustration of the Integrated Vaal River System (Mkhize & Meyer, 2011)

A complex bulk water supply system like the IVRS is bound to have competing and evolving demands. Furthermore, it's also bound to have significant energy costs for pumping the water to long distances and different elevations (Van Niekerk & Du Plessis, 2013). Consequently, thorough, and accurate water resource planning is required.

2.3 Pumping station control policies

The Department of Water and Sanitation (DWS) is responsible for the formulation and implementation of the policies governing how water resources and infrastructure should be managed (Scheepers, et al., 2013). According to the Chapter II of the Water Services Act (No.108 of 1997) and the Strategic framework for water services (DWAF, 2003), water services providers must operate waters services effectively and efficiently to be financially viable.

In Bulk water transfer infrastructure, operators should be provided with detailed operation and maintenance documentation for each component of the water supply infrastructure. In a reservoir system, the reservoir or dam in the case of bulk water transfer has its own control policy that dictates what the dam should be used for and the storage volume of the dam at any given point in time. Pumping stations also have a control policy which is used to dictate how many pumps should be run, when and how often they should be run.

To ensure effective operation, the following questions must be answered prior to the pumping station design (Department of Water Affairs and Forestry, 2009):

- The present need as well as future demand.
- Consistency of the water source.
- The possibility of a standby or additional sources.
- The availability and costs of electricity.

Once the above information has been obtained, the pumping station can then be designed. Pumping systems are designed to the smallest of margins where the pump operates in a specific region of flows to ensure the highest possible efficiency during operation in order to save as much electricity as possible. Small divergences from the design can increase the power consumption, which across the lifespan of the pump station equate to significantly additional expenditure.

DWS has a set of guidelines to promote effective pump operation including the ones listed below:

- Delivery and control valves should always be fully open when the pump is in operation. Throttling is not advisable.
- Frequent starting and stopping of the pumps should be avoided as it has cost implications on operations, electricity costs and wear on the pumping equipment.

- Although not always possible, pumping should be minimized as much as possible during demand peak hours and maximized during demand off-peak hours.
- Pump stations should be operated to meet the required demand and should be operated as close to the pump Best Efficiency Point as possible, to ensure efficient operations and limit operational costs.

Determining the optimal pumping schedule for minimizing costs is complex as the following need be considered (Van Zyl, et al., 2004):

- Both electricity tariff and required water demand vary in a typical operating cycle.
- Number of pump switches in an operating cycle must be minimized to avoid excessive pump and motor maintenance costs.
- Minimum water levels must be maintained in reservoirs and all pumping must stop when this level is reached.
- The non-linear nature of the hydraulic behaviour of water distribution systems.

A considerable number of DWS bulk water pumping stations have outdated control policies while others do not even documented control policies leaving the operators without a guideline on how to operate them (Scheepers, et al., 2013). An example of this was documented in a basic condition report by Hatch (2017) on the Jericho pump station located in Mpumalanga, which indicated that there was no documented pump station control policy and that it was highly likely that the control policy had changed in the history of the pump station (Hatch, 2017a).

Improving the operations of an existing pump station is difficult due to factors such as inefficient pumps, inefficient pump combinations and inefficient pump scheduling (Guyer, 2012). All these three aspects can be largely attributed to inadequacies in the pump station’s operational control policy.

2.3.1 Reservoir / Dam levels

As the focus of this study is DWS bulk raw water transfer schemes, the control policy of the pump stations differs from that of portable/clear water pump stations which directly pump water to households and other consumers. The control policy in bulk water pump stations is more affected by the levels in the dams/reservoirs from which the pump stations receive water or the one to which it pumps water to, as is illustrated in Figure 2-6.

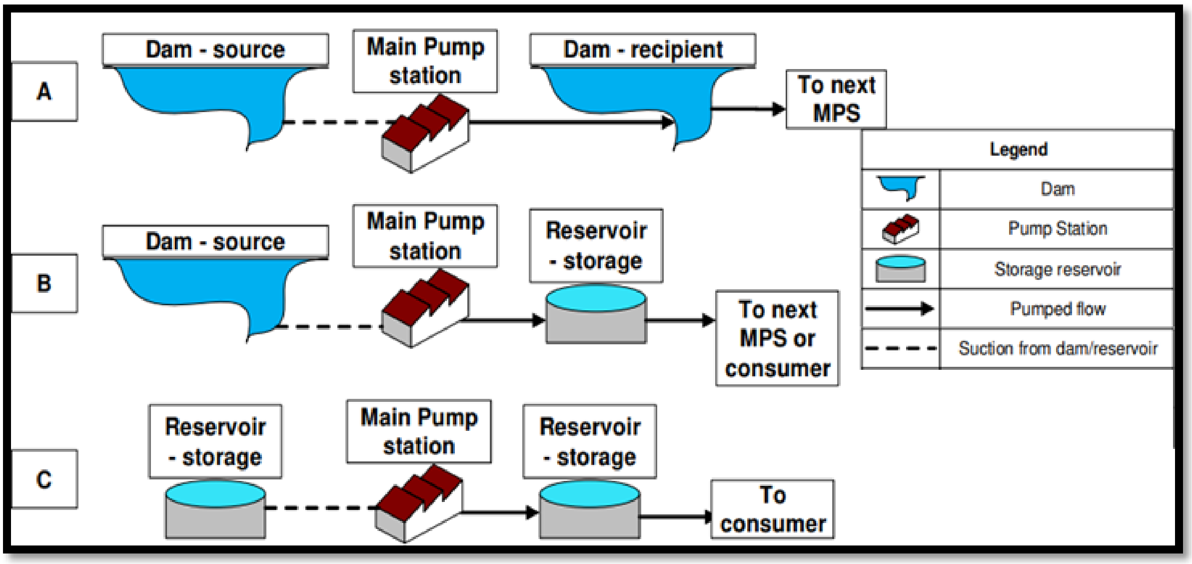


Figure 2-6: Schematic layout of the types of bulk water transfer schemes (Duvenhage, 2015)

The pump stations in the bulk water transfer schemes (A-C) in Figure 2-6 would be operated differently as described below:

- In transfer scheme A, the pump station is operated based on storage rules of the source and recipient dams. An example of this set up is the Heyshope dam – Grootdraai dam transfer, where transfer is recommended from Heyshope to Grootdraai only when Grootdraai is below 75% storage capacity (WRP Consulting Engineers, 2019).
- In transfer scheme B, the pump station is most likely to supply a required daily flow rate to ensure the reservoir does not drop below its specified levels. This flow will depend on the use of the reservoir and fluctuations of the level (Duvenhage, 2015). An example of this set up is the Jericho Dam – Jericho Pump station – Onverwacht reservoir – Eskom Camden power station, where the pump station must deliver a daily flow of 2,8 cubic meters per second (WRP Consulting Engineers, 2019).
- The pump station in transfer scheme C will be operated similar to the one in transfer scheme B, except that both reservoirs will have to remain within the specified levels. An example of this set up is the Khutala reservoir – Khutala pump station – Matla reservoir – Eskom Matla power station.

There have been several studies on pump operational management either through using reservoir storage trigger levels to control the pumps or through use of pump scheduling to control the time of pumping. A study by Ertin, et al. (2001) showed that 12.5% energy savings could be obtained when pump scheduling is used instead of using reservoir storage trigger levels. Ramos et al. (2011) reported that using pump scheduling instead of resevoir storage trigger levels did not directly result in energy savings but that operating costs could be significantly reduced when pumping was done at off-peak electricity periods. Therefore, the consideration and inclusion of power supply tariff structures in pump scheduling can have significant positive results. This was detailed in recent studies in pump scheduling on south african municipality storage systems (Ngancha, et al., 2022) and in the reduction of energy consumption costs in water networks (Abdelazeem & Hossam, 2021).

2.3.2 Electricity tariffs

The total cost of the power consumed over the lifetime of the pump station is many times that of the capital cost of the equipment installed, and as such it is imperative that pump stations minimize power usage in the operations. Amongst the methods that can be used to effectively reduce electrical consumption and energy costs is the careful planning of pumping operations according to the electricity tariffs (Department of Water Affairs and Forestry, 2009).

Electricity tariffs are varied by power suppliers in order to shed load or distribute the load more evenly so as to operate at a high load factor and minimize electricity costs (Illemobade, et al., 2005). This brought about the Time-Of-Use (TOU) periods, which are time blocks based on the volume of electricity demand during high, mid, and low demand periods. They are typically, peak, standard, and off-peak periods, which vary during high demand and low demand seasons (ESKOM, 2021). The TOU charges are based on a higher KWh rate during high demand periods and a lower one during low demand periods, so as to encourage users to manage their loads such that they use electricity during low demand periods (Zhang, et al., 2012).

Aside from TOU tariffs, electricity suppliers also make use of Notified Maximum Demand (NMD) which is the highest averaged demand measured in kVA during an integrated period which is usually 30 minutes within a specific billing period (Department of Water Affairs and Forestry, 2009). Electricity suppliers assign a maximum NMD to consumers and additional charges are only applicable in the event a consumer exceeds the assigned NMD, which will then be in addition to the TOU period tariffs. In South Africa, Eskom, the electricity supplier has specific tariffs for different consumers depending on their classification of the area and the consumers.

Megaflex tariffs are used for DWS pump stations as they are usually in urban areas and have NMDs higher than 1 MV. Figure 2-7 shows the high and low demand TOU periods and based on the figure it can be deduced that to minimize electrical costs, it is better to pump in the evenings (Off peak) that has lowest charge rate.

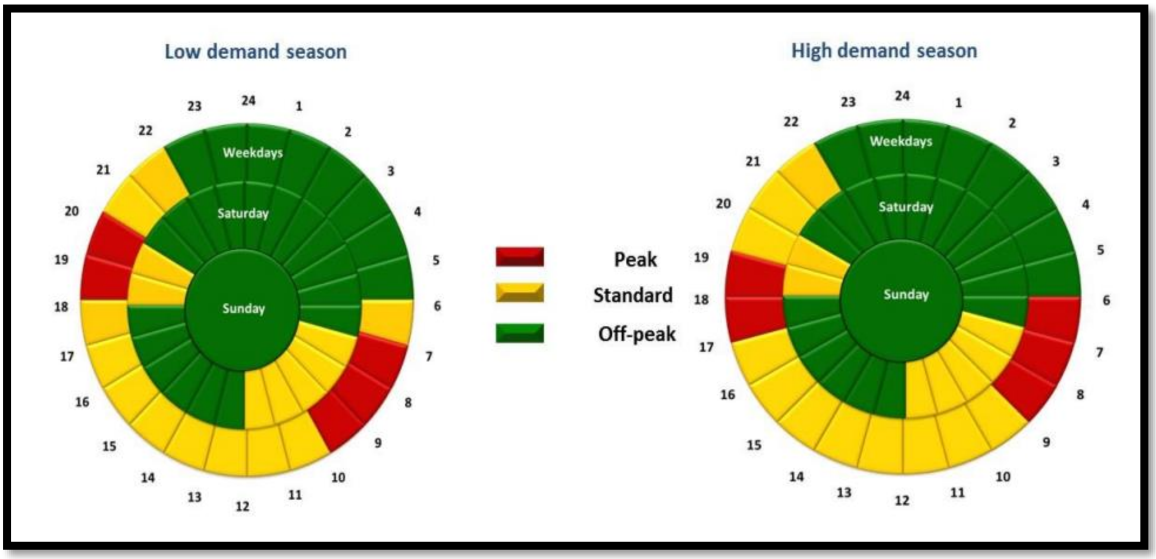


Figure 2-7: Low and High demand TOU periods (Eskom, 2022)

From Figure 2-7 its clear that peak periods are only prevalent during weekdays when the demand for electricity is high, with Saturday having 7 hours of Standard periods and 17 hours of off-peak periods, and the whole of Sunday being off-peak. As such minimization of electrical costs is more significant during weekdays when peak tariffs applicable. Table 2-1 shows the Megaflex tariffs.

Table 2-1: Eskom Megaflex rates per TOU period *(Eskom, 2022)*

	Rates (cents/KWh)	
	High demand season (June to August)	**Low demand season (September to May)**
Peak	517.83	168.9
Standard	156.87	116.27
Off - Peak	85.2	73.76

Scheepers et al. (2013) noted pump control issues in Grootdraai, Grootfontein and Rietfontein pump stations in South Africa where control policies were outdated, and operators switched on pumps based on reservoir levels without considering consider Time-Of-Use (TOU) periods. This resulted in higher than necessary operating costs and could be avoided by shifting the load towards Off-peak and possibly even Standard TOU periods.

2.3.3 Pump switches

Starting and switching off a pump frequently in an operating cycle can lead to unusually high maintenance requirements of the pumping system due to the energizing and de-energizing of the pump motor. This is because the cumulative effects of the energizing and de-energizing a pump motor shortens the life of the motor controller and the pump assembly (Hydraulic Institute & U.S. Department of Energy, 2006).

Several authors have developed criteria on the maximum number of pumps switches permitted. Van Zyl, et al (2004) proposed a maximum of 10 pump switches per day, where as López-Ibáñez, et al (2008) and De Paola, et al (2016) recommended a maximum of 8 pump switches per day.

Frequent pump switches are more prevalent in intermittent pump operations where pumps are often required to fill up tanks that frequently emptied in an operating cycle (Hydraulic Institute & U.S. Department of Energy, 2006). Intermittent operations are not prevalent in DWS bulk water transfer pump stations and according to large motor manufacturers, 1000 starts / stops a year of a motor in a pump station will have no influence on the lifetime of the motor. As such this aspect will not be considered in this study.

2.4 Pump selection

2.4.1 Centrifugal pumps

In South Africa, the Department of Water and Sanitation (DWS) is one of the largest users of pumps for the transfer of raw and clean water, and also in the treatment of wastewater. DWS makes use of various pump types and sizes depending on the specific application and demand required. With regards to the pump type, DWS mainly uses centrifugal pumps as they operate over a wide range of conditions and require minimal maintenance.

Centrifugal pumps operate by adding kinetic energy to the fluid by means of a rotating impeller, and the kinetic energy is converted into pressure as the fluid slows in the diffuser section of the pump. These pumps have a variable flow/pressure relationship, and consequently, a centrifugal pump that is pumping against a high-pressure head generates less flow and one that is pumping against a low-pressure head generates more flow (Hydraulic Institute & U.S. Department of Energy, 2006).

Figure 2-8 shows an example of a centrifugal pump installed at the Nottingham pump station in the Northern Cape province of South Africa.

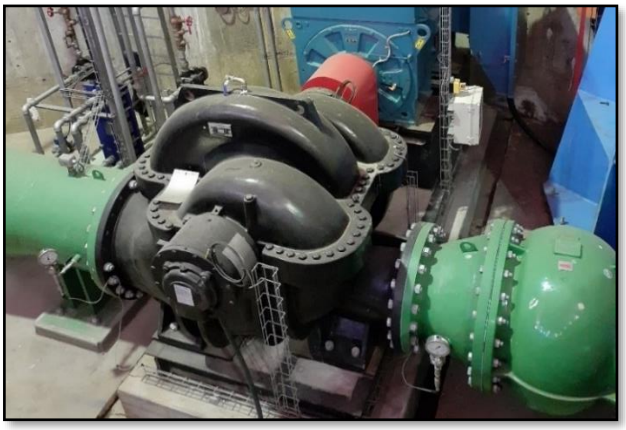


Figure 2-8: Photograph of a centrifugal pump at the DWS Nottingham Pump Station in the Northern Cape

Although centrifugal pumps operate across a broad range of conditions, they will not provide an efficient and satisfactory performance the broad range. In order for the pump to run efficiently, its design characteristics must be suitable for the intended operating conditions, as such to ensure efficient operation the pump should be correctly selected for the intended service and should also be operated for the intended conditions (Larralde & Ocampo, 2010).

Figure 2-9 shows a typical performance curve of a centrifugal pump. The variance flow/pressure relationship can be seen from the ‘pump head’ curve which shows decreasing pressure head as the flow volume increases. The ‘system curve’ represents the system head, which is composed of static and frictional head, that the centrifugal pump has to pump against. The ‘BEP’ point on the pump curve is the Best Efficiency Point where the centrifugal pump is most efficient as shown as the point aligns with the maximum of the ‘efficiency curve’. The ‘Duty’ refers to the conditions (pressure head and flow rate) that the pump will be operated on. It is shown that the separation of the ‘Duty’ point from the ‘BEP’ point results in a drop in efficiency of the pump and an increase in power consumption.

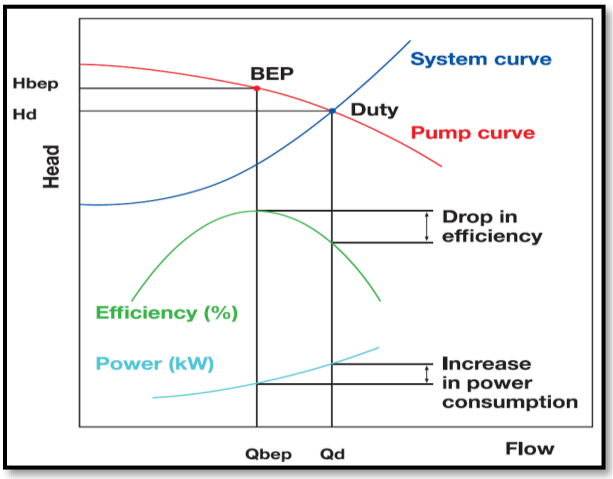


Figure 2-9: Performance curve of a centrifugal pump (Larralde & Ocampo, 2010)

The negative effects of operating a centrifugal pump at a duty point that is far away from the BEP point are more than just a drop in efficiency and increase in power consumption. The pump is designed to operate as close to its BEP point as possible in order to have a long life and ensure stable operation. Operating it far from the BEP can cause unfavourable operational conditions such as noise, vibrations, increases in temperature and shaft loads (Jaminet, 2003).

The adverse effects of operating a centrifugal pump away from the BEP are further illustrated in Figure 2-10. The preferred operating region within which efficient performance can be obtained from the centrifugal pump is shown the Figure 2-10 as between 80% and 110% of the flow rate delivered.

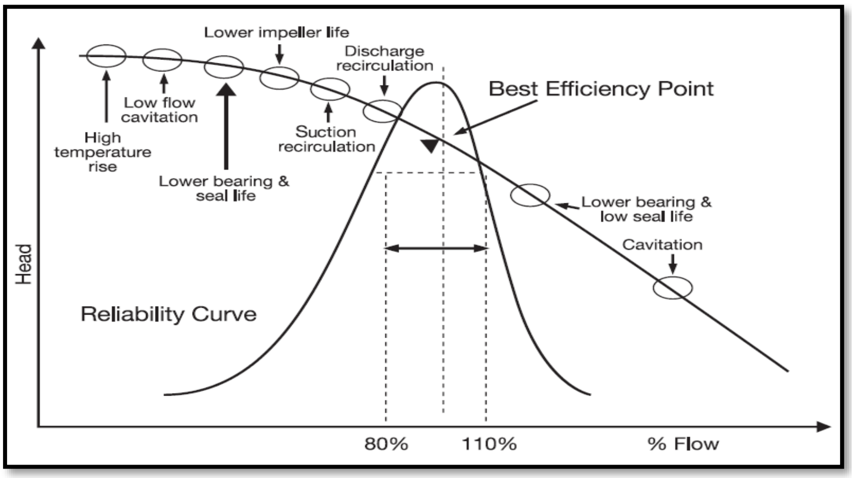


Figure 2-10: Adverse effects of operating far away from BEP (Larralde & Ocampo, 2010)

2.4.2 Oversizing of pumps

The demand that the pump is supposed to meet is prone to changes as a result of factors such as growing populations and consequently increasing demands, and also demand changes from the commercial water users that DWS provides with water such as Eskom power stations and SASOL extraction refineries.

To adapt to the changing demands that the pumps have to operate in, engineers size pumps conservatively to ensure that pumps can operate across a wide range of system demands, by sizing the pump based on the peak demand expected instead of the normal demand where the pump will mostly be operating. This unfortunately results in higher than necessary operating and maintenance costs. In addition, oversized pumps typically require more frequent maintenance than optimally sized pumps. Excessive flow energy increases the wear and tear on system components, resulting in valve damage, piping stress, and excess system operation noise (Hydraulic Institute & U.S. Department of Energy, 2006).

The Hydraulic Institute identified indications that could be attributed to oversized pumps:

- Excessive flow noise, which is indicative of vibrations in the system, which overtime may cause leakages and accelerate bearing and seal wear.
- Highly throttled flow control valves, which result in the pump shifting to a different system curve, consequently, the operating point of the pump moves away from its best efficiency point (BEP) resulting in the pump operating inefficiently.
- Frequent bearing and seal replacements
- Intermittent pump operation, where the pump operates at intervals, starting and stopping instead of continuously operating.

2.5 Pumping costs

The operation of pumps requires a considerable amount of energy, and according to the Hydraulic Institute (2006), 27% of all the energy consumed by motor-driven equipment in manufacturing facilities is used to operate pumps. Considering the amount of energy consumed, it is important that pumps are as efficient as can be during their operation; however, this is not always the case. Many pumping systems operate inefficiently due to issues such as: Improper pump selection, poor system design, lack of maintenance and incorrect operation. According to KSB (2021), one of the major pump suppliers in South Africa, the total costs of a pumping system throughout its service life are as shown in Figure 2-11.

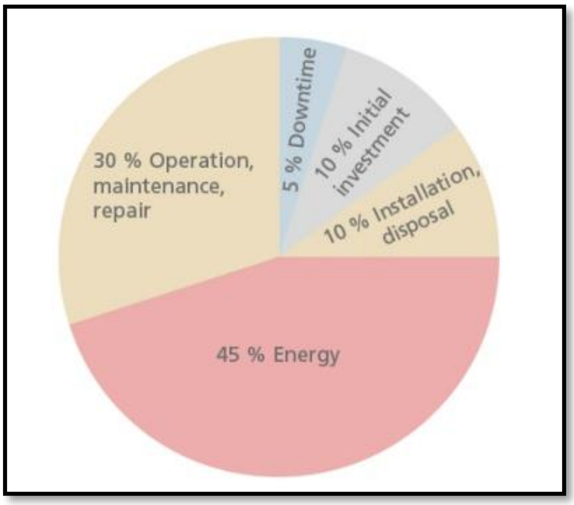


Figure 2-11: Pumping costs throughout pump service life (KSB, 2021)

From the Figure 2-11, it is clear that the costs of energy, operation and maintenance dominate the total costs of pumping systems. Inefficient pump operations result in unnecessary energy costs, additional operating, and maintenance costs, and may also lead to increasing pumping systems breaking down.

2.5.1 Construction costs

The capital costs required to construct a pump station are dependent on the size of mechanical, civil, and electrical items necessary for the operation of the pump stations as well as the pricing of the suppliers and contractors. The civil items include the construction of the pump house where the mechanical and electrical equipment is housed, as well as other civil infrastructure which makes the pump house accessible and labour costs involved.

The mechanical items include the pumps, pipework, valves and lifting equipment, and the electrical items include motors, switchgears, and instrumentation. Additionally, there costs for the installation and commissioning of the mechanical and electrical equipment.

2.5.2 Maintenance costs

The annual maintenance costs of a pump station can be estimated as a percentage of the capital costs for the respective components (mechanical, civil, and electrical). Table 2-2 shows the maintenance cost percentages, which were obtained from internal DWS sources. Inefficient pump operations lead to an increase in the maintenance requirements and therefore additional maintenance costs (Hydraulic Institute & U.S. Department of Energy, 2006).

Table 2-2: DWS approximation of annual maintenance cost percentages

Component of pump station	Percentage of capital cost
Civil	0.25%
Mechanical and Electrical	4%
Pipeline	0.5%

These additional costs can be in the form of additional hours required for maintenance of components; additional costs of replacing components such as seals, gland packing, bearings, and wear rings among other components and also the downtime when the pump station will not be operating at full capacity due to required maintenance.

Quantifying the total maintenance costs will require an audit of a pump station's maintenance records, which becomes problematic as the necessary additional maintenance may not have been done due to lack of funds or personal judgement by the operators (Giliomee, 2016) .

2.5.3 Energy costs

The energy costs of a pump station are due to its power requirements. These include lighting, control panels, monitoring systems and motor required to operate the pumps. In DWS bulk water transfer pump stations, the only objective of the pump station is to transport the water, and consequently the electrical motors required for driving the pumps account for over 90% of the electricity consumed (Giliomee, 2016).

The hydraulic power, which is the power required to drive the pump is dependent on the pressure head, flow rate and efficiency of the pump when operating, this is shown in Equation 2-1 (Douglas, et al., 2011).

$$P_{Hydraulic} = \frac{\rho g Q H}{\eta}$$ ***Equation 2-1***

Where:
ρ - is the density of the fluid
g - is the gravitational acceleration 9,81 m/s^2
Q - is the flow rate of the pump fluid
H - is the pressure head being pumped against
η - is the efficiency of the pump during operation

The motor power required to operate the pump is slightly higher due to the inefficiencies associated with the motor, casing and inlet loses, impeller losses and mechanical loses (Douglas, et al., 2011). The losses and inefficiencies are due to the mechanical and electrical components and not the manner in which the pumps are operated, as such only the hydraulic power will be considered for this study. Equation 2-2 will be used for quantifying the hydraulic energy costs.

$$Hydraulic\ energy\ costs = P_{Hydraulic}\ x\ C_{Active}$$ ***Equation 2-2***

Where:
C_{Active} – Active energy charge is the Megaflex tariffs for the TOU periods during high and low demand seasons.

2.6 Pump station operational efficiencies

The operational efficiency of bulk water transfer pump stations can be linked to the above discussed points, namely: operational capability of pump station under uncertain demands, pump station control policies, proper use of the centrifugal pumps and consideration of the pumping costs, specifically the energy costs. Most studies on optimal pump scheduling assume that the pump configuration is fixed and as such do not consider the number and size of pumps. A water distribution system’s optimal pump operation can only be determined when the pump design and operation are optimized simultaneously. (Jung, et al., 2016).

Zhang et al. (2012) considered the POET (Performance, Operation, Equipment & Technology) framework when improving pump station efficiencies, particularly the operation efficiency component of the framework. The operational efficiency is based on the physical, time and human coordination of a system's components. In pumping systems, the physical coordination is the optimal sizing of the pumps to match the physical system; the time coordination is the optimal scheduling and control of the operation that minimizes costs and improves efficiency; and the human coordination is the influence operators have on the pump stations.

2.6.1 Optimal pump selection and sizing

Selecting the correctly sized pump for the system conditions and operating close to the pump's BEP point is one of the requirements for efficient operations that minimizes operation and maintenance costs. Energy consumption in pumps can be reduced by up to 20% if proper pump selection and sizing is done (Tolvanen, 2007).

One of the major challenges to optimal pump sizing is the changing and uncertain demands that the pumps have to meet, which can be dealt with by including reliability, robustness and using flexible design approaches. However, engineers tend to rather oversize the pumps to compensate for the uncertainties in the demand, which ultimately leads to inefficiencies because the system is designed for peak loads while the normal operating loads are much smaller (Hydraulic Institute & U.S. Department of Energy, 2006).

A common practice in DWS pump stations is the use of multiple pump arrangements. A number of DWS pump stations use parallel pumping combinations using two or three pumps in parallel instead of one pump that is limited to a narrow region of efficient operation making it more susceptible to variations in demands. Parallel combinations offer the system flexibility, redundancy and the ability to cater to changing flow rates efficiently in systems that have to pump across high static heads (Hydraulic Institute & U.S. Department of Energy, 2006).

To ensure the parallel pumps have balanced load sharing, they are usually identical, providing the same flow rate and the pump pressure head. Using disimillar pumps with different flow rates and pressure heads, results in the larger-sized pump dominating the smaller sized pump/s and forcing them to operate inefficiently. Using pumps in parallel shifts the duty point to the right along the system curve, thereby increasing the flow rate. Figure 2-12 illustrates the operation of multiple pumps in parallel, where the duty point shifts to the right with each of a pump in the parallel combination.

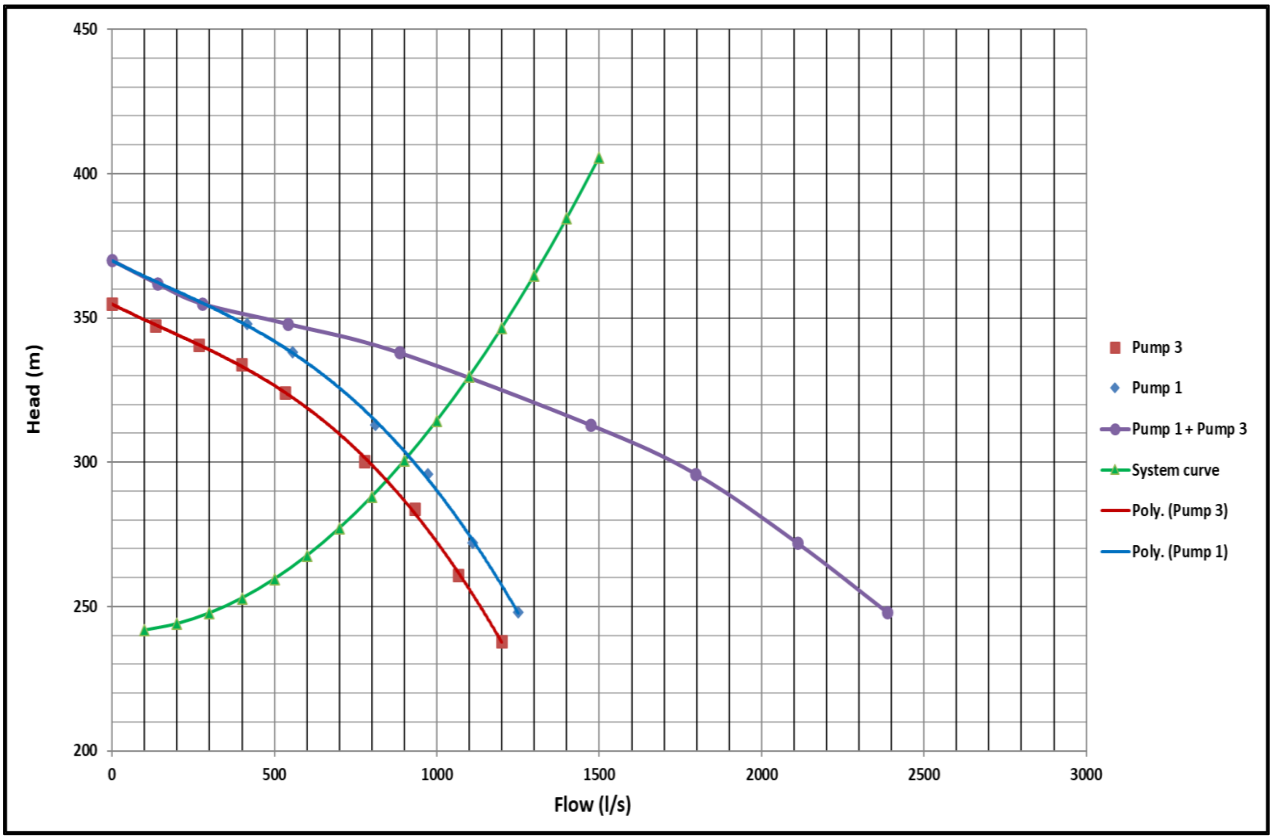


Figure 2-12: Pump curves of the parallel combination of pumps at the DWS Jericho pump station in Mpumalanga (Mudau, 2018)

Another common practice at DWS is the consideration of the deteriorating pipeline and consequently, increased frictional losses which lead to an increased system head that pump has to pump against. From the pump curves on Figure 2-12, it can be seen that as the pressure head increases, the duty point will move towards left resulting in less flow.

To accommodate the eventual increase in pipe friction, DWS engineers select a pump such that the duty point is on the right of the BEP while still within the best efficiency region. As the pipeline deteriorates and the system head increases, the duty point will move left towards the BEP, and later on slightly to the left of the BEP, while still within the best efficiency region. Figure 2-13 illustrates the duty point movement as the pipe roughness increases with time, from the beginning of the pump to its end. In this philosophy, efficient operation of the pump is preferred over the magnitude of the flow transferred. The pump curves illustrated in Figure 2-13 are for KSB WL 400/2 pump installed at the DWS Jericho pump station in the Mpumalanga province.

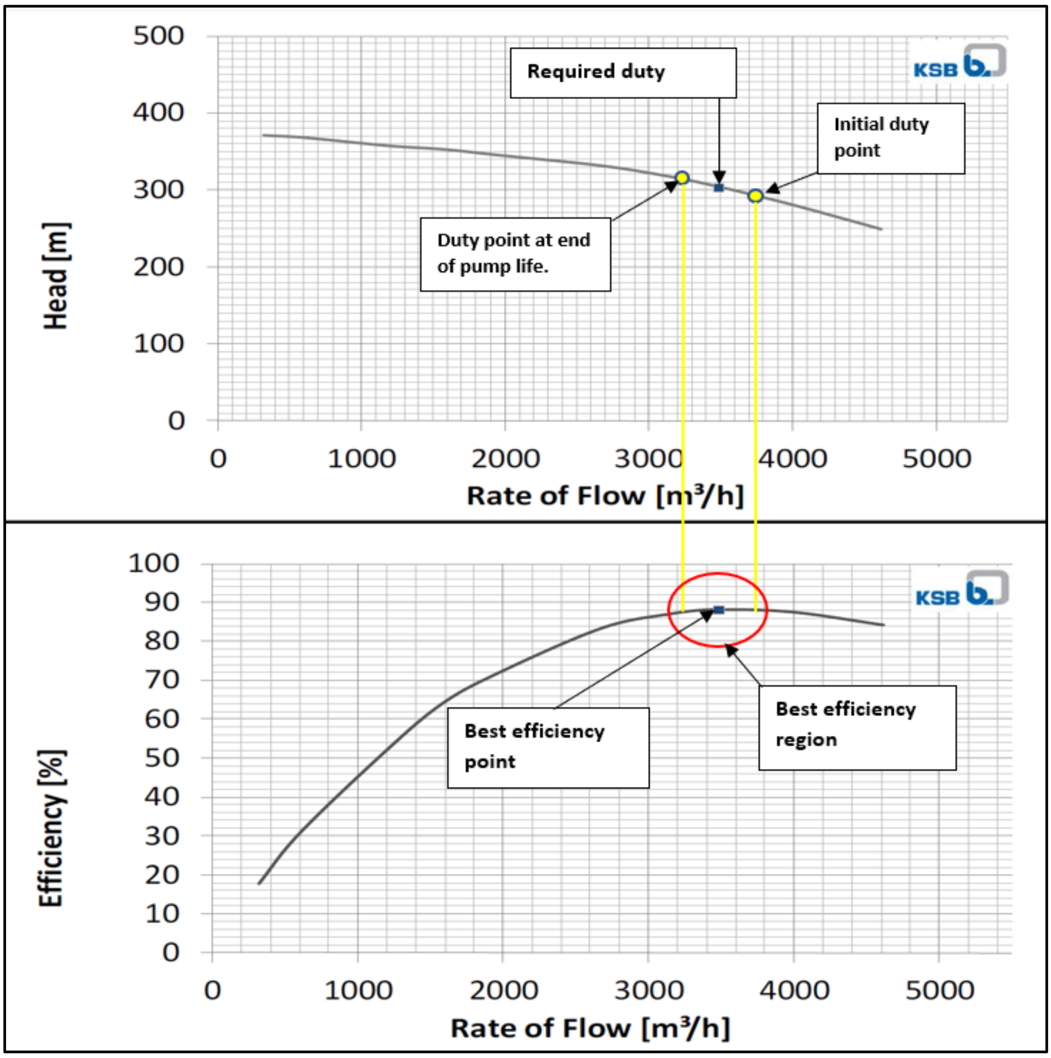


Figure 2-13: KSB WL 400/2 pump curves (KSB Service, 2013)

There are pump selection softwares that have been developed to assist in optimal pump selection, such as KSB SPAIX pump selection software and Sulzer ABSEL water and wastewater pump selection tool. These sofwares use the known operating data to suggest the configuration of the pump system and the most suitable pumps. However, they only select the most suitable pumps for the specified operating demand, and do not take into consideration possible changes in demand.

There are also optimization algorithms that have been developed for optimum pump combinations in water supply systems, that minimizes costs and ensures efficient operation in the defined system conditions. Pulido-Calvo et al. (2006) developed a non-linear programming algorithm for selection of least cost pump combinations to evaluate the pumping system's energy cost of inland intensive fishfarms.

2.6.2 Optimal pump scheduling

Optimal pump scheduling is an optimization problem to determine which pumps to operate and when to operate them in a day to meet the required demand of water at the minimum cost of electricity (Walters & Savic, 1996). Optimal pump schedules for WDSs are developed using heuristic methods where practical methods are used to generate schedules, or mathematical optimization methods that guide the search for optimality where the problem is solved using an objective function (Menke, et al., 2016). The mathematical representation of optimal pump scheduling can be represented as below:

$$Minimize: Pumping\ Cost$$
$$Subject\ to: Energy\ balance\ and\ Mass\ balance$$

Heuristic methods solve the hydraulic problem independently from the optimization using a hydraulic simulation of the system requiring optimization. After which, the optimization is done through evolutionary methods such as Genetic algorithms, Harmony search optimization and particle swarm optimization amongst other methods (Menke, et al., 2016).

Mathematical optimization methods include mathematical approaches such as Dynamic programming and iterative methods. Iterative methods involve breaking down the pump scheduling problem into smaller problems that can be solved through mathematical methods such as linear programming and the graph search method (Menke, et al., 2016). Similarly, Dynamic programming divides the optimization problem into a set of smaller problems, where each is solved until an overall optimum solution is reached through a network of nodes and links (Loucks & van Beek, 2017).

Theoretical studies and results from implementations of optimal pump scheduling in various types of supply systems indicate that 10% of annual energy costs can be saved if proper optimization methods are used (Mackle , et al., 1995). In the past two decades, optimal pump scheduling has been done to optimize the pumping operations under various constraints such as: multiple demand conditions; the number of pump switches during the day; variations in power prices amongst other aspects (Jung, et al., 2016).

In an effort to reduce energy consumption and costs in variable water demand patterns, Georgescu & Georgescu (2015) set an optimal pump station schedule on EPANET based on user-defined patterns of water demand, pressure head, pump speed and energy price, for a water distribution network. Recently, Negishi & Ikegami (2021) developed a robust pump scheduling method in a water distribution system under uncertainty of activating regulation reserves using electric energy prices, regulation reserves, hourly water demand profiles and the electricity consumption of water pumps.

Gencoglu & Merzi (2016) prioritized switching of pumps and usage of electricity tariffs in a multi-objective optimization method for a pump scheduling problem in water supply system. They investigated the optimal combinations for operational reliability, energy consumption and energy costs in the water supply system by trading-off between pump switches and electricity tariffs. Eck et al. (2014) developed an operational technique for generating optimal pump schedules and quantifying the uncertainty in the schedule’s costs in dynamic pricing schemes where the energy price was assumed to fluctuate at 30-minute intervals. Historical data and forecasts on energy prices were used to create electricity price profiles which were classified into scenario classes. Optimal pumping schedules were then developed for each price class.

2.6.3 Improved pump station control

Optimal pump selection and sizing, as well as optimal scheduling are necessary factors for improving the operational efficiency of pump stations. However, what is often forgotten is the human factor. Most bulk water transfer pump stations are operated by individuals, and they not only have to ensure the pump station is being operated according to the operational control policy, but also have to make decisions when faced with demand changes. The demand that the pump station has to meet can either be higher or lower than the normal demand, and pump operators are expected to still supply the specified volume of water. To accommodate demand changes, flow from the pump station can be controlled by four methods, namely: Throttling of valves, Variable Speed Drives (VSDs), On/Off control and the use of Bypass lines. Figure 2-14 shows the illustrations of these four methods.

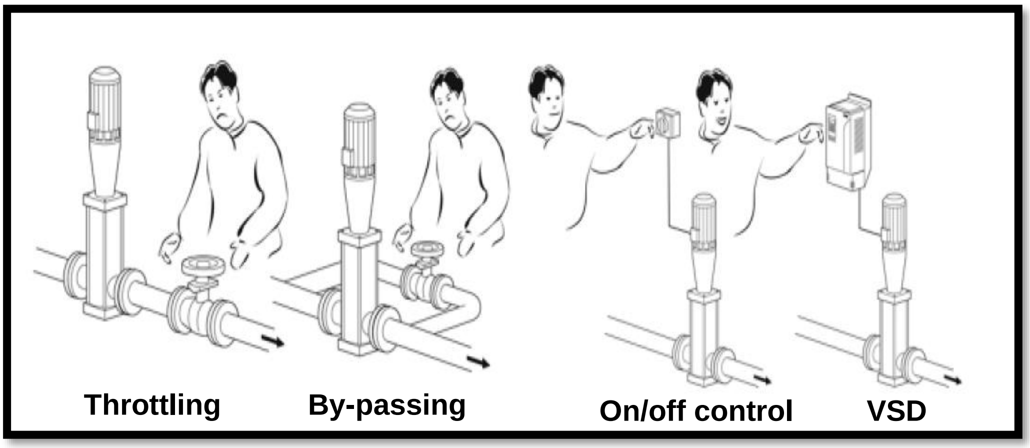


Figure 2-14: Illustrations of pump control methods (ABB, 2006)

Throttling of valves

DWS pump stations are usually fitted with a control valve which is required for throttling the flow. The control valve is used to control the flow rate and pressure in the pipeline when necessary. This is done through the process of throttling, where the control valve reduces the flow area thus reducing the flow rate and dissipating the fluid energy. Throttling is useful when the demand that the pump station has to meet is less than the flow delivered by the pump, therefore, using throttling reduces the flow rate to match the lower demand. Although this method is useful, throttling makes the pumping system less efficient and therefore increases the energy costs (Hydraulic Institute & U.S. Department of Energy, 2006).

Variable Speed Drives (VSDs)

VSDs are usually brought up to manage changing demands and uncertainties. VSDs are used to adjust the pump speed as a means to control the pump flow ensuring that the pump matches the required demand (Hydraulic Institute & U.S. Department of Energy, 2006). In terms of being able to adapt to varying demands, the use of VSDs is the most practical solution, and when energy consumption is concerned, one of the preferred methods of reducing energy consumption is the use of variable speed control of pumps to meet variable demands (NRCS, 2010). VSDs can be used to match demands higher and lower than the pump's rated flow rate, by increasing and reducing the motor speed respectively.

Although they help in effective control of the pumps and reducing operating costs, they are not applicable in all systems. In high static head applications, using VSDs can slow down a pump down to a point below the pump's minimum flow rate where it operates at or near shut-off head conditions, resulting in greater shaft deflections, vibrations, and high bearing loads (Hydraulic Institute & U.S. Department of Energy, 2006).

On/off control

This method involves switching pumps on to deliver the required flow for a period of time, and then switching the pump off. The pumps are operated in steps throughout a day and not pumping for extended periods of time. As discussed earlier in Section **2.5.3** starting and switching off a pump frequently in an operating cycle can shorten the life of the motor controller and the pump assembly and therefore leads to higher maintenance costs if a certain number of switches is exceeded daily (Hydraulic Institute & U.S. Department of Energy, 2006).

Bypass lines

This method is not commonly used and mostly applied to circulation pumps. The pumped flow is reduced by bypassing a portion of to the pump suction, resulting in reduced flow rate and a higher frictional head (ABB, 2006). The process of bypassing the flow however leads to loss of energy and therefore increased costs.

Relative power consumption

Amongst the above four methods, VSDs are the most efficient solution, as demonstrated by ABB (2006) where VSDs were found to use the least amount of energy, with throttling and bypassing consuming the most amounts of energy.

2.7 Changes and sources of uncertainty in water demand

As discussed in Section **2.1**, the population in South Africa is continually growing and consequently increasing the demand for water. This can be planned for based on population growth rate projections, with the success of the plans based on the accuracy of the projections. A problematic issue that is difficult to plan for is the uncertainty in the water demand.

There are various sources of uncertainty, that can affect water demand, these include: new manufacturing and power generation technologies that utilise less water, as well as phasing out of water intensive technologies. While drive the to use less water is inherently good, this results in water infrastructures having to manage a different demand from the one they were designed for. In the case of water pumping stations this can lead to inefficient and costly operations as discussed in Section **2.4.1**.

In the context of South Africa, Eskom coal power stations have primarily been wet cooled with large consumptions of water. However, the new power stations being built utilise new technologies and are dry cooled and the water requirements are one order of magnitude lower than those of wet cooled power plants (Pouris & Thopil, 2015). Consequently, the pump stations will have to manage a lower demand than the one that they were initially designed for.

2.7.1 Methods used in water transfer systems under demand uncertainty.

Over the past years, several methods have been developed for optimal design of Water transfer and distribution systems under varying and uncertain demands. These include Stochastic approaches; Deterministic equivalent formulations; Surrogate approach; Fuzzy logic; Scenario-based approaches and flexible design approaches (Vertommen, et al., 2021).

2.7.1.1 Reliability-based approaches

Stochastic approaches are usually expressed in terms of System Reliability. System reliability is the ability of a network to continue providing service in spite of uncertain system conditions (Goulter, 1995). Its use is very prevalent in WDSs, where it has been used to quantify uncertainties in nodal pressures and water demands. Additionally, reliability-based design models require that the demand conditions be defined either probabilistically or statistically (Jung, et al., 2014).

The Surrogate approach involves the use of a substitute for reliability such as the resilience index, which acts as a measure of reliability of the system (Vertommen, et al., 2021). The resilience index was used by Creaco et al (2015) for water network design under conditions of uncertain future demands it was found that the resilience index was an effective indication of reliability and robustness.

Fuzzy logic techniques have been used in many fields successfully to represent imprecise and vague information and as such can be used to represent uncertainties (Simonovic, 2009). The uncertainty in water demands can be represented using fuzzy logic with membership functions, where the objective of the optimization would be minimization of costs and maximation of reliability (Vertommen, et al., 2021). Pandey, et al. (2020) determined the fuzzy approach to be the most ideal for models where the data was insufficient. The uncertainty in water demand is random and imprecise and can be treated as a fuzzy-random variable.

The above-mentioned reliability-based approaches, namely: Stochastic, Surrogate and Fuzzy logic, all manage uncertainty in water demand by generating random demands according to a probability distribution with a specified mean and variance, ensuring that the system meets a certain level of reliability (Vertommen, et al., 2021). Reliability-based approaches require knowledge of probabilities of the worst-case scenario the system will have to manage. However, these probabilities are usually unknown which makes the determination of the reliability of the system uncertain (Puccini, et al., 2016).

Another approach that is used is the deterministic concept of ‘Robustness’ where known and possible water demands are used to ensure that a system is still capable of operating efficiently under uncertain demands.

2.7.1.2 Robustness-based approach

Robustness can be defined as the ability of a WDS to continue functioning efficiently under different conditions, which in this case refers to all the possible water demands that the system would have to manage. Robustness optimization is a relatively new approach to handle optimization problems affected by uncertainty such as varying water demands (Vertommen, et al., 2021). There is currently a shift away from traditional probability-based optimization towards system performance variation, Robustness, and other Resilience-based performance indicators (Jung, et al., 2019).

The use of redundancy or addition of safety margins to uncertain demands result in a deterministic equivalent formulation (Vertommen, et al., 2021). This approach was used by Babayan et al (2005, 2007) in the least cost design of WDSs under demand uncertainty, where safety margins were added to the demand uncertainty turning the problem into a deterministic optimization problem.

Brown (2010) argues that because WDSs are designed to be reliable based on their historical data which does not apply in the current times due to changes in climate and land use. He recommends design of WDSs such that they are capable of managing the consequences of failure that may occur, which is similar to the definition of Robustness by Vertommen et al (2021) and other authors.

Uncertainty is incorporated differently in Robust optimization, where instead of defining the uncertain parameters such as varying water demands through probability distributions, all possible scenarios of the uncertain parameter are identified and a solution which is feasible and the most optimal for all the different scenarios is determined (Vertommen, et al., 2021).

There does not seem to be a universal quantification for Robustness, which has led to researchers proposing their own robustness indicators based on their own optimization problems. An example of this is Jung et al. (2014) where a new robustness index for Water Distribution System design was proposed, where the system would maintain its function under system disturbances such as uncertain water demands and pipe roughness.

In this approach, the optimal design model minimized the coefficient of variation (COV) of stochastic pressures due to demand and pipe roughness variability. Using the COV, the robustness of the systems was quantified and calculated using Equation 2-3 (Jung, et al., 2019).

$$ROB_i = 1 - \left(\frac{\sigma_P}{P_{avg}}\right)_i$$ ***Equation 2-3***

Where:

ROB_i is the robustness at node *i*, P_{avg} and σ_P are the respective average and standard deviations of stochastic pressure.

Apart from pipes, WDS also consists of pumps and valves which vary their state dynamically during operation. There has been little success in the incorporation of robustness in operation problems involving the optimization of pump and valve operation (Jung, et al., 2019).

One of the studies to develop a robustness indicator for water distribution network pump design and operation was by Jung et al. (2015). The proposed optimization model minimized the pump construction costs and operation costs with constraints on the system robustness, pressure requirement and tank level. The robust-based operation resulted in a more consistent performance throughout the day and involved the use of a large number of small pumps instead of the few large pumps that were recommended by the least-cost solution.

Robust optimization models do not require probability distributions as they make use of scenarios. However, scenario-based optimization models can also be complex and become computationally demanding as the number of scenarios considered increase (Vertommen, et al., 2021). Furthermore, the use of robustness indexes for water distribution systems has a significant drawback in that there isn't a standard acceptable robustness level, and as such extensive analysis must first be done before robustness indexes can be used to support engineering decision making (Jung, et al., 2014).

2.7.1.3 Flexible design approach

The use of long-term planning phased and flexible designs of WDS is considered as one of the better methods to manage uncertain future conditions that may be faced by a WDS (Vertommen, et al., 2021). The traditional approach in WDS design is the use of deterministic future water demand projections which makes the system vulnerable to poor performance when the actual demand differs from the demand projections (Basupi & Kapelan, 2015).

Basupi and Kapelan (2015) evaluated the use of flexible WDS design under uncertain future water demand, with their methodology tested on the New York Tunnels and the Anytown network interventions. In their methodology, they considered demand uncertainty using probability density functions with increasing mean and increasing variance over the planning horizon. A flexible intervention plan which was represented as a decision tree with threshold demand values was used to make decisions along the timeline based on how water demand evolved over time.

Figure 2-15 represents the flexible design in the form of decision tree presented by Basupi and Kapelan (2015).

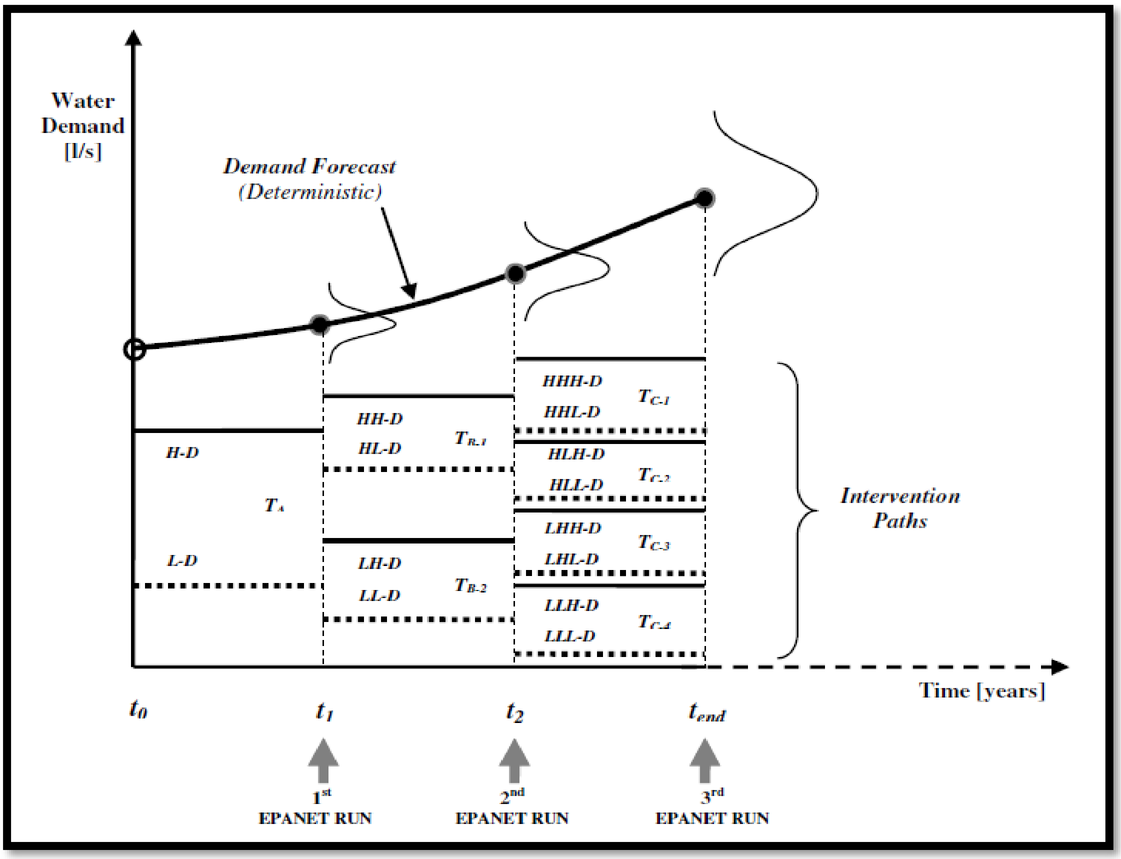


Figure 2-15: Representation of the flexible WDS design (Basupi & Kapelan, 2015)

Each branching of the tree which occurs at the design stages [i.e., t(0), t(1), t(2) and t(end)], represents a set of interventions (e.g., H-D, L-D, HH-D, LL-D etc.) that can be made to the WDS. The interventions are optional with the decision of whether to perform the intervention or not dependent on the demand at that point. The intervention decision is taken based on the demand at the design stages relative to the corresponding predefined threshold demands [e.g., T(A), T(B-1), T(C-1) etc.].

The results from this approach showed that the flexible design approach can have less economic costs and improved hydraulic performance when compared with the traditional precautionary approaches when faced with uncertain future water demand conditions (Basupi & Kapelan, 2015).

2.7.1.4 Other methodologies and technologies

Some of the more recent methodologies have been near real-time pump scheduling that remove the necessity of iterative optimizations of the system where the predicted demand is updated after a set interval such as 1 hour (Jung, et al., 2016). Examples of such methodologies include artificial neural network methods (Wu & Behandish, 2012); and Linearization of the full network (Jung, et al., 2015).

Jung et al. (2015) proposed real-time pump optimization and scheduling using Supervisory Control and Data Acquisition (SCADA) system in pump stations. SCADA systems can be described as a distributed computer system that is used by operators for process monitoring and automation (Finnan, 2002). In the approach, the system data is collected from the SCADA, and the optimal control decisions are determined elsewhere using an optimizer and sent to the pump stations for implementation. This approach requires a pump station with SCADA system and personnel dedicated to optimizing the system and sending optimal decisions.

One of the techniques that has been utilized for hydraulic system modelling through machine learning is Artificial Neural Networks (ANNs). ANNs are computational models composed of several processing elements that receive inputs from a system and using predefined functions deliver outputs (Eshragh, et al., 2015). ANNs are currently used in different fields of engineering and science, and have been used to successfully predict hydraulic information (Negm, et al., 2004)

Wu & Behandish (2012) used the ANN meta modelling technique in conjuction with a GA for optimizing pump operation, where the meta model was used to predict the hydraulic response and the GA was used to optimize the pump operation schedule. The technique was tested real-life pumping system in the UK and was capable of reducing the daily costs and limiting the number of pump switches.

ANN is a very useful tool with regards to pattern recognition and prediction, however, it does have its drawbacks, one of which is the requirement for large amounts of historical data that are not always available for many systems. ANNs have to be trained to learn patterns of data and as such are used to predict the behaviour of similar data sets. When different datasets are used re-training of the ANNs is required or else they could perform poorly, making them inappropriate to dynamic systems where parameters are bound change (Eshragh, et al., 2015).

2.7.2 South African water transfer schemes: Incremental approach

As Inter-basin transfers (IBTs) involve pumping water across varying elevations which involves high energy costs, a robust planning method is required to assess the future costs of water transfer in future IBT projects.

An appraisal method, also called the Incremental approach is a deterministic planning approach that was used on most of the schemes in South Africa and is still in use (Van Niekerk & Du Plessis, 2013). The incremental approach is staged deterministic planning approach, similar to the flexible design approach described in Section **2.7.1.3**. In this approach, increases in water demand beyond the capacity of the existing IBT necessitates a new IBT to manage the excess demand. This approach is illustrated graphically in Figure 2-16 where Y1 is the capacity of the existing IBT, and as the demand exceeds Y1 at time T1, a new IBT constructed to manage the excess demand. The combined capacity of the two IBTs is Y2, which when exceeded by the demand at T2, would then necessitate the construction of a third IBT.

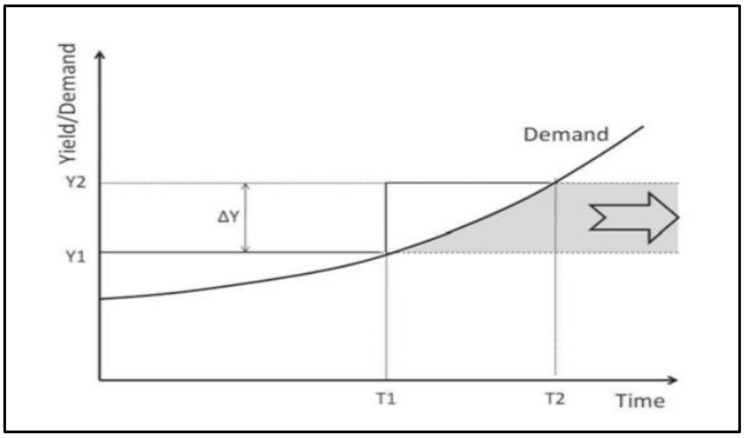


Figure 2-16: Graphical representation if the incremental approach (Van Niekerk, 2013)

Examples of some of the South African water transfer schemes that utilised the incremental approach in planning for future demands, include the Usuthu Vaal River Government Water Scheme which was implemented across three phases for supply to power stations and municipalities and the Tugela-Vaal Scheme which was also implemented in phases from a transfer capacity of 160 to 347 and then 631 m^3/year (Snaddon, et al., 1999).

2.7.3 Case studies on uncertainty in the water demand managed by bulk water transfer pump stations.

2.7.3.1 Usutu-Vaal GWS: Heyshope Dam and pump station

The Usutu-Vaal IBT has been in operation for 24 years and was planned for using the Incremental approach. It consists of the Heyshope dam and a bulk water pump station to pump the water into the Vaal River catchment, upstream of the Grootdraai to the supplement the water resources of the Vaal River system (Van Niekerk, 2013). The assumption by the incremental approach that an increase in demand is beyond the capabilities of the existing system, can have negative consequences on operational and capitals costs if actual transfers are different from the predicted transfers (Van Niekerk, 2013). Figure 2-17 shows the historical and predicted transfers of the 2nd phase of the Usutu Vaal Government Water Scheme.

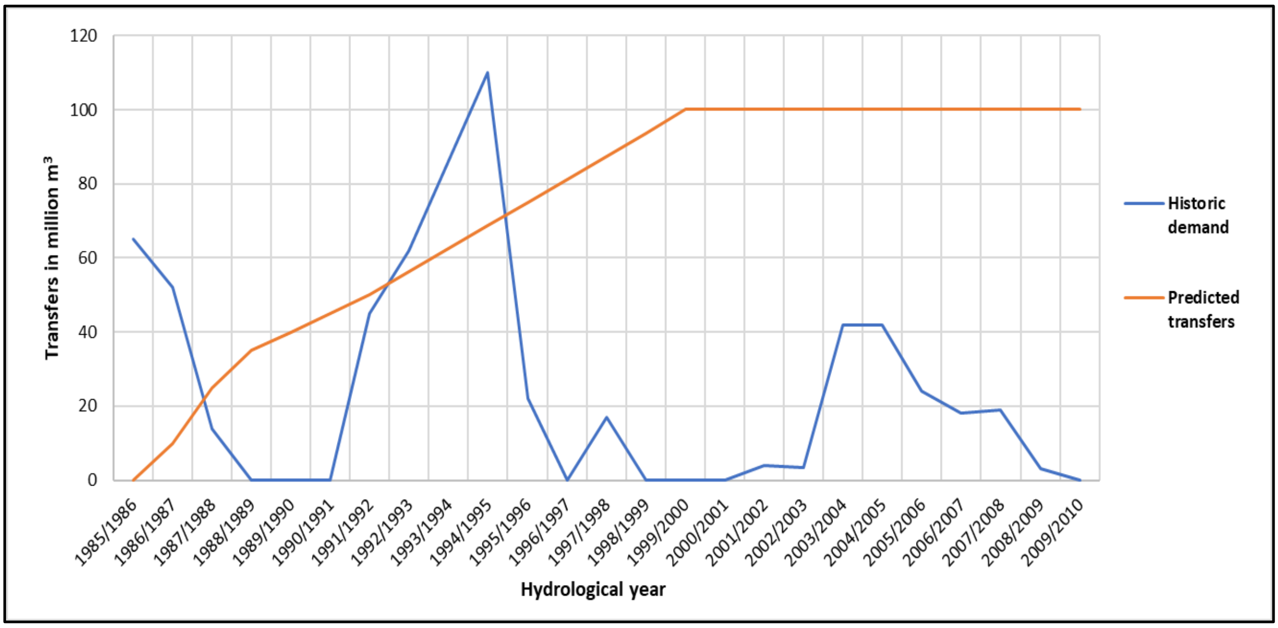


Figure 2-17: Historic vs predicted transfers from Heyshope Dam. Adapted from (Van Niekerk & Du Plessis, 2013)

The original water demand projection was an almost linear growth of the transfer volume that would be capped by the capacity of the pump station around the year 1999. However, the actual transfers were erratic, increasing and decreasing throughout the period between 1985 and 2010. Furthermore, Heyshope dam was recorded to be relatively full during the period according to the records, therefore, it was not an issue of supply constraints (Van Niekerk, 2013). To determine the reasons for the differences between the demand projections and the actual transfers Van Niekerk (2013) evaulated the Annual Operating Analysis (AOA) of the vaal river system for the 24 years of operations, in which DWA's Water Resources Planning Model (WRPM) was used for planning purposes to determine how the dam must be operated.

The evaluation of the AOAs led to the conclusion that the Heyshope dam was operated based on the storage level of the Grootdraai dam where it was transferring water. If Grootdraai dam was below a specified storage capacity X %, then Heyshope could operated to supplement the dam. The specified storage states (X %) throughout the 24 years water were either 75% or 90%. However, the average storage of the Grootdraai dam during normal seasons was mostly above 95% due to the surface runoff into the dam, except during periods of drought in the Vaal River System when the storage in the Grootdraai dam dropped significantly requiring large transfers from Heyshope as shown in the mid 1990s in Figure 2-17 (Van Niekerk & Du Plessis, 2013). The conclusion was that the Heyshope dam transfers were affected primarily because of the hydrological uncertainty associated with the surface runoff from the Grootdraai catchment, resulting in the Heyshope dam only being required during periods of drought (Van Niekerk & Du Plessis, 2013).

2.7.3.2 Slang River GWS: Zaaihoek transfer scheme

The Zaaihoek dam and pumping station were built specifically for supplying water to the Majuba power station and its coal mine (Van Niekerk, 2013). The pump station has a capacity of 3 m^3 /s but generally supplies 0.34 cubic m^3 /s when required to the Majuba power station. This is because the Majuba power station is running under capacity (ORASECOM, 2013). The scheme is also used for surplus supply to the Vaal catchment. Figure 2-18 shows the transfers to the Vaal catchment from 1992 to 2010.

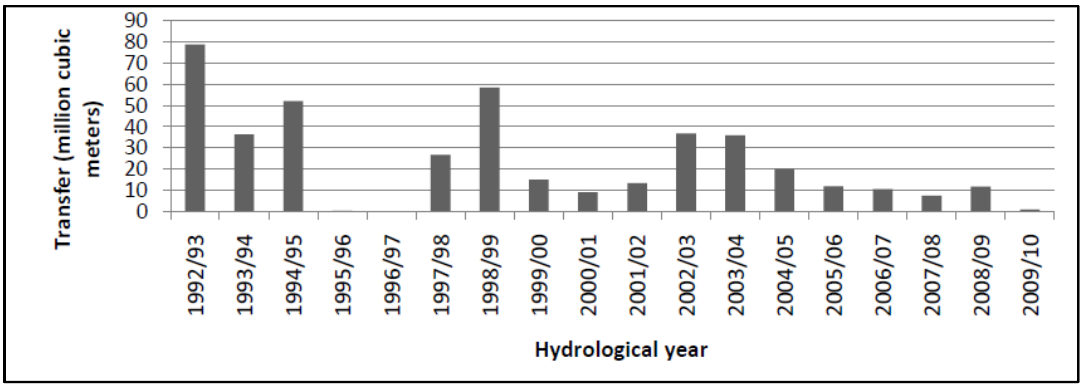


Figure 2-18: Historic transfer volumes from the Slang River GWS to the Vaal catchment (Van Niekerk, 2013)

2.7.3.3 Tagus-Segura inter-basin transfer scheme (Spain)

The scheme was designed to transfer 650 million cubic meters per year from the Tagus River system to the Segura River basin. Water was to be pumped at 33 cubic meters per second against a static head of 262 m (Andreu, et al., 1996). Transfers have varied significantly since 1979, as shown in Figure 2-19.

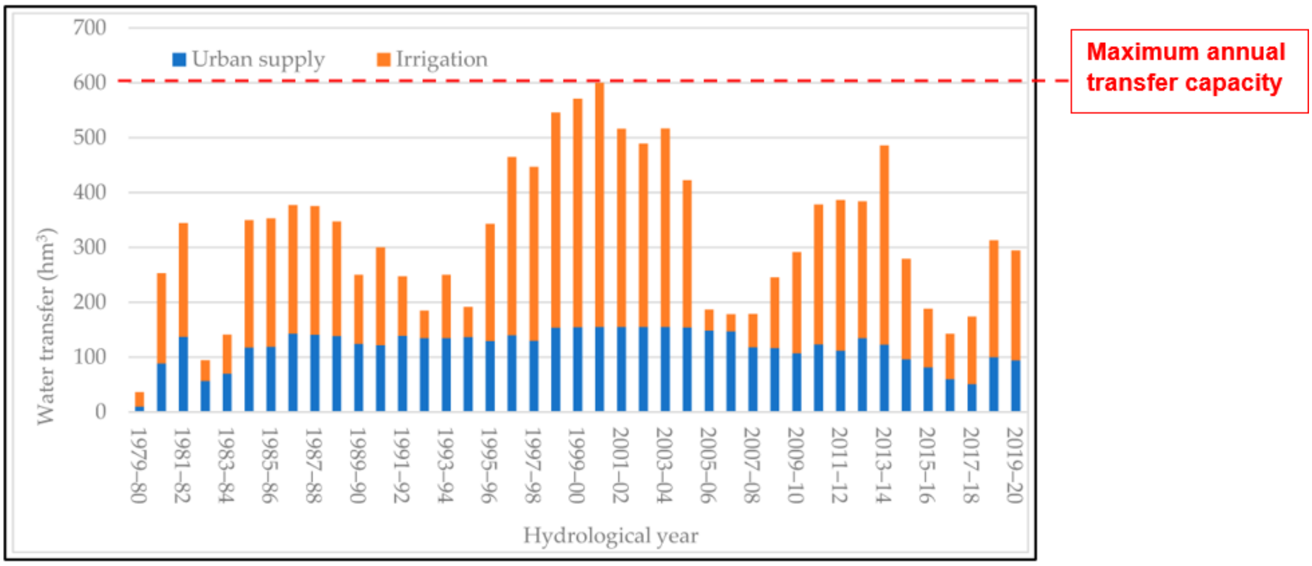


Figure 2-19: Historical transfer volumes of the Tagus-Segura scheme pump station (Garcia-Lopez, et al., 2022)

2.8 Use of computational technologies for pump station operations in South Africa

Over the last few decades, South Africa has been steadily developing and applying innovative technologies to improve the water sector. However, the country is still plagued by challenges such as water losses, aging water infrastructure, energy limitations (Alabi, et al., 2019). Consequently, the South African water industry needs to improve its operation, control, and monitoring systems.

The water sector in SA is yet to integrate the above technologies in the management and operation of the water supply systems, which shows unpreparedness of water digitization. The current workforce in the water industry is used to traditional methods of operating water resource infrastructures (Alabi, et al., 2019). Consequently, technologies such as ANNs and other real-time optimization systems are hardly being utilised in the South African water sector.

Skills in digital technologies are therefore required before smart technologies can be implemented, skills such as data analysis and literacy, digital literacy, mobile technologies, and SCADA training will need to be acquired by operators and other staff.

In the current times, there is a need for management systems and technology that allows for real-time monitoring of water networks and resources. Technologies such as the Internet, Machine Learning, Cloud computing and Advanced data analytic tools can be used for these (Coward, 2018).

Alabi, et al. (2019) informed that the South African water industry was not ready for 4th industrial revolution technologies based on the lack of the following in the water sector:

- Cloud-based real-time water data capturing systems,
- Advanced data analysis
- Applications of machine learning techniques in water processes
- Predictive maintenance of water infrastructure,

2.9 Findings from the Literature review and the rationale for this study

The actual demand that bulk water transfer pump stations have had to manage has varied from the projected demand that the pump stations were initially design for. The changes in the demand, be it an increase or a decrease, result in the operating and control policy of the pump station changing. This becomes a challenge as pumps are designed to operate efficiently in a narrow region and operating them from their best efficiency region results in inefficient pumping operations and increased operating and maintenance costs.

To manage the changing demands and uncertainties that the pumps operate under, pump design engineers and pump station operators face several challenges including the following:

- Sizing pumps to operate across wide range and ensuring that their operations will still be efficient across the wide range.
- Demand changes render the original operating and control policy of the pumps ineffective, and this results in operators: operating the pumps inefficiently, operating without regard to power supply tariffs or not meeting the demand requirement.
- When faced with higher demands, pump operators operate the pump/s for however long is required to supply the required demand without consideration of the power TOU periods. Consequently, these results in higher charges and higher electrical costs.
- When faced with lower demands, pump operators often throttle the pumps to reduce the flow output, however, throttling consumes unnecessary energy and makes the pumping inefficient, leading to higher operating and maintenance costs.

There have been several approaches and methods developed for managing water transfer and distribution systems under demand uncertainty. The design approaches include reliability methods such as stochastic approaches to predict demands; robustness-based approaches to ensure the system can manage the demands; flexible design approaches where the system is continuously evolving to match the demands and recent technologies such as combinations of ANNs or SCADA systems with optimization for real-time pump scheduling. Each of the approaches to managing uncertainty in demand has significant drawbacks particularly when considering their possible implementation in DWS pump station operations, because they are computationally intensive, require expensive equipment and involve technologies that the South African water industry is not yet prepared for.

Several pump control methods for managing different flows are in use, with VSDs being more efficient than throttling, by-passing, and on/off controls. VSDs are often applied to manage pumping with variable water demand but they are not suitable for all pumping systems. In systems with high static heads, slowing the pump speed induces vibrations and causes performance problems (Hydraulic Institute & U.S. Department of Energy, 2006). This is significant for the current study as majority of the Department of Water and Sanitation's bulk water transfer pump stations have to pump against high statics heads as raw water is transferred across large distances with steep inclines along the way.

De Swardt and Barta (2008) noted that there is often a divide between the theoretical designs of pump stations by engineers and the practical operation of these pump stations by local authorities in South Africa. Scheepers et al. (2013) noted pump control issues in Grootdraai, Grootfontein and Rietfontein pump stations where control policies were outdated, and operators did not consider Time-Of-Use (TOU) periods when running the pumps. Reis, et al. (2023) identified research gaps in the development of methods to assist decision-making in the operation of water supply systems, and that optimization techniques on complex water systems were still scarce.

Bulk water transfer systems are necessary for the transfer of water from regions with surplus water to regions with water deficits, furthermore, they are integral for integral industries such as power generation. They are expected to manage changes in the water demand, and although they operate across a wide spectrum and therefore capable of doing so, this can lead to inefficient and costly operations. Technologies such as VSDs, ANNs and other computer intensive methods for managing the demands have been developed. However, in South Africa, they are not yet feasible across the whole country.

This study seeks to quantify the effects of varying and uncertain demands on bulk water transfer systems and seeks methods for minimizing the operational energy costs and mitigating the effects of demand variations on the operation and control of pump stations.

Chapter 3 : Research methodology

3.1 Introduction to methodology

As found in the Literature Review, the operation of pump stations is often not in accordance with the initial optimal control policy, with a major contributing factor to this being changes and uncertainties of the demand that operators need to manage. Prior to searching for solutions to the problem, it is necessary to first quantify the effects of changes and uncertainties on the operations, performance, and costs of operating the pump stations.

This chapter details the methodology followed in the quantification of the effects of the demand changes and uncertainties. The quantification of the effects is in the form of a case study on one of the bulk water transfer pump stations in South Africa. The methodology then describes the approach taken to search for managing the effects of demand changes and uncertainties in attempting to improve system performance while minimizing costs.

The Jericho pump station located in the Mpumalanga province in South Africa was selected for the case study. The pump station was primarily chosen as it has had varying demands and system changes throughout its operational life, the effects of which can be assessed and quantified. This system is described in more detail in Chapter 4.

3.1.1 Methodology

The following were the main steps of the methodology:

i. The hypotheses of this study were detailed.
ii. Data collection procedure was discussed including the resources and equipment that were used.
iii. The method for comparison of the actual transfers and the demand projections of the pump station was described.
iv. The method of quantifying the effect of demand uncertainties and changes on the operation of the pump station was detailed.
v. The method of reducing the operational costs at the pump station was described.

3.2 Hypotheses

This study aimed to assess the impact system changes and demand uncertainties have on the operation and control of pump stations, pump performance and operational costs of DWS bulk water transfer pump stations. Furthermore, approaches to mitigate the adverse impacts of these changes and uncertainties on the operation and control of pump stations are explored.

The following hypotheses were used for this study:

- Demand changes and uncertainties have resulted in pumps being operated inefficiently and not according to TOU structures, resulting in inefficient operations and increased energy costs.
- TOU structures can be used to optimize the operation of the pump stations, and guide operators towards reducing energy costs when faced with varying demands and uncertainty.

3.3 Comparison of actual transfers and projected demands

To assess how well the pump station has managed the required demand, its necessary to compare the projected demands to the actual transfers from the pump station.

The demand targets that the pump station has had to manage throughout its operational life were obtained from the end-user reports of annual water requirements and the Annual Operating Analysis (AOA) reports of the Integrated Vaal River System (IVRS) (DWS, 2016). The AOA reports are undertaken annually by DWS at the end of April each year and take into account the storage level of the dams in the IVRS at the beginning of May. The AOA involves running the Water Resources Planning Model (WRPM) to simulate the behaviour of the IVRS for a stochastic time-series of flows of a 20-year duration. The WRPM considers growth projections, rainfall patterns and future changes to the system and is then used to set the demand targets for the next year taking into consideration the dam storage levels (Department of Water Affairs, 2013).

The actual volumes of water transferred were obtained from DWS hydrological website (DWS - Hydrological Services, 2023), where monthly volumes of water transferred which were recorded by the pump station operators throughout the pump station's operational life are stored.

Simply comparing the projected demands and the actual transfers does not provide the full information required to meet the study objectives, and the actual hydraulic functioning of the system including the associated constraints on water supply are required. The case study pump station, which is described in more detail in Chapter 4, obtains its water from a dam and the effect of the dam's storage levels on the pump station's functioning will be included in the analysis.

The main steps used to assess how well the case study pump station has managed the required demand throughout its operational life were:

1. Data collection of the historical water requirements of the end users and analysis of the fluctuations in the requirements.
2. Data collection of the annual transfers from the case study pump station.
3. Analysis of the data from Step 1 - 2 and determine whether the pump station has consistently met the demand and if not identify the reasons.

Additionally, to assess the pumping operations on weekly basis, the following steps were used:

1. Identify the pumping combinations used and why.
2. Determine the effect of water availability on the weekly transfers.
3. Determine the effect of pump availability on transfers.
4. Daily pumping durations are determined to assess whether TOU periods are considered.

3.4 Quantification of demand changes and uncertainty

3.4.1 Adherence to control policy.

As discussed in Section **2.3**, DWS has a set of guidelines to promote effective operation of the pumps. The operation of the pump station over its life period was assessed in accordance with DWS operation policy. The aspects below were used for this assessment:

i. Efficient operations and matching the target demand.
ii. Throttling of pumps
iii. Frequency of pump starts.
iv. Optimal pump scheduling to minimize power costs by using off-peak hours.

3.4.2 Performance and efficiency of operations

3.4.2.1 Operational performance of the pump station

The Usuthu River Government Water Scheme in which the case study system is located, compiles weekly pump performance reports of the bulk water pump stations, which include how many pumps are available, how many are being run, the duration which they are being run for, the pumping efficiency, the pump's maximum pumping capacity and whether the flow target is being met. Weekly pump performance reports for a period of 12 months from May 2022 to May 2023 were obtained from the Jericho pump station operator to ascertain the pumping performance of the pump station over the period.

A pump's output is dependent on the bulk water transfer system in which it is installed. The system includes other pumps that the pump is meant to operate in conjunction with, the rising main pipeline and the source of the water pumped. During the initial implementation of a pump station, a pump is selected such that it operates at maximum capacity within the system around it.

During a pump station's operational life, changes to the system usually occur in response to a change in the water demand or the water supply source. The chosen case study pump station has undergone several system changes in response to changes in demand, as per the incremental approach used to increase its transfer capacity. The pumps that were initially designed for a particular system, were consequently then operated in a modified system.

The operational performance of the pump stations is defined as the ability to meet the required demand. Constraints in the bulk water transfer system in which the pump station is operating may affect its ability to meet the required demand. Therefore, the operational performance of the pump station was defined using Equation 3-1.

$$P_{operation} = 1 \quad ; if\ V_{Supplied} \geq V_{target}$$ ***Equation 3-1***

$$= 1 \quad ; if\ V_{Supplied} \geq V_{Constraint}\ \ and\ V_{target} > V_{Constraint}$$

$$= \frac{V_{Supplied}}{V_{constraint}} \quad ; if\ V_{target} > V_{Constraint}$$

$$= \frac{V_{Supplied}}{V_{target}} \quad ; if\ V_{target} \leq V_{Constraint}$$

Where:

$V_{Supplied}$ – is the volume of water transferred from the pump station

V_{target} – is the water demand target for the period

$V_{Constraint}$ – is the maximum allowable volume that can be transferred from the dam

3.4.2.2 Efficiency of the pump station

To assess the operational efficiency of the pumping system, the current duty points (flow rate and pressure head) of the pumps were used in conjunction with the pump curves of installed pumps. The flow rate of the pumps was obtained from the operator's weekly pump performance reports, which were recorded from the installed flow meters. The operating efficiency was then compared to the initial efficiency according to the pumping policy, and the efficiency drop was calculated as shown below:

$$\eta_{loss} = \eta_{Optimal} - \eta_{operating}$$ ***Equation 3-2***

Where:

η (optimal) – is the initial efficiency as per the original system

η (operating) – is the efficiency with which the pumps are currently being operated

η (loss) – is the loss in efficiency

3.4.3 Energy costs

This involved the calculation of the additional energy consumption due to the difference between the optimal (control policy) pump efficiency and the pump efficiency with which the pumps were being operated at, and the cost associated with it. The weekly pump performance reports for a period of 12 months from May 2022 to May 2023 were used, as they have actual weekly pumping durations, from which the daily pumping durations could be inferred. A number of assumptions were made in this calculation, namely:

- The losses associated with the motor running the pump were not considered as the motor losses and inefficiencies were due to the mechanical and electrical components and not the manner in which the pumps were operated, furthermore, they were minimal compared to hydraulic losses which are the largest factor in terms of the pumping efficiency (Pumps & System, 2012).
- The hydraulic losses such as impeller losses, leakage losses and casing losses, are usually small compared to the actual hydraulic power and as such were not considered (Pumps & System, 2012).
- Only the active energy charges were considered. Transmission network charges; Ancillary service charges; Service charges and Distribution network charges were not considered as they are fixed monthly charges that are dependent on the maximum voltage of the pump station and not the units of energy consumed.

The operational cost associated with the energy consumption was defined as the cost of the electrical energy consumed during the operation of the pumps in a day. The active electricity charges were defined in Eskom's Megaflex tariffs, including peak (C_{Peak}) at, off-peak ($C_{Off-peak}$) and standard tariffs ($C_{Standard}$).

Equation 3-3 was used for the calculation of the daily pumping electrical energy costs.

$$E = C_{Peak} \sum_{i=0}^{n_p} P^p{}_i + C_{Standard} \sum_{i=0}^{n_s} P^s{}_i + C_{Off-peak} \sum_{i=0}^{n_o} P^o{}_i$$ ***Equation 3-3***

Where:

C_{Peak} - is the peak tariff active energy charge (c/KWh)

$C_{Standard}$ - is the standard tariff active energy charge (c/KWh)
$C_{Off-peak}$ - is the off-peak tariff active energy charge (c/KWh)
${P^p}_i$ - is the electrical energy consumed by the pumps during Peak TOU periods (KWh)
${P^s}_i$ - is the electrical energy consumed by the pumps during Standard TOU periods (KWh)
${P^o}_i$ - is the electrical energy consumed by the pumps during Off-peak TOU periods (KWh)
n_p – total number of hours that the pumps operated during Peak TOU periods (hours)
n_s – total number of hours that the pumps operated during Standard TOU periods (hours)
n_o – total number of hours that the pumps operated during Off-peak TOU period (hours)

3.5 Reducing energy costs at the pump station.

In this Section, measures of reducing the energy consumption at the pump station were explored. Electricity is required to operate the pumps, which contribute the highest in terms of energy costs in the pump station. The cost of electricity varies throughout the day based on the power supplier as discussed in Section 2.3.2**,** with the cost at its highest during peak hours, followed by standard hours.

In order to reduce the energy costs, solutions that maximize pumping operations to off-peak periods and then to standard periods if needed are determined. The capital and operational costs of these solutions were compared to the operational costs of the existing system for the study period to assess the financial viability. Prior to developing solutions, it was first necessary to determine the constraints of the system, in order to assess whether solutions could be implemented. This was done through a mass balance of the system.

To assess whether the solutions reduce the energy costs, the pump station energy costs of solutions and the existing system were compared over the 12-month study period between May 2022 to May 2023, during which the operational data was obtained.

3.5.1 Pump station capital costs

In the year 2005, DWA compiled a spreadsheet that can used for estimating pump station costs, which is shown in Figure 3-1. The estimated costs were based on the costs of DWS pump stations that were constructed.

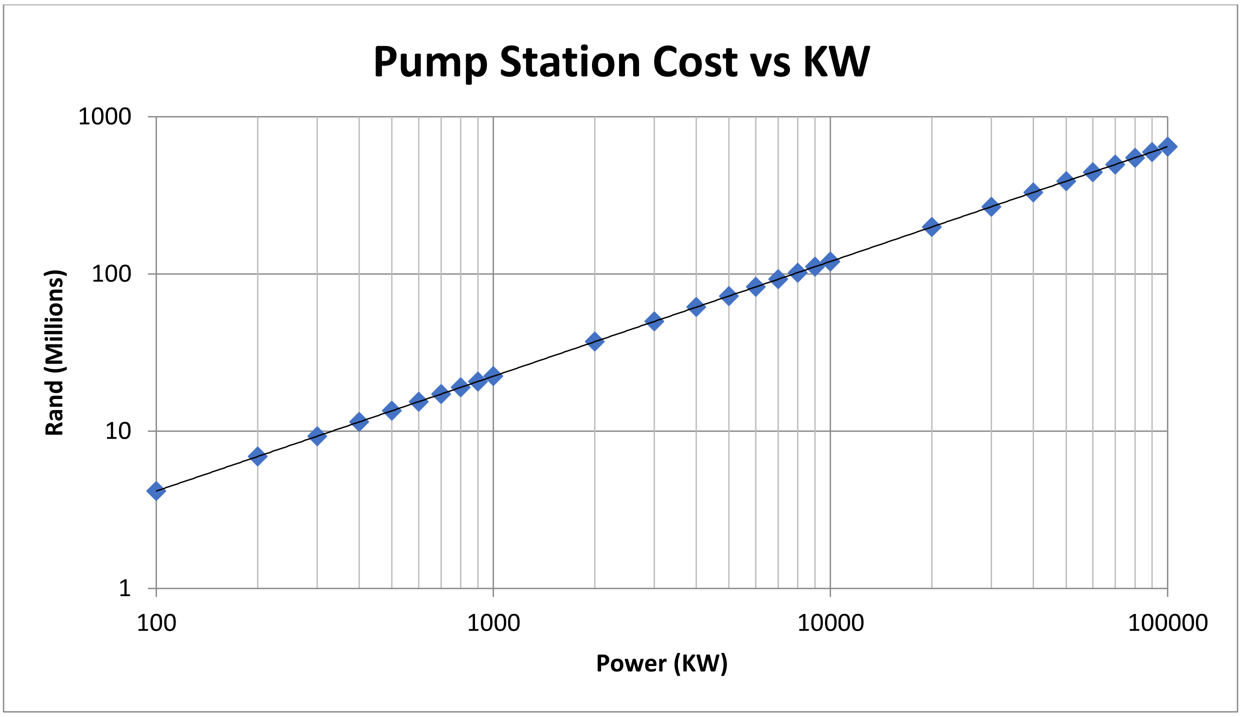


Figure 3-1: Pump station cost vs power capacity for year 2005 (DWA internal sources)

Figure 3-1 was used to estimate the capital cost of constructing a pump station. As the costs from the Figure were for the year 2005, the costs were discounted to account for the inflation rise of prices to the study period as shown in Equation 3-4.

$$FV_t = PV(1+r)^t \qquad \textbf{Equation 3-4}$$

Where:

FV_t - is the present-day value of the capital costs.

PV – represents the capital costs

r – is the average interest rate

t – is the time period

3.5.2 Pump station operational costs

The pump operation costs were based on Equation **3-3** in Section 3.4.3 and to account for the inflation Equation **3-4** was used to obtain the operational costs of the pump station throughout its operational life.

Chapter 4 : Data acquisition, processing, and analysis

In this chapter the collected information on the Jericho pump station is presented. This includes the current control policy of the pump station; flow volumes delivered and the historical demand trends; the Annual Operating Analysis and weekly pumping performance.

The collected data is then analysed to assess the impact demand changes and uncertainties have had on the Jericho pump station's adherence to the control policy, operational performance, and energy costs.

4.1 Case study: Jericho pump station

The Jericho pump station is part of the Usuthu River Government Water scheme and supplies water from the Jericho dam via the Kliphoek booster pump station primarily to Eskom coal-powered stations, namely: Camden power station and when required to Kriel, Matla and Kendal power stations, and the DWS 3rd party users which are Davel and Ermelo municipalities. The pump station also transfers water to the Nooitgedacht Dam to support the Komati scheme sub-system power stations.

Figure 4-1 shows the locations of the Jericho dam and pump station, Kliphoek pump station, Onverwacht reservoirs and the end users of the pumped water. Figures 4-2 and 4-3 are of the pump station building and dam, as well as the pumping equipment, to give the reader a visual understanding of the pump station.

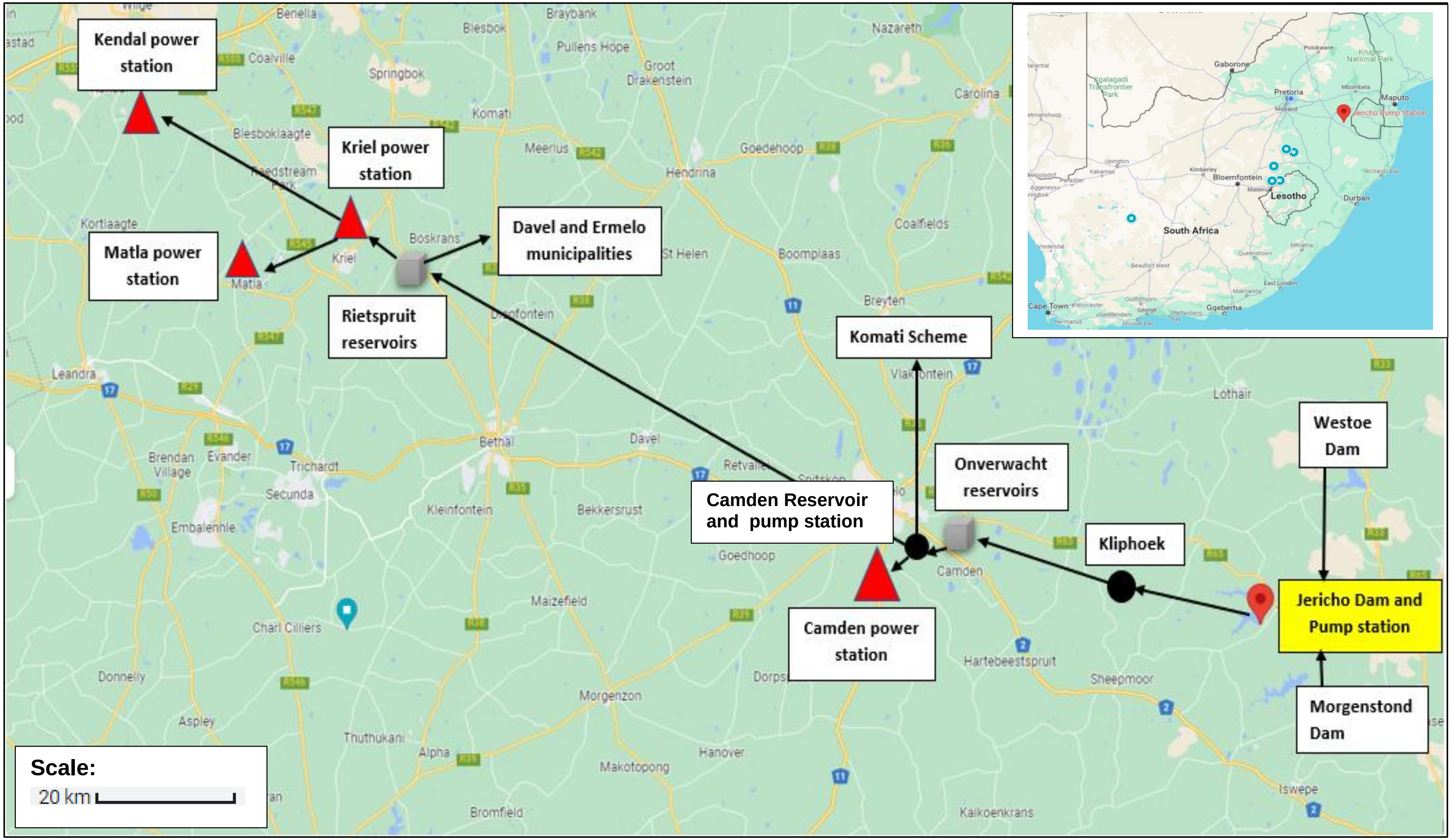


Figure 4-1: Location of the Jericho pump station

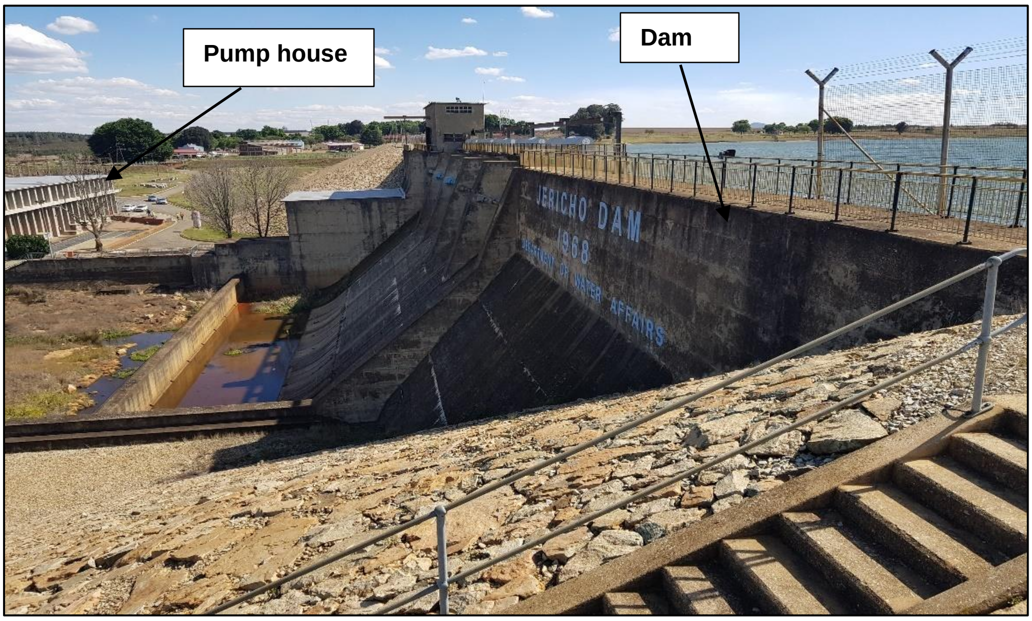


Figure 4-2: Photograph of the Jericho pump station and Jericho dam.

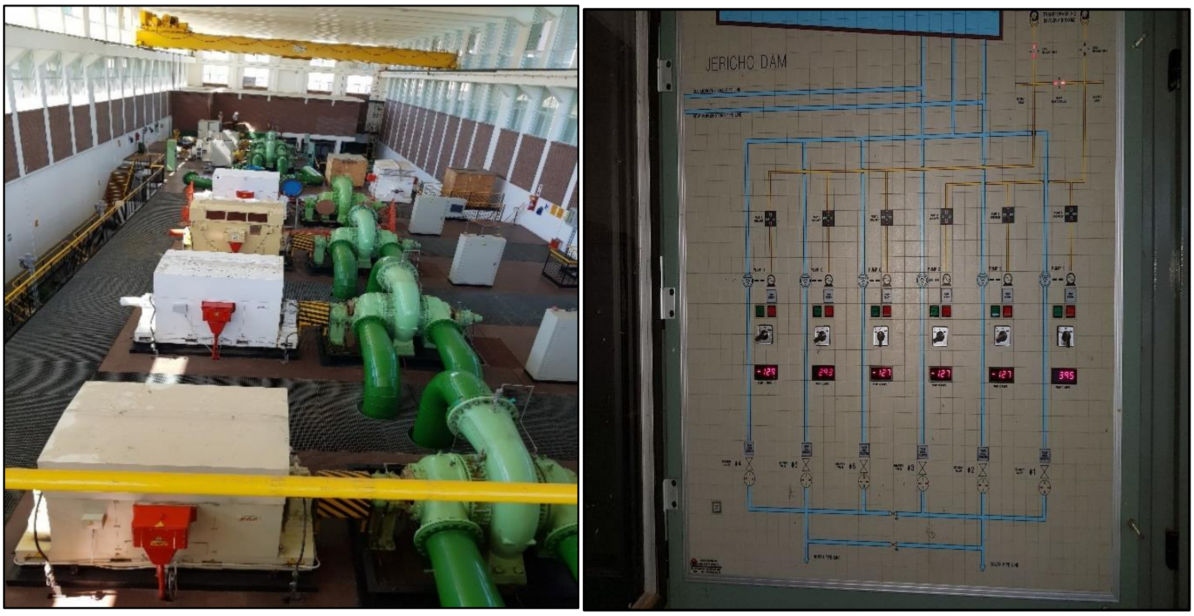


Figure 4-3: Photographs of Jericho pump station equipment.

The pump station was constructed in phases:

1. Between 1964 and 1966 the pump station was constructed with a single rising main pumping into two Onverwacht reservoirs, two pumps, one duty and one stand-by.
2. Between 1969 and 1971, a second rising main was added along with a third reservoir at Onverwacht to increase the amount of water transfer. Two additional pumps were added, increasing the number pumps to four.
3. Once more to increase water transfer capacity, the Kliphoek booster pump station was constructed, and the Jericho pump station enlarged from four pumps to six in 1981.

The layout of the entire pumping system from the Jericho Dam through the Jericho and Kliphoek pump stations to the Onverwacht reservoirs and then to the end users as illustrated in Appendix B.

The pump station currently has six centrifugal pumps installed, with three pumps dedicated to each of the two pipelines. Both sets of the three pumps are in parallel combination. In 1981 after the completion of all the phases the pump station had a design capacity of 3540 l/s. This was to be achieved by operating 4 pumps at Jericho pump station in conjunction with 2 pumps at Kliphoek pump station.

Figure 4-4 shows the layout of the Jericho pump station, where it's shown that Pump 1 and 2 both pump into the South line, and Pump 4 and 5 both pump into the north line. Pumps 3 and 6 are standby pumps and can be used in either pipeline. All the pumps have a duty of 972 l/s at 300m. Pumps 1, 2, 4 and 5 have an installed power rating of 3455 kW and Pumps 3 and 6 have an installed power rating of 3650 kW (KSB Service, 2013).

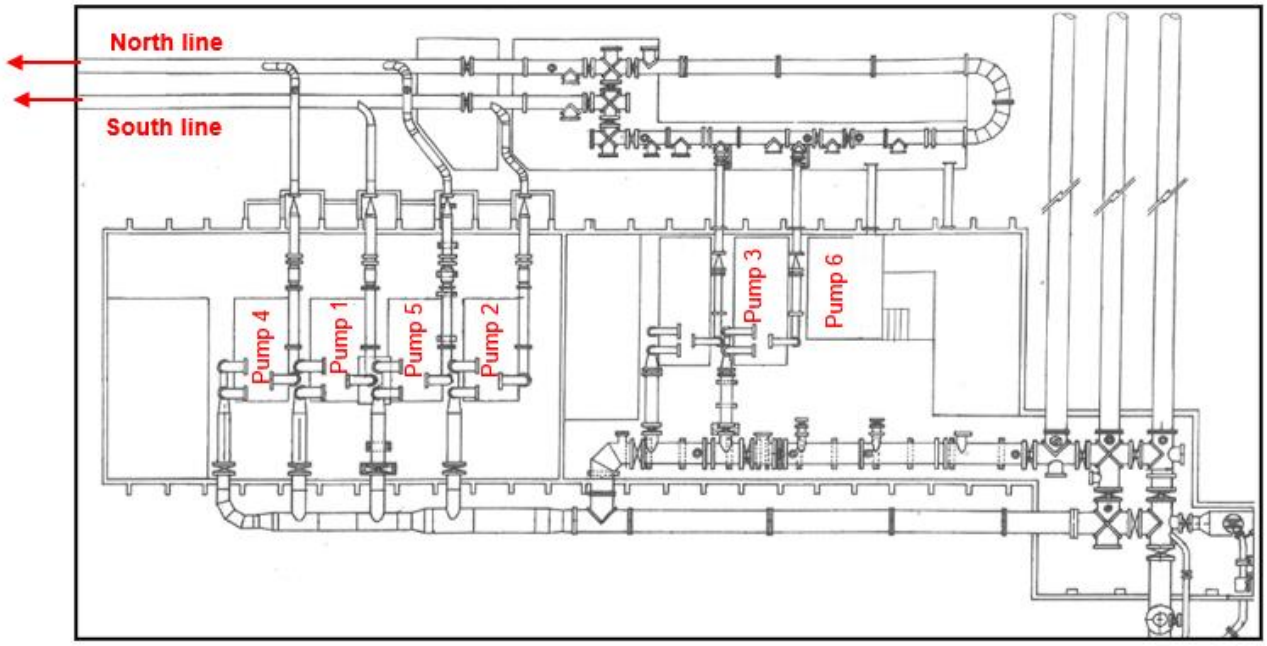


Figure 4-4: Illustration of the Jericho pump station layout (Niebuhr, 2015)

Figure 4-5 shows the layout of the Kliphoek booster pump station where it's shown that Pumps 1 and 2 both pump in the South line with one pump being the duty pump and the other being the standby pump. These pumps operate in conjunction with Pumps 1 and 2 at the Jericho pump station which also pump water into the South line. Pumps 3 and 4 pump into the North line in a similar set-up. These pumps operate in conjunction with Pumps 4 and 5 at the Jericho pump station which also pump water into the North line.

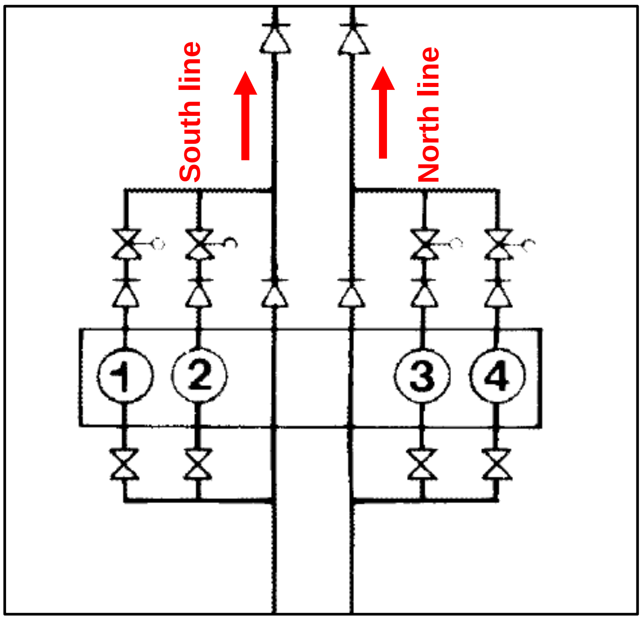


Figure 4-5:Illustration of the Kliphoek pump station layout (Department of Water Affairs, 1979)

For any pump at Kliphoek to operate, two pumps at Jericho should be pumping on the same line to ensure there is sufficient backpressure. Pumps 1 - 3 at the Jericho pump station can only be operated on the south pipeline in conjunction with Pumps 1 and 2 at the Kliphoek pump station. Pumps 4 - 6 at the Jericho pump station can only be operated on the north pipeline in conjunction with Pumps 3 and 4 at the Kliphoek pump station.

There is an option of bypassing the Kliphoek pump station as shown in the Figure 4-5, whereby the Jericho pump station supplies water without pumping at the Kliphoek pump station.

4.1.1 Pump station data

The researcher had reasonable access to pump stations and data records for several DWS pump stations. DWS keeps records of the daily and monthly pumped flow rates from the pump stations. The Jericho operators also keep records of pump performance, condition and pumping duration. The following information was obtained using DWS data records and reports, and site visits.

- The pump station control policy if available and over what periods it has been followed.
- The daily demand that the pump station is required to supply and its variation since the commissioning of the pump station.
- The number of hours of pump operation in a day, the variation of this since the across different periods and the periods over which the pumps are throttled during operation.

- The flow rates that the pumping system has been delivering over the operational life of the pump station.
- If available, the power consumption and its variation over different periods in the pumping station.
- Pump curves and original duty point of the pumps and any variations to these during the operational life of the pump station.

4.2 Current and historical pump station control policies

There is no control policy on the amount of water pumped in relation to the water level in the Jericho Dam. There are however inter-reservoir operating rules depicted in Figure 4.6, that are used to ensure there is always sufficient water at Jericho Dam. This is between Jericho Dam, and Westoe and Morgenstond dams, which both supply water to the Jericho Dam, using a gravity line and a pump station respectively.

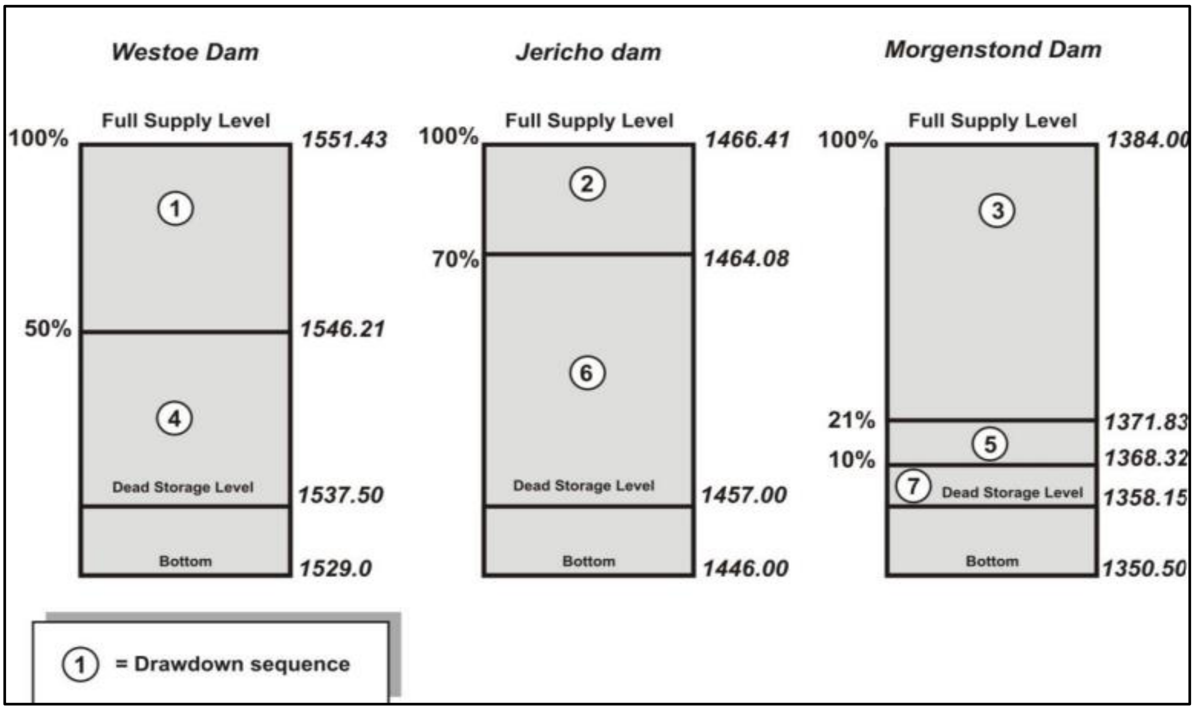


Figure 4-6: Inter-reservoir operating rules for the Usutu subsystem

Figure 4-6 illustrates the drawdown sequence indicated as numbers in the different dam storage zones. The drawdown sequence represents the storage conditions within which water must be released from Morgenstond and Westoe dams to the Jericho dam, to ensure that the Jericho dam has sufficient water.

The pump station primarily receives water from the Jericho Dam which has a live storage capacity of 59,8 million m^3 and then pumps to the Onverwacht reservoirs which have a considerable capacity each, with a combined capacity of 205 536 m^3. The Onverwacht reservoirs are 6 m in height and must not drop below 60% (3.6 m) as the pressure to gravitate to the required locations would not be sufficient (Department of Water & Sanitation, 2017). Furthermore, vortices in the reservoirs have been reported when the reservoir drops below 3 m (Hatch, 2017b).

From the Onverwacht reservoirs, water then gravitates to the Camden power station and the Camden reservoir and pump station from which water is the transferred to the Davel, Kriel and Ermelo municipalities, the other Eskom power stations and the Nooitgedacht Dam.

Adherence to control policy and Historical information

A written document on the control operational policy of the pump station was not available, as such, discussions with the operators, the weekly pumping records, the currently used control policy, and changes that affected the Jericho pump station were used to deduce the following:

a. The pump station has had multiple control policies as the policies changed each time the pump station was upgraded: Initially, the pump station was designed with a control policy to operate one pump in a single rising main; it was then upgraded with additional pumps and a second rising main, and the control policy changed to one pump or two pumps in parallel per rising main; and it was once upgraded with additional pumps and the construction of the Kliphoek booster pump station to operate in conjunction with Jericho where in four pumps would be operated at Jericho simultaneously with two pumps at Kliphoek. The design objective for each control policy was to transfer water from the Jericho Dam to the Onverwacht reservoirs efficiently and without incurring high operational costs.
b. In 1989, the Camden power station which was the primary recipient of the Jericho pump station, was mothballed because of the country’s economic downturn and consequent decrease in electricity demand, resulting in a reduction in the water requirements to be supplied by the pump station (Tsekoa, 2017). This resulted in a change in the operating policy of the pump station, wherein the pump station was primarily used to supplement water supply to power stations in other schemes when required. Consequently, the required demand had significantly reduced such that the Jericho pump station could by-pass the Kliphoek pump station and not be operated in conjunction with it.
c. In the year 2002, the pipelines were re-lined with cement mortar due to the deteriorated condition of the lining in the pipelines at the time. The re-lining significantly reduced

the internal pipe diameter, which changed the system curve and had detrimental effects on the transfer capacity of the Jericho pump station as shown in Table 4-1.

d. In 2003 the Camden power station was re-commissioned to support the country's power supply because of a rapid increase in electricity demand (Tsekoa, 2017).

e. The Camden power station is reported to have a five-day water storage capacity of 229 800 m^3 (Department of Water Affairs, 1979), during which maintenance at the Jericho pump station can occur.

f. As a result of the population growth in the recipient municipalities and increased demand for electricity, the result has been higher water demand and consequently more water supplied from the Onverwacht reservoirs. According to the operators the Onverwacht reservoirs cannot be allowed to drop below 60% (3.6 m) as the pressure to gravitate to the required locations would not be sufficient. Consequently, the allowable downtime of the Jericho pump station has significantly reduced.

g. The current undocumented control policy used by the operators is to operate two pumps at the Jericho pump station in conjunction with one pump at Kliphoek booster pump station as a means to meet the daily target using the minimum number of pumps operating continuously. Consequently, pumps are operated continuously with no consideration given to the Eskom peak tariffs as per DWS operating guidelines throughout the week and only stopped during weekends when the demand is low.

h. The pumps are operated without any throttling to limit the flows from the pump station.

i. Operators run the minimum number of pumps required to meet the daily demand through continuous pumping. The number and combination of pumps used is chosen based on the demand target, such that the pumping flow rate is close to the target.

Based on the discussions with the operators, Table 4-1 details the summary of the assessment on whether the Jericho pump station is adhering to the DWS control policies and the implications thereof.

Table 4-1: Summary of Jericho pump station operations policy assessment

Criteria	Findings and Implications
Operations adhering to original control policy	There is no evidence that a revised control policy that takes the changes 1989 and 2002 into account was done for the pump station. The current unofficial policy is to operate the minimum number of pumps required to meet the daily demand. This implies that the operating policy of the pump station has not been revised to cater for changes in the demands, consequently, operators have had to manage demands as per their discretion.

Throttling of pumps	Pumps are not throttled during operations. As a result, the pumps have been operated in adherence to DWS policy in this particular regard.
Frequency of pump starts	Pump starts are minimal as pumps are started and ran continuously for an entire day with no stops. This implies that the pump starts per day guidelines are being adhered to.
Optimal pump scheduling to minimize power costs	Pumps are operated continuously without consideration of the high operating costs that are incurred because of operating during Eskom peak hours. Consequently, the operating costs of the pump stations are unnecessarily high.

As there are six pumps installed at Jericho and the option of using the Kliphoek pump station simultaneously, there are several operational combinations that can be used. These operational combinations were determined based on the layout of the Jericho and Kliphoek pump stations and rising mains, and correlation between pumps at Jericho and those at Kliphoek as detailed in Section 4.1. Table 4-2 lists these operational combinations based on the pump curves.

Table 4-2: Pump operational combinations

Pump combination	**Description**	**Total flow rate (l/s) prior to re-lining**	**Current total flow rate (l/s)**
A	1 pump at Jericho on one pipeline	972	920
B	2 pumps at Jericho on two pipelines	1944	1840
C	2 pumps at Jericho on same pipeline	1270	1135
D	3 pumps at Jericho (2 pumps on one pipeline and the other pump on the other pipeline)	2242	2055
E	4 pumps at Jericho (2 pumps per pipeline)	2540	2270
F	2 pumps at Jericho on 1 pipeline + 1 pump at Kliphoek	1770	1650
G	3 pumps at Jericho + 1 pump at Kliphoek	2742	2570
H	4 pumps at Jericho + 1 pump at Kliphoek	3040	2785
I	4 pumps at Jericho + 2 pumps at Kliphoek on two pipelines	3540	3300

4.3 Historical demand, projections, and actual transfers

The Jericho pump station primarily supplies water to Eskom power stations and also supplies water to municipalities within its vicinity through the Onverwacht reservoirs. The demand managed by the Jericho pump station can be broken down into the components shown in Figure 4-7. Camden power station receives 100% of its supply from Jericho pump station, whereas Kriel and Kendal only receive 75% and 17% of their total supply respectively. Matla power station received 47 % of its water supply from Jericho from 1980 to 1995 when it started receiving all of its supply from Grootdraai dam.

The Jericho pump station also supplies water to the Komati Sub-system when the water requirements of the Eskom Power Stations supplied from the Komati Sub-system (Arnot, Hendrina, Duvha and Komati) exceed the short-term yield capability of the Komati Sub-system. When this occurs, water is transferred into Nooitgedacht dam (Department of Water Affairs, 2011). The DWS 3rd party users are the Kriel, Davel and Ermelo municipalities shown in Figure 4-1 in Section 4.1, which receive water through offtakes from pipelines transferring water to the Eskom power stations.

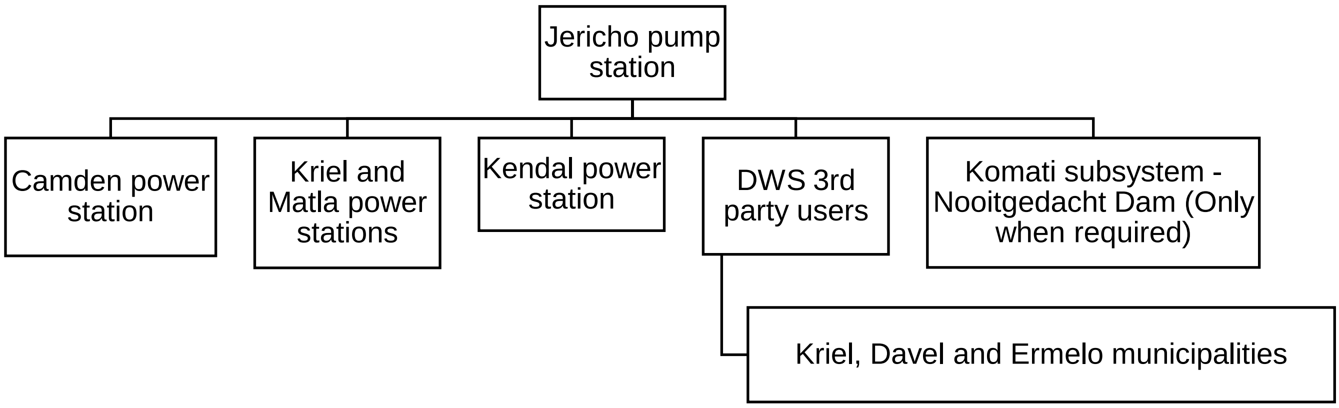


Figure 4-7: Components of the Jericho pump station demand

4.3.1 Eskom coal-powered stations (Camden, Kriel, Matla and Kendal)

Eskom has a monthly pattern for the water demand required for all their power stations, which is shown in Figure 4-8 in terms of the Water demand factor. The water demand factor is the ratio of monthly water demand to the average monthly demand throughout the year. From the Figure it’s clear that peak water requirements for the power station occurs during the winter months of June, July and August where electricity demand is high, with the July having the highest water demand.

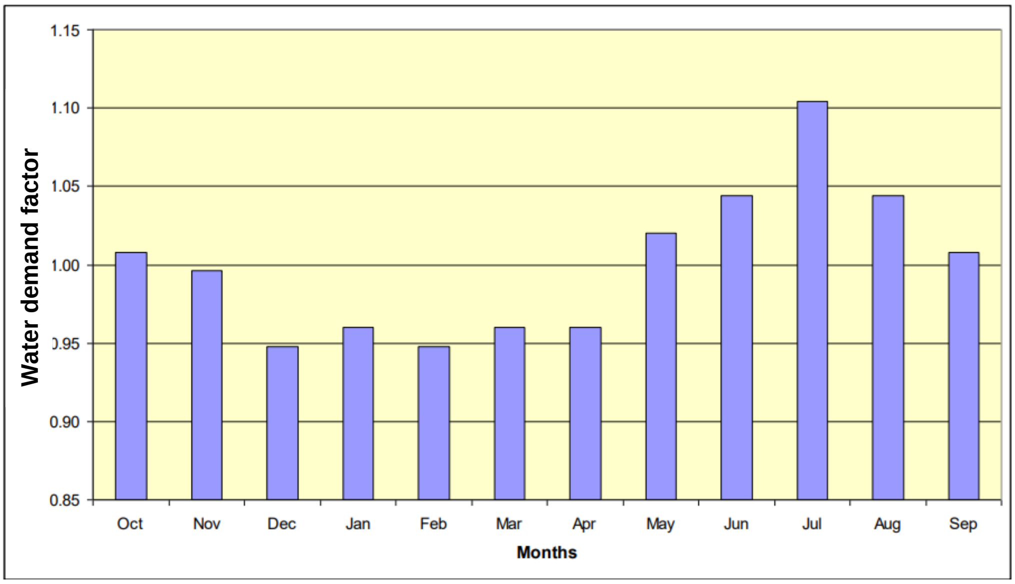


Figure 4-8:Monthly variation of Eskom water demands (DWS, 2016)

The weekly variation of Eskom’s water demands could not be obtained. However, as the water demands are directly proportional to the electricity demand, the weekly electricity load profiles can be used as an indicator of the weekly water demand variations. Figure 4-9 shows the weekly plot of daily peak electricity demand in South Africa (Chikobvu & Sigauke, 2012).

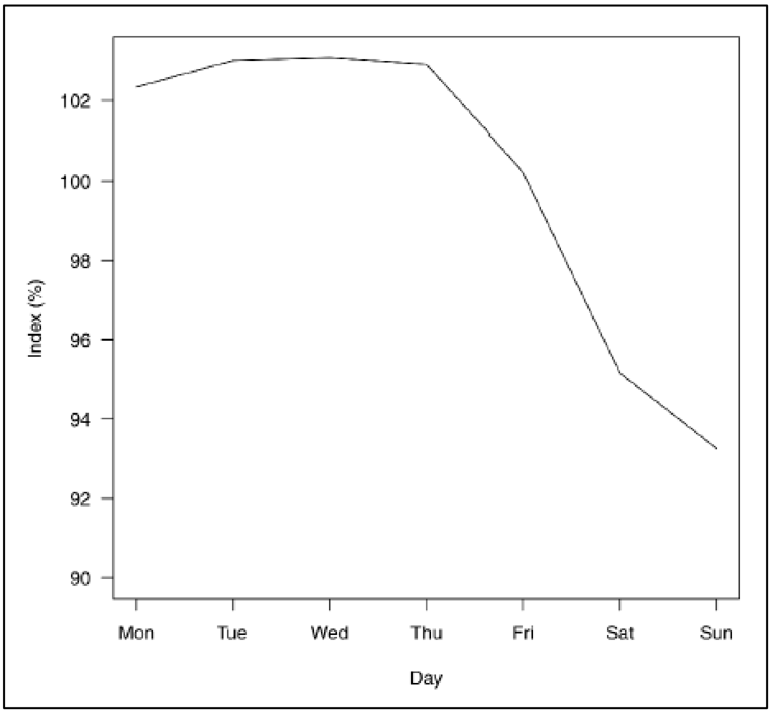


Figure 4-9: Weekly electricity demand profile (Chikobvu & Sigauke, 2012)

Eskom’s weekly generation peak demands reports were assessed and showed similar weekly demand profiles to Figure 4-9 (Eskom , 2022). The profile in Figure 4-9 aligns with the operator’s reports of the water demand being lower during weekends. Table 4-3 details a brief history of the Eskom power stations that receive water from the Jericho pump station.

Table 4-3: Brief history on the operations of the Eskom power stations (Eskom, 2013).

Eskom power station	**Brief operational history**
Camden power station	The power station became operational in 1967 and was operated consistently until it was mothballed in 1989 and ceased operations as a result of other power stations being built. Due to increased power requirements, it was brought back into operation in 2003. It is a wet cooled power station, but due to its age, it has low thermal efficiencies and therefore has considerably high-water requirements compared to the more recent wet cooled power stations.
Kriel power station	The power station became operational in 1979. It has been operated consistently since it became operational. It is a wet cooled power plant, therefore has considerable water requirements.
Matla power station	The power station became operational in 1983. It is a wet cooled power plant, therefore has considerable water requirements. It currently no longer receives its water supply from the Jericho pump station.
Kendal power station	The power station became operational in 1989, and at full capacity in 1993. It has been operated consistently since it became operational. It is a dry cooled power plant, therefore has considerably low water requirements.

Table 4-4 and Figure 4-10 shows the average water requirements and annual water requirements of the Camden, Kriel, Matla (Only for the period when it was supplied water by Jericho pump station) and Kendal power stations from their commissioning to the year 2022 respectively. The data on the water requirements were obtained from Eskom (2013), DWA (1981) and Pouris & Thopil (2015).

Table 4-4: Average water demands of the Eskom power stations.

Power station	**Average water requirements (million m^3)**
Camden	26.97
Kriel	27.69
Matla	17.2
Kendal	0.5

Table 4-4 shows that majority of the water pumped from the Jericho pump station is transferred to Camden, Kriel and Matla power stations, with very little being transferred to Kendal power station. As detailed in Table 4-3, Camden, Kriel and Matla are wet cooled power stations heavily reliant on water supply, and Kriel uses recent technologies and uses considerably less water with it being a dry cooled power station.

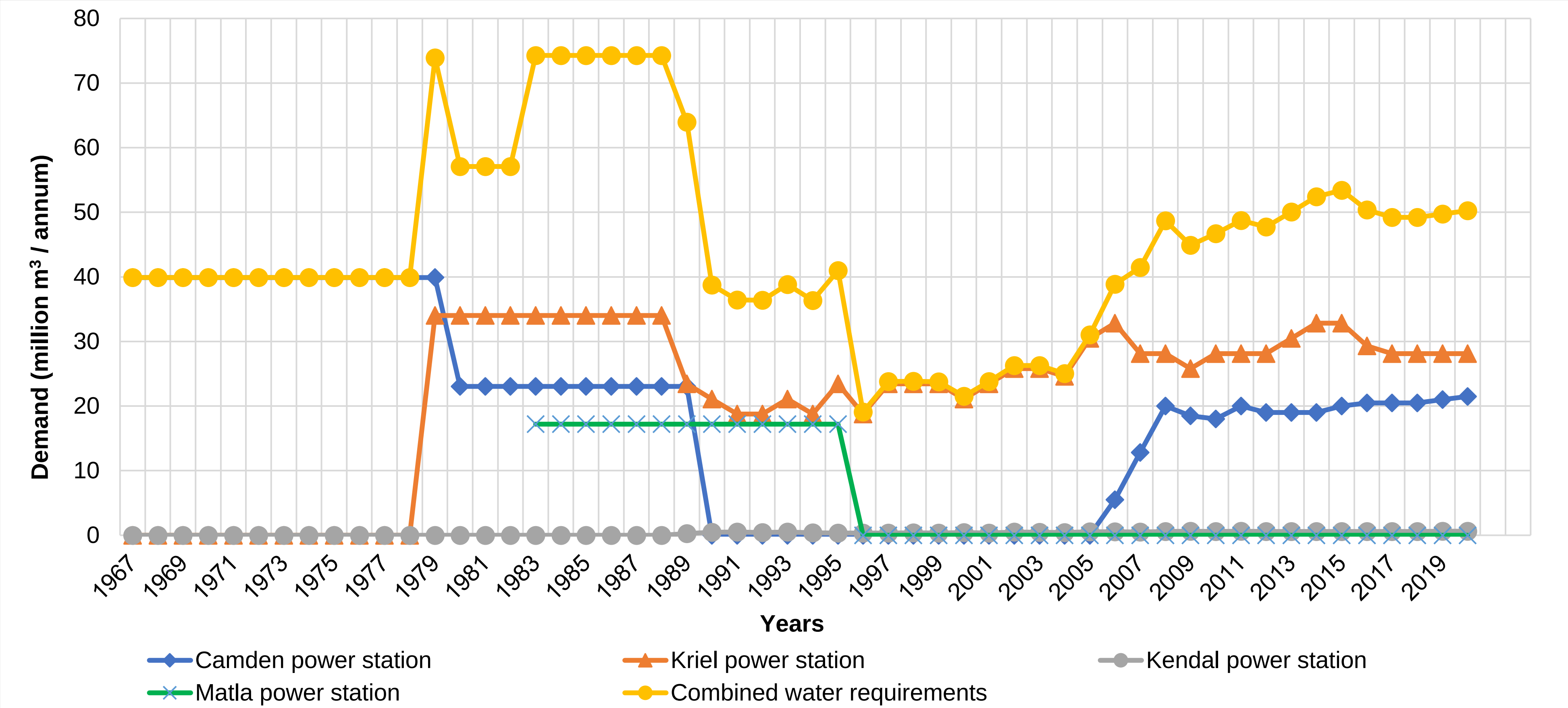


Figure 4-10: Water requirements of the Eskom power stations supplied by Jericho pump station.

4.3.2 DWS 3rd party users

The water requirements of the DWS 3rd Party Users supplied from the Usutu sub-system, namely: Kriel, Davel and Ermelo municipalities are illustrated in Figure 4-11. The annual water requirements from 2017 to 2022 were not reported on and are therefore assumed to have remained constant since the 2015/2016 Annual Operating Analysis report (Department of Water & Sanitation, 2015).

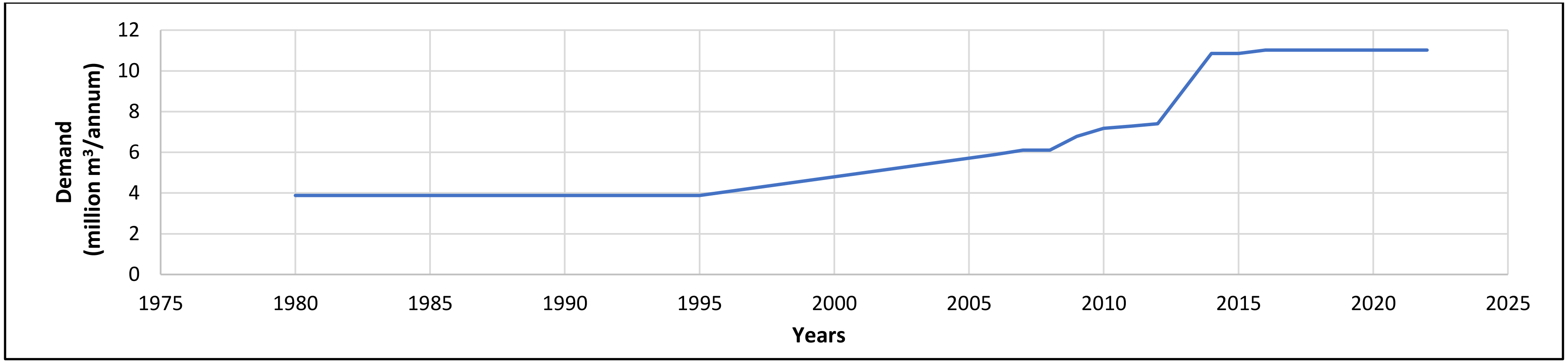


Figure 4-11:Water requirements of the DWS 3rd party users.

From Figure 4-11, the water requirements of the Kriel, Davel and Ermelo municipalities (3rd party users) are shown to have increased over the years. Therefore, more water has increasingly been required to be pumped from the Jericho pump stations for these users.

4.3.3 Komati scheme – Nooitgedacht Dam

As discussed earlier, the Jericho pump station is also responsible for supporting the power stations in the Komati scheme sub-system when the Nooitgedacht Dam storage levels significantly drop such that the dam cannot provide sufficient water the Komati sub-system power stations, namely: Arnot, Hendrina, Duvha and Komati power stations.

The transfer system between the Jericho pump station and the Komati scheme was completed in 1982 (Director General of Environmental Affairs, 1982). Transfers from the Jericho pump station to the Komati scheme ceased in 2015 as a result of the reduced demand in the Komati scheme (DWS, 2016). The water requirements of the Komati scheme from the Jericho pump station were found from the 2009 to 2021, with no information of the water requirements between 1982 and 2009 available. As the water requirements of the Eskom power stations (Camden, Kriel, Matla, and

Kendal) and the DWS 3rd party users are known. The water requirements of the Komati system can be assumed to be the difference between the known water requirements and the annual transfers from the Jericho pump station during the period (1982-2009).

Figure 4-12 shows the water requirements of the Komati scheme sub system power stations that the Jericho pump station had to supply between 2008 and 2019.

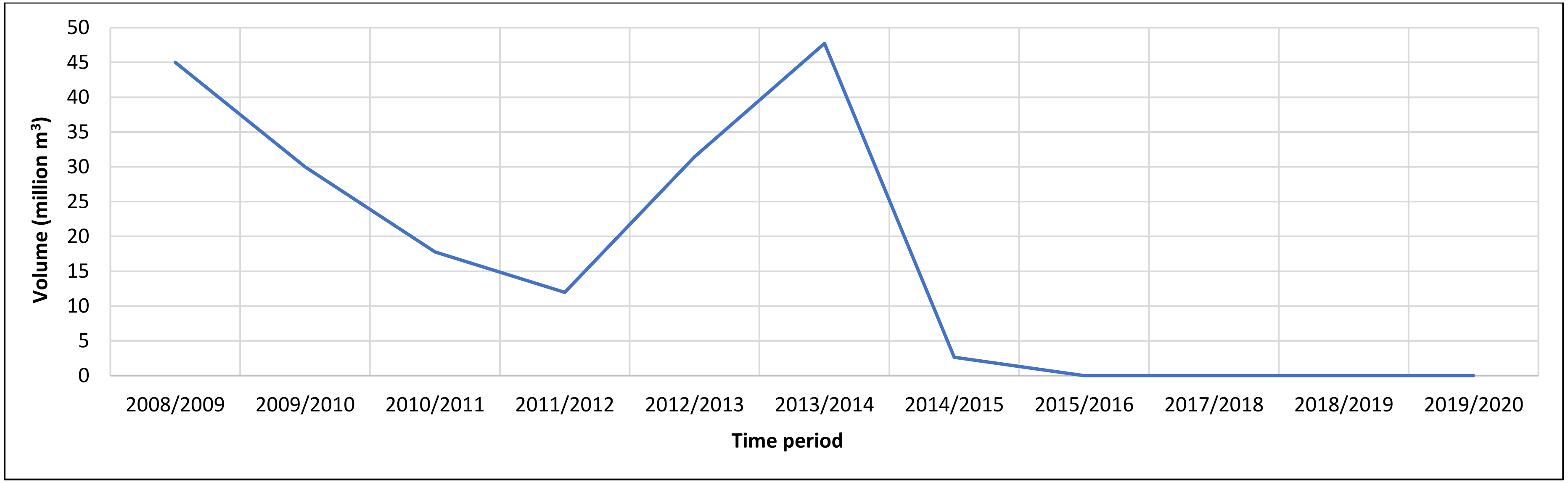


Figure 4-12: Water requirements of the Komati scheme from the year 2009 to 2020.

The varying demand volumes of the Komati scheme sub system power stations depicted on Figure 4-12, shows the uncertainty that the Jericho pump station had to manage. From the Figure, its clear that the pump station's operational philosophy would have had to be revised each to adapt to the varying demands.

4.3.4 Total water annual requirements

Figure 4-13 shows the known total water requirements that the Jericho pump station was expected to supply throughout its operational life.

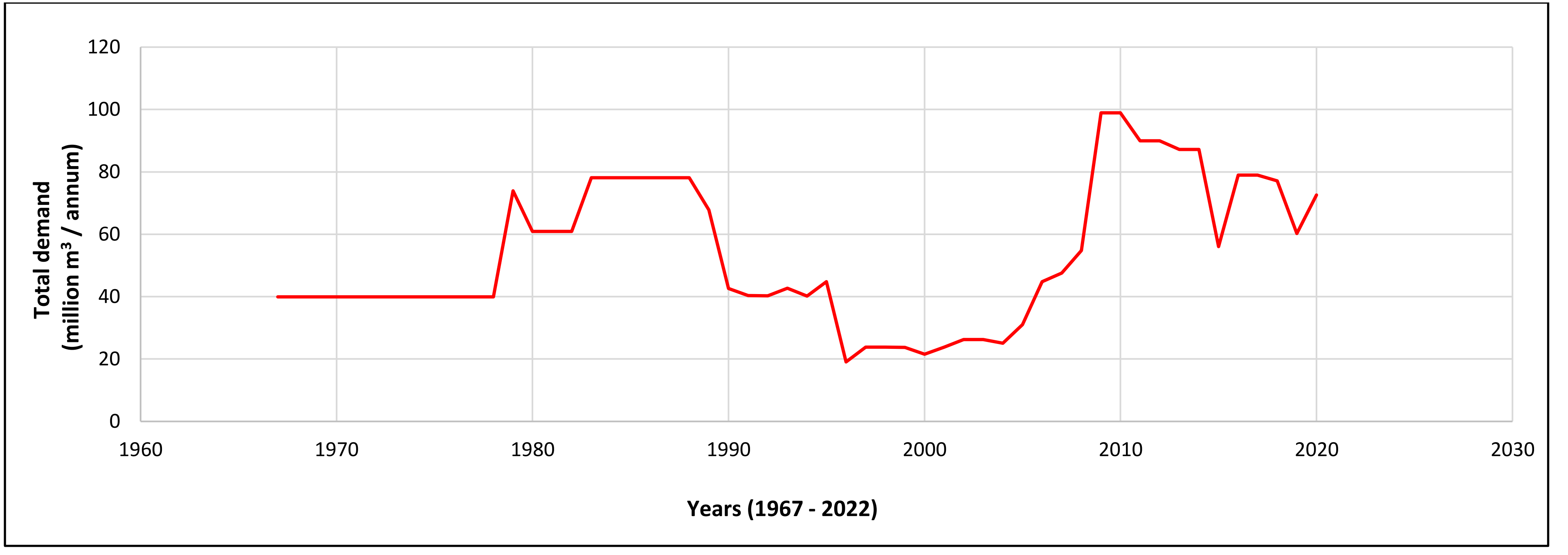


Figure 4-13: Total water requirements for Jericho pump station.

From Figure 4-13, its clear the water requirements that the Jericho pump station had to supply have varied significantly throughout its operational life. As detailed in Section 4.2, one of the reasons the water requirements have varied significantly is because of the uncertainty with the operation of the Camden power station, which was de-commissioned in 1989 due to the country's economic downturn and consequent decrease in electricity demand and re-commissioned 14 years later when the electricity demand was rapidly increasing. Additionally, as detailed in Section 4.3.3, the Jericho pump station also had to support the Komati scheme sub-system when the scheme was struggling to meet the water requirements of its recipient power stations.

4.4 Historical transfers

4.4.1 Annual transfers

DWS pump station operators do not keep records of the demands of water that they have to supply, as they either have a set daily volume of water that they must supply each day or are informed telephonically on the day of how much water to pump. Instead of recording the daily demands, they record the daily volumes of water the pumped or the number of hours in which they were pumping. Figure 4-14 shows the annual recorded flow volumes pumped from 1966 when the pump station was commissioned to end of the year 2022.

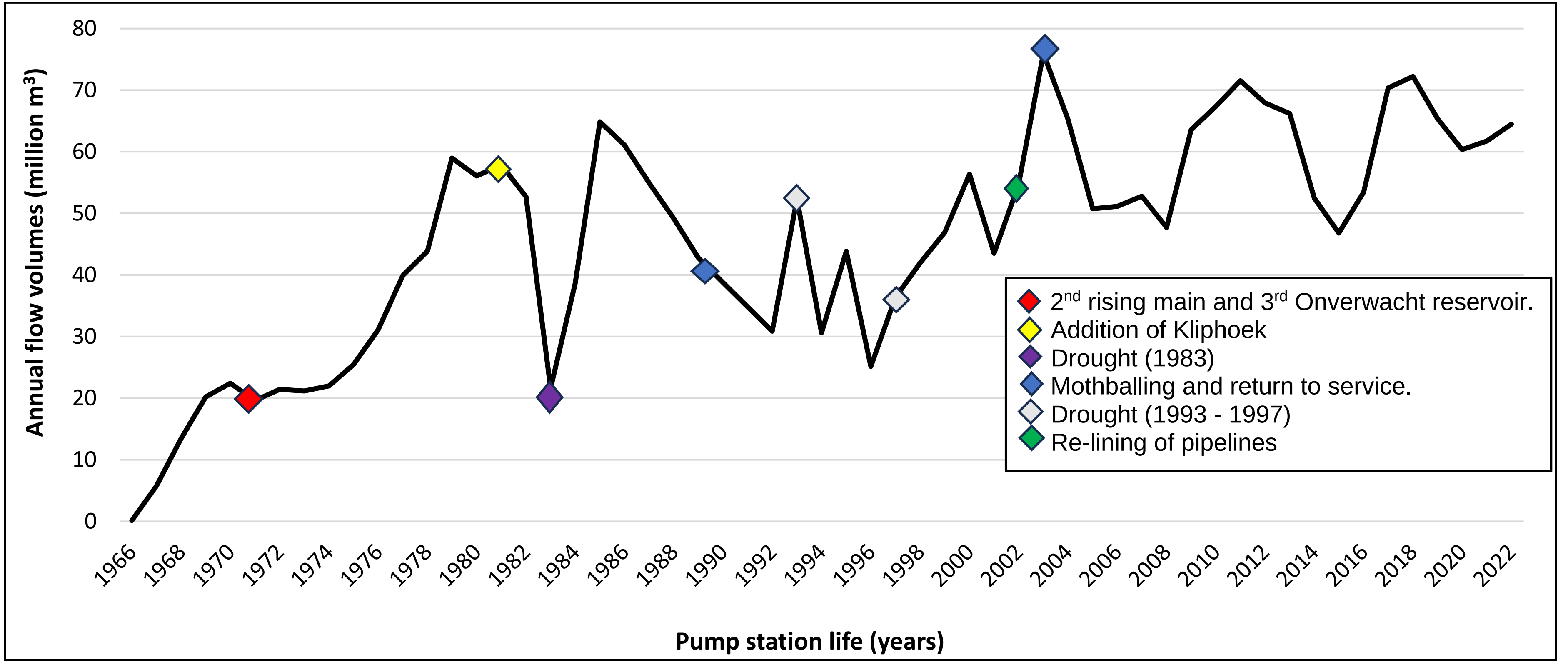


Figure 4-14: Jericho pump station annual recorded flow volumes throughout its operating life.

It is clear from Figure 4-14 that there have been fluctuations in the amount of water supplied by the pump station from its construction. The coloured marks represent the major changes to the pumping system and the demand. With the major changes in the system being the addition of a 2nd rising main in 1971 and addition of the Kliphoek booster pump station and additional 2 pumps at Jericho pump station. Analysis of the transferred flows from the Jericho pump station are detailed in Table 4-5 below.

Table 4-5: Annual flow statistics for the Jericho pump station

Statistic	**Annual flow volumes (million cubic meters)**			
	Year 1-6 (1965-1971)	**Year 6-16 (1971-1981)**	**Year 16-38 (1981-2002)**	**Year 38-57 (2002-2022)**
Average	13.597	37.791	45.353	60.609
Minimum value	0.136	21.184	21.585	46.792
Maximum value	22.427	58.967	75.972	72.219
Standard deviation	8.952	15.700	13.258	8.411
Average + Std. deviation	22.548	53.491	58.611	69.019
Average - Std. deviation	4.645	22.091	32.095	52.198

The demand based on the average annual flow volumes transferred has been steadily increasing from Year 1 to Year 57 of the Jericho pump station life. The standard deviation in the four periods is high, especially the two periods between Year 6 and Year 38. This indicates that although the demand has been steadily increasing, there have been large fluctuations in the demand imposed on the Jericho pump station.

It should be noted that there was drought between 1992 and 1996 which resulted in water restrictions to municipalities and the Eskom power stations. Therefore, the sharp decrease in water transfers between year 28 and 31 is not a result of a change in demand but the water restrictions due to the drought (Van Niekerk & Du Plessis, 2013). Similarly, there was a drought in 1983 where the Camden power station received no water (Eskom, 2013).

4.4.2 Weekly transfers

The Jericho pump station operators record all the weekly transfers from the pump station in the weekly pump performance reports. The available recorded weekly data is depicted in Figure 4-15 and ranges from December 2003 to September 2022.

From Figure 4-15, its clear that there are considerable variations in the weekly transferred volumes. However, as detailed in the Section 4.3.1 water demands for users such as power stations, vary with months, as such an analysis of the monthly transfers is required.

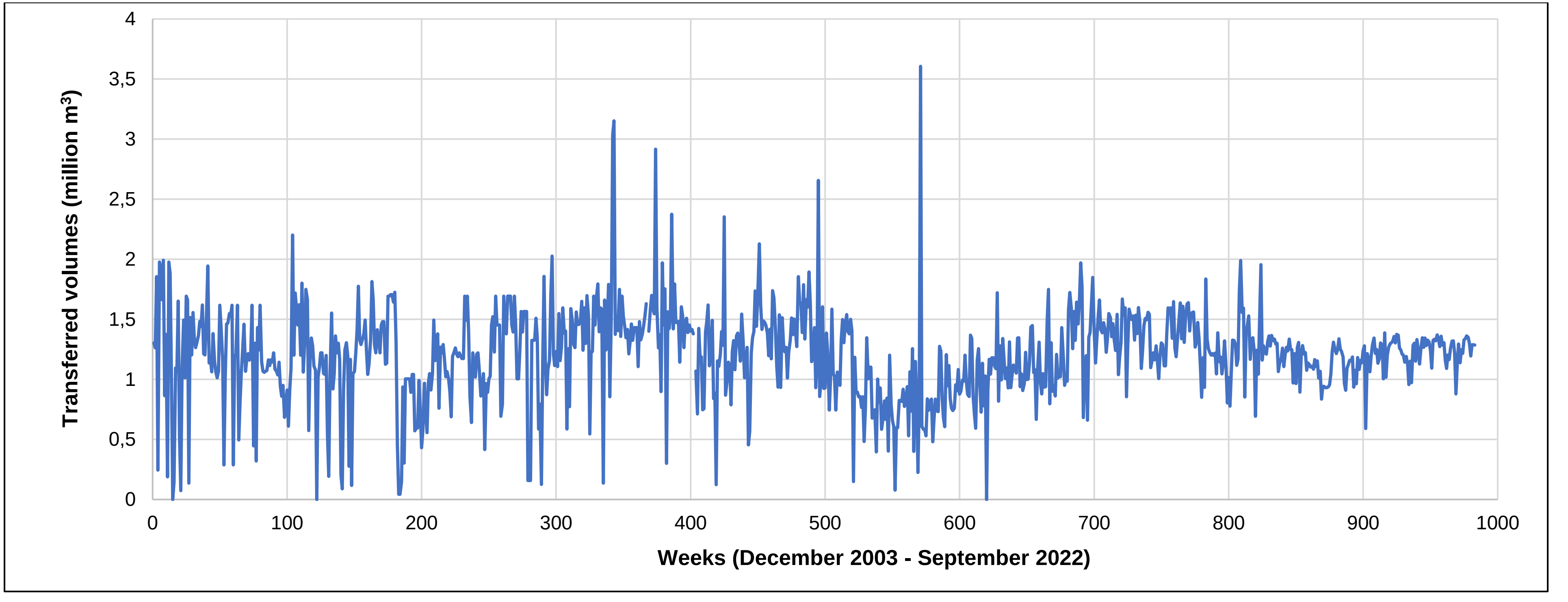


Figure 4-15: Recorded weekly transfers from the Jericho pump station.

4.4.3 Monthly transfers

Using the weekly transferred volumes recorded by the operators at the Jericho pump station, and the volumes transferred for each month can be determined. The monthly variations of the transferred volumes from the Jericho pump station for the periods between 2004 and 2012, and between 2013 and 2022 are depicted in Figures 4-16 and 4-17 respectively.

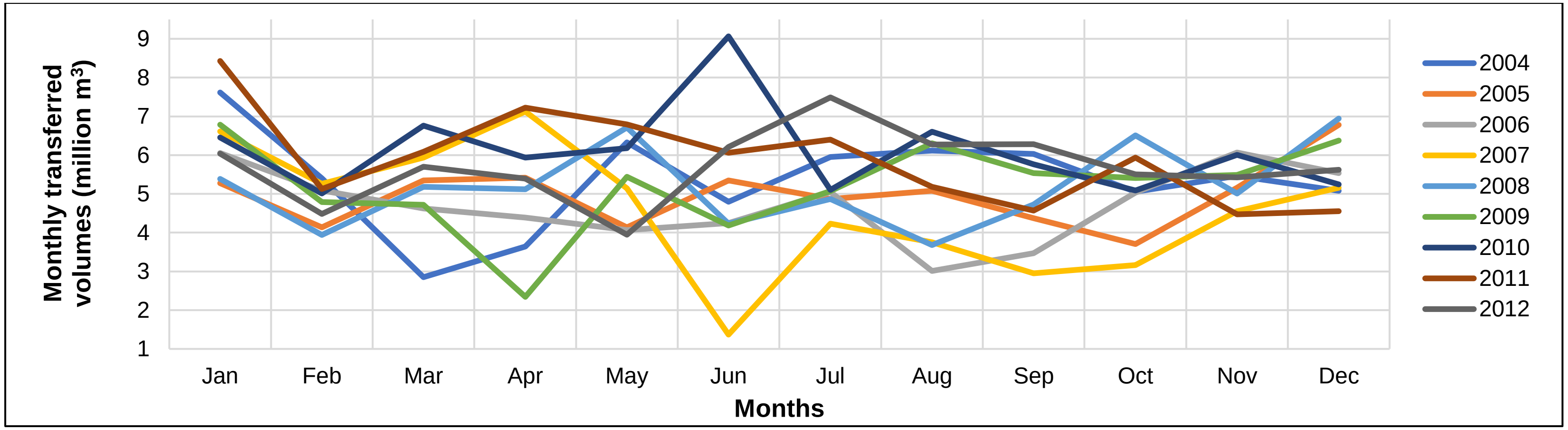


Figure 4-16: Monthly variations of transferred volumes between 2004 and 2012

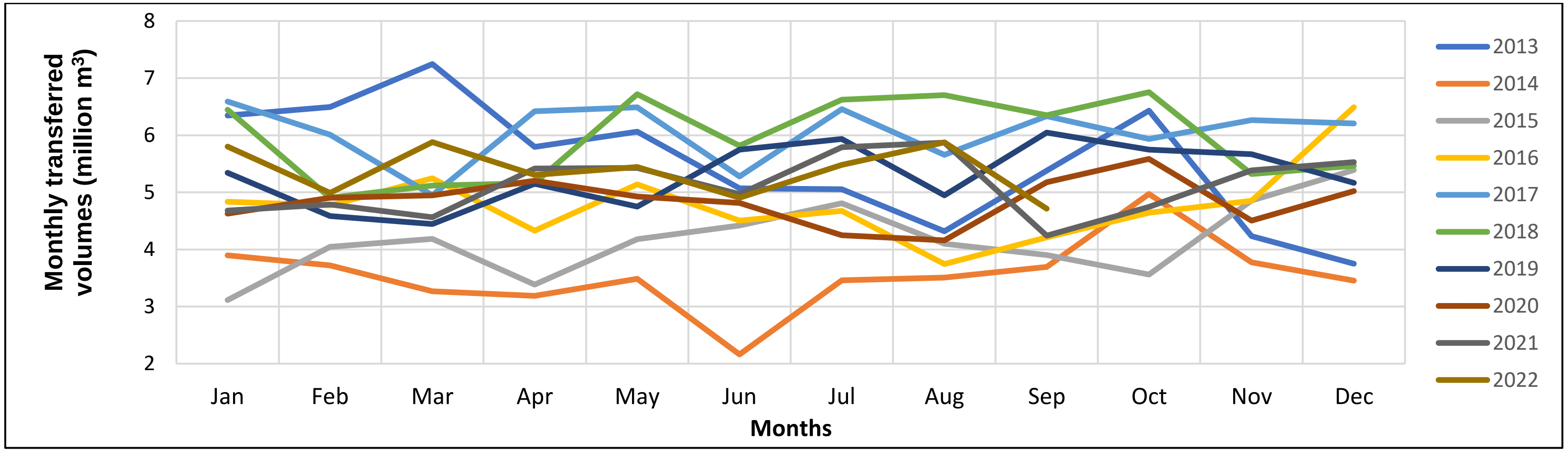


Figure 4-17: Monthly variations of transferred volumes between 2013 and 2022

From Figures 4-16 and 4-17, its clear that the monthly transferred volumes from the Jericho pump station have varied from one year to the other between the years 2004 and 2022.

4.5 Comparison between Jericho pump station annual demands and transfers.

Figure 4-18 shows the comparison between the annual recorded transfer flow volumes from the Jericho pump station, and the total water requirements obtained for the Eskom power stations, End user municipalities and the Komati system. However, it should be noted that the water requirements of the Komati system between the years 1982 and 2009 will be assumed to be the difference between the known water requirements and the annual transfers from the Jericho pump station during the period. This is because although it is known that the transfers from the Jericho pump station to the Komati scheme began in 1982, no information on the recorded transfers or water demands prior to 2009 were available.

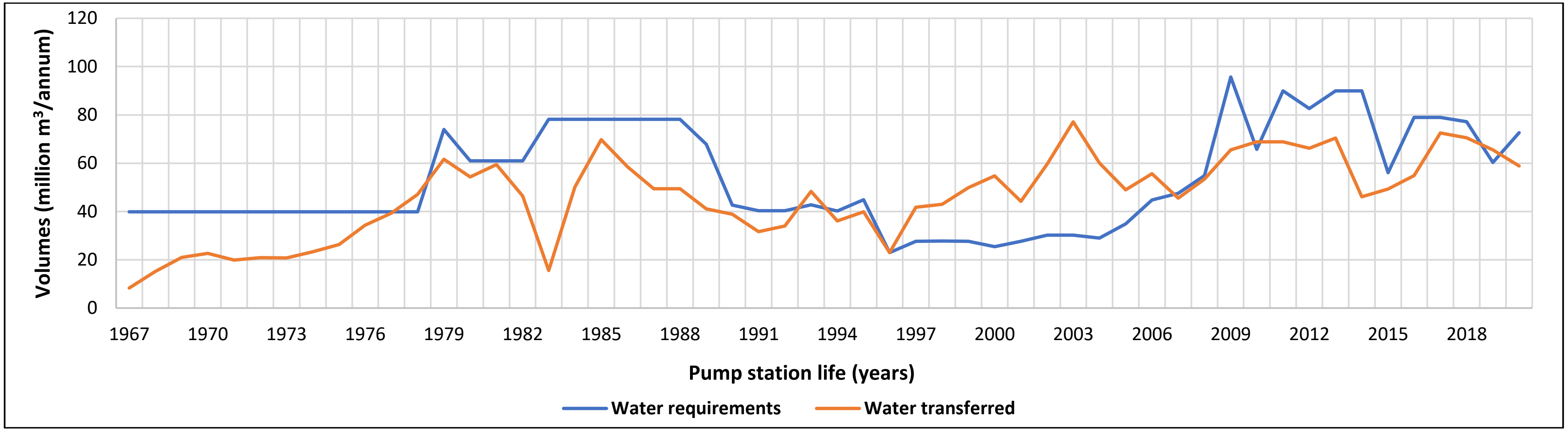


Figure 4-18: Comparison between annual transferred volumes and water requirements.

From Figure 4-18 it can be observed that the water requirements of the Jericho pump station have exceeded the water transferred from the pump station to meet the demand for majority of the period, with the exception being the period between 1996 and 2007. During this period the Camden power station was decommissioned which resulted in the decreased water requirements, however, as the pump station was supplying an unknown quantity of water to the Komati system. Therefore, it can be deduced that the difference between the water requirements and the water transferred in Figure 4-18 is the water transferred to assist the power stations in the Komati system.

The water requirements obtained from Eskom for the respective power stations supplied by the Jericho pump station were provided for the planned operational period of the power station with planned maintenance considered. However, unplanned breakdowns and periods of unexpected, reduced capacity could have resulted in reduced water requirements from those provided by Eskom for the period in Figure 4-18. Furthermore, the water requirements of the DWS 3rd party users (Kriel, Davel and Ermelo municipalities) are based on demand projections and not the actual demand.

4.5.1 Eskom and DWS 3rd party users – Demands vs actual transfers.

In this Section, a comparison is done of the transfers from the Jericho pump station to meet the demands of the Eskom power stations in the Usutu sub-system and the DWS 3rd party users. The recorded flow measurements obtained from the DWS hydrological website (DWS - Hydrological Services, 2023) throughout the life of the Jericho pump station do not show distinctions between transfers to the individual end users, and instead show the total flows transferred. However, the Annual Operating Analysis (AOA) reports differentiate between the transferred flows to the Eskom power stations in the Usutu sub-system along with the 3rd party users, and the transfers to supplement the Komati system. The reports that were available are for the years ranging from 2008/2009 to 2019/2020.

Figure 4-19 below shows the reported water requirements of the Eskom power stations and the 3rd party users and the actual transfers from Jericho pump station towards these requirements between 2008 and 2020.

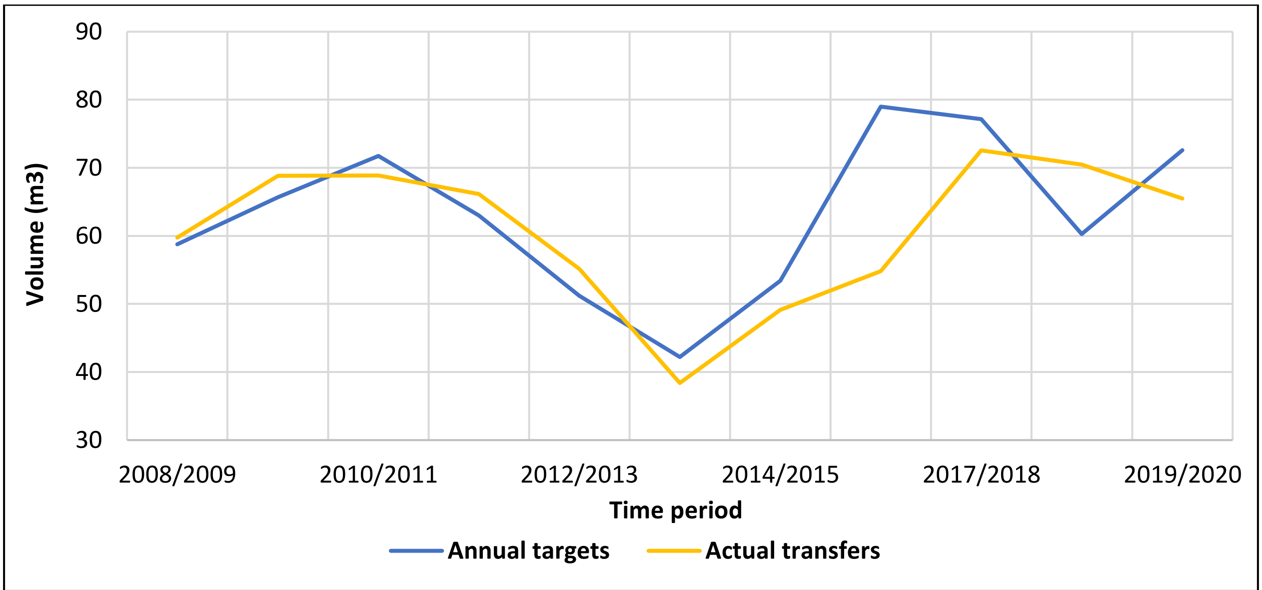


Figure 4-19: Water requirements and transfers of the Eskom power stations and 3rd party users.

From Figure 4-19, it can be deduced that the pump station only struggled to meet the users' demands between 2015 and 2018. This occurred as the dam levels at Jericho dam and the Usutu dams (Morgenstond and Westoe) which supply water to the Jericho dam were considerably low due to the drought that affected South Africa at the time. Consequently, the actual transfers from the Jericho pump station were lower that the transfer targets (Department of Water Affairs, 2016).

Additionally, maintenance issues in the 2014 at Onverwacht resulted in reduced transfer capacity to the end users, resulting in the reduction of the pumping capacity at Jericho (Department of Water & Sanitation, 2015). In 2019, maintenance issues resulted in reduced transfers to the Jericho Dam from Morgenstond dam, which resulted in reduced transfers from the Jericho pump station (Department of Water & Sanitation, 2020).

4.5.2 Komati scheme - Demands vs actual transfers.

In this Section, a comparison is done of the transfers from the Jericho pump station to meet the demands of the Komati scheme sub-system which includes the Nooitgedacht dam. These transfers are done when the Nooitgedacht Dam storage levels significantly drop such that the dam cannot provide sufficient water to the Komati sub-system power stations as discussed in Section 4.3.3.

Figure 4-20 below shows the reported water requirements of the Komati system and the actual transfers from Jericho pump station towards these requirements between 2008 and 2020.

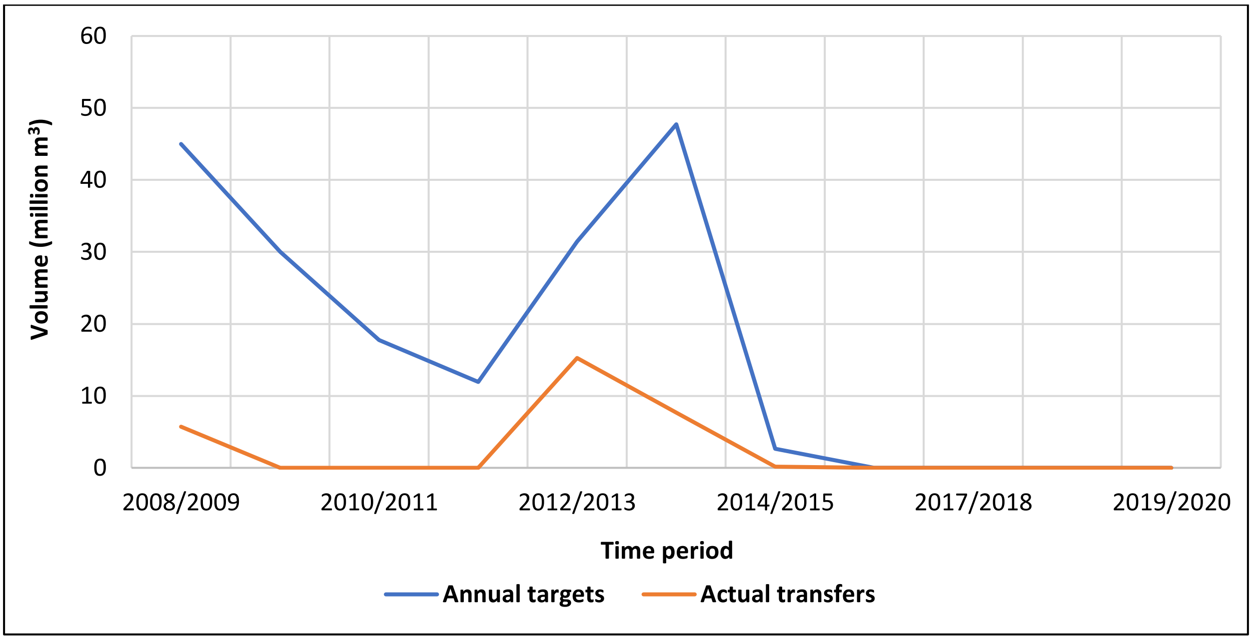


Figure 4-20:Water requirements and transfers of the Komati system.

From Figure 4-20, its clear that between 2008 and 2014, the water requirements of the Komati Sub-system were not met. This was because of reduced demand in the Komati system resulting in the actual water requirements being considerably less than what was initially projected for the year. From the year 2015, no transfers have been made from Jericho to the Komati system (Nooitgedacht dam) due to reduced demands in the Komati Sub-system.

4.6 Weekly pump performance reports

As mentioned in the research methodology, the Usuthu River Government Water Scheme compiles weekly pump performance reports that can be used to describe how well the Jericho pump station has been performing on a weekly basis.

The weekly pump performance reports were compiled for a study period of 12 months from May 2022 to May 2023. The pumping combinations that can be used at the Jericho pump station with/without Kliphoek booster pump station are detailed in Table 4-2. Table 4-6 shows which pumping combinations were used on a weekly basis during the period, which are deduced based on the following:

- Number of pumps used as indicated in the weekly performance reports.
- Layout of the pump stations (Figure 4-4 and 4-5) and the operational layout as described in Section 4.1.
- The operating rule described in Section 4.1 that states that for any pump at Kliphoek to operate, two pumps at Jericho should be pumping on the same line to ensure there is sufficient backpressure. Therefore, the pumps at Kliphoek can only be operated if two corresponding pumps are simultaneously operated at Jericho.

The information compiled and obtained from the operator is shown Table 4-6.

Table 4-6: Pumps available, operated and duration of pumping at Jericho and Kliphoek from May 2022 to May 2023.

Reporting period (May 2022 and May 2023)	Weekly transferred volumes (million m^3)	Jericho Pump Station			Kliphoek Booster Pump Station			Pumping Combinations used *
		Pumps available	Pumps operated	Pumping duration (hours)	Pumps available	Pumps operated	Pumping duration (hours)	
23 - 30 May	1.319	4	4	489.4	2	1	168	H,G,F
6 - 13 June	1.217	4	4	458.3	2	1	168	H,G,F
13 - 16 June	0.879	4	3	486.45	2	1	168	G,F
20 - 27 June	1.121	4	3	421.45	2	1	168	G,F
27 June - 4 July	1.295	4	3	491.3	2	1	168	G,F
4 - 11 July	1.139	3	3	491.3	2	1	142	G,D,C
18 - 25 July	1.216	3	3	452.05	2	1	161	G,F
25 July - 1 Aug	1.329	3	3	500.4	2	1	115.15	G,D
1 - 8 Aug	1.337	3	3	497.25	2	2	155.3	G
8 - 15 Aug	1.361	3	3	504	2	1	168	G
22 - 29 Aug	1.351	3	3	342.09	2	1	168	G,F
29 Aug - 5 Sept	1.194	3	3	449.95	2	1	122.2	G,B
5 - 12 Sept	1.288	4	4	578.4	1	1	140	H,G
12 - 19 Sept	1.288	4	4	543.85	2	1	168	H,G
19 - 26 Sept	1.286	4	4	545.85	2	1	132.5	H,G,B,A
26 Sept – 3 Oct	1.051	4	4	447.75	2	2	103.3	I, H, A, B
3 – 10 Oct	1.283	4	4	527.85	3	3	155.3	I, H, E, D, B, A

10 – 17 Oct	1.284	4	4	508.9	3	3	147.15	I, E
17 – 24 Oct	1.311	4	4	565.8	3	3	115.9	I,H,E
24 – 31 Oct	1.316	4	4	589.7	3	3	144.45	I,H,D
31 Oct – 7 Nov	1.298	3	3	480.72	3	1	168	G
7 – 14 Nov	1.268	3	3	498.75	3	1	160.15	G
21 – 28 Nov	1.009	3	3	503.05	3	1	161.55	G
28 Nov – 5 Dec	1.318	3	3	494.45	3	1	155	G
5 – 12 Dec	1.264	3	3	472.3	3	1	145.55	G,D
12 – 19 Dec	1.316	3	3	493.8	3	1	100.35	G,D
19 – 26 Dec	1.296	3	3	489.6	3	1	143.45	G
26 Dec – 2 Jan	1.253	3	3	479.2	3	1	165.25	G
2 – 9 Jan	1.191	3	3	437.45	3	1	163.3	G
9 – 16 Jan	1.298	3	3	480.8	3	1	122.25	G,D
16 – 23 Jan	1.354	3	3	501.2	3	1	165.2	G
23 – 30 Jan	1.316	3	3	489.8	3	1	157.45	G
30 Jan – 6 Feb	1.186	3	3	497.5	3	1	135.2	G,D
6 – 13 Feb	1.321	3	3	494.5	3	1	152.5	G
13 – 20 Feb	1.286	4	4	538.15	3	1	124.55	G,E
20 – 27 Feb	1.267	4	4	589.3	3	1	76	H,E,D
27 Feb – 6 Mar	1.380	4	4	599.1	3	1	99.05	H,D
6 – 13 Mar	1.513	4	4	622.8	3	2	178	I,H,D
13 – 20 Mar	1.519	4	4	642.85	3	2	184.55	I,H,D

20 – 27 Mar	1.336	4	4	571.45	3	1	130	H,B,A
27 Mar – 3 Apr	1.493	4	4	629.2	3	2	188.6	I,H,G
3 – 10 Apr	1.411	4	4	563.1	3	2	193	I,H,E,C
10 – 17 Apr	1.385	4	4	586.4	3	2	130.3	I,H,E,C
17 – 24 Apr	1.403	4	4	586.45	3	2	179.35	I,H,G,C
24 Apr – 1 May	1.384	4	4	550.9	3	2	179.65	I,G,D,C
1 – 8 May	1.299	3	3	480.05	3	1	167.35	G.F
15 – 22 May	1.361	3	3	504	3	1	168	G
22 – 29 May	-	3	3	267.45	3	1	67.35	G,C,A
29 May – 5 June	91.25	3	3	491.75	3	1	163	G

* The pumping combinations are specified in Table 4-2

From the compiled pump performance reports of the period between May 2022 and May 2023 above, the following observations were made:

- Certain pump combinations were used more often than others , and there was a standard method of operation throughout the study period.
- There was some correlation between the pump availability and the number of pumps operated.
- The pumping durations of some of the pumps indicate that the pumps were operated without regards of the Eskom time-of-use periods and operated even during peak periods.

A more detailed assessment of the above is shown in the following sections.

4.6.1 Pumping combinations

The pumping combinations are an indication of how the pump station is operated. Figure 4-21 shows the frequency of each of the pumping combinations used during the specified period.

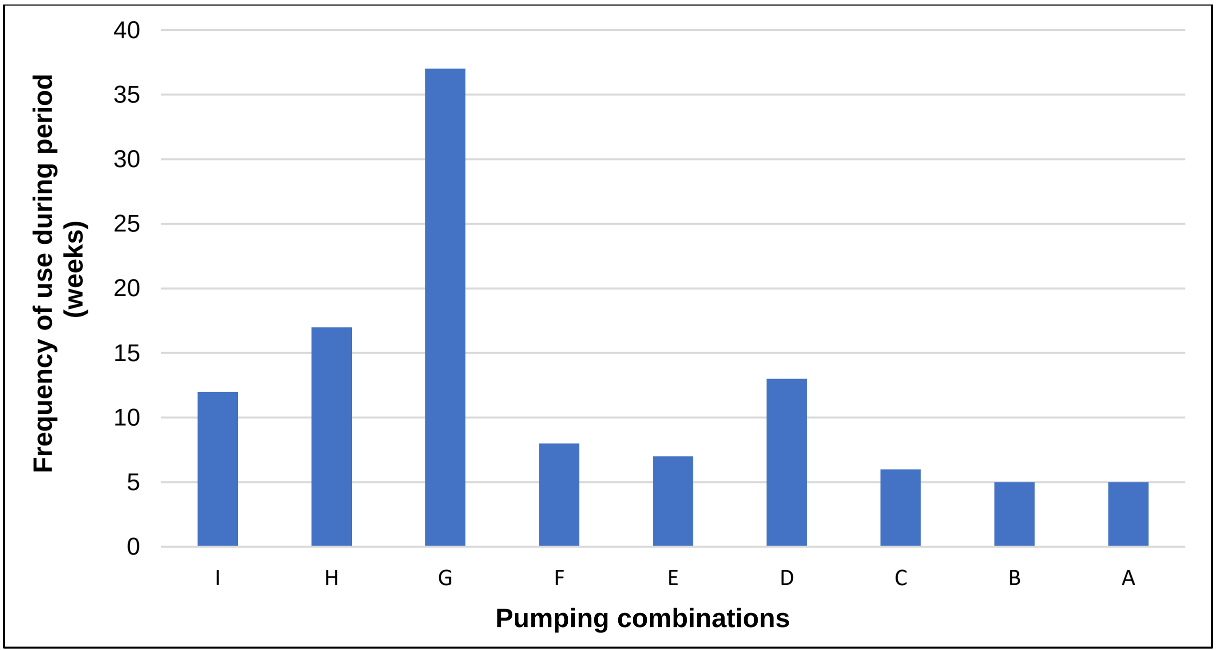


Figure 4-21: Frequency of pumping combinations used.

Figure 4-21 shows that the most used pumping combination is G, which involves three pumps at Jericho in conjunction with one pump at Kliphoek delivering a total flow of 2570 l/s. Figure 4-21 also shows that other pumping combinations are used during the period, with pumping combination H and I used when four duty pumps are available, and pumping combination G when there are three duty pumps available. Pumping combinations A-F are used during periods where the demand was less, most likely during weekends. As such it can be deduced that, the pumping combination used by the operators is dependent on the number of pumps available and the water requirements on the day and not a specific control policy.

4.6.2 Effect of water availability on weekly transfers

As discussed in Section 4.5, the transfer capacity of the Jericho pump station can be reduced when the storage levels in the Jericho dam drop significantly. This occurred in 2014 and 2015 when the Jericho pump station was only pumping half of its transfer capacity due to the dropping storage levels in the Jericho dam which were affected by the drought at the time (Department of Water & Sanitation, 2015). Aside from rainfall and its tributary river, the Jericho dam is also dependent on the Morgenstond and Westoe dam as described in Section 4.1.

Both the Morgenstond and Westoe dams were affected by the drought during the 2014/2005 period. To ascertain whether the storage levels in the Jericho dam had an impact on the weekly pumping operations as per Table 4-6 during the study period, Figure 4-22 shows the weekly dam storage percentage in relation to the weekly transferred volumes from the Jericho.

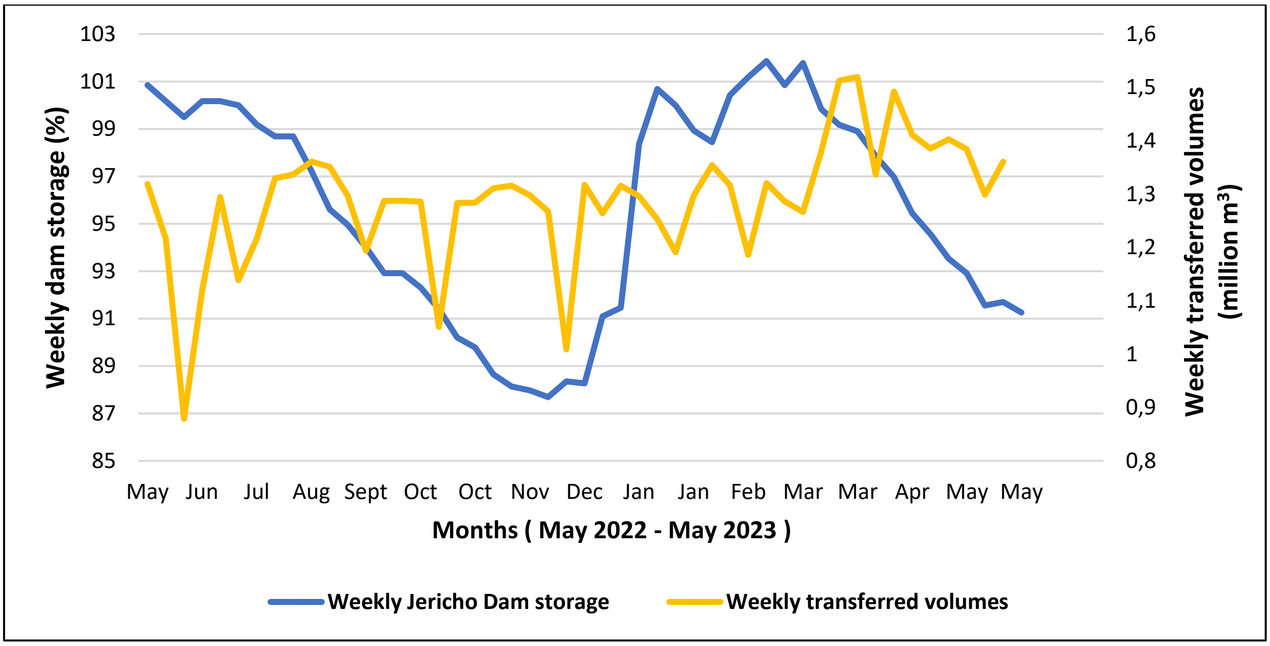


Figure 4-22: Comparison between weekly transfers and dam storage levels

From Figure 4-22, it can be deduced that the pumping operations were not affected by the storage levels in the Jericho dam for the study period. The Morgenstond and Westoe dam had average storage capacities of 99.62% and 89.15% respectively, therefore there was sufficient water to supplement the Jericho Dam if required.

As shown in the Annual Operating Analysis reports (Department of Water & Sanitation, 2015), dry seasons with low rainfall can affect pumping operations of the Jericho dam, however, for this study's period under investigation, it's clear that the dam's storage levels had little effect on the pumping operations. Consequently, the effect of the dam storage levels on the pumping operations cannot be assessed correctly on this report, and study period with a wider range of dam storage levels is required to accurately assess the effect of dam storage levels on the Jericho pumping operations.

4.6.3 Effects of pump availability on pumping operations

As shown in Figure 4-22, the weekly transferred volumes varied throughout the period and from the analysis on the dam storage levels had little impact on the pumping operations. This Section focuses on the effect of pump availability on the pumping operations.

The Jericho pump station has four duty pumps, and it was determined from the weekly pump performance reports that there were periods when there were only three duty pumps available. The effect of the missing duty pump on the pumping operations should be determined. Similarly, the Kliphoek booster pump station has two duty pumps, and there when periods were there was only one pump available. Figure 4-23 below shows the number of duty pumps that were available in comparison to the actual number of pumps that were operated.

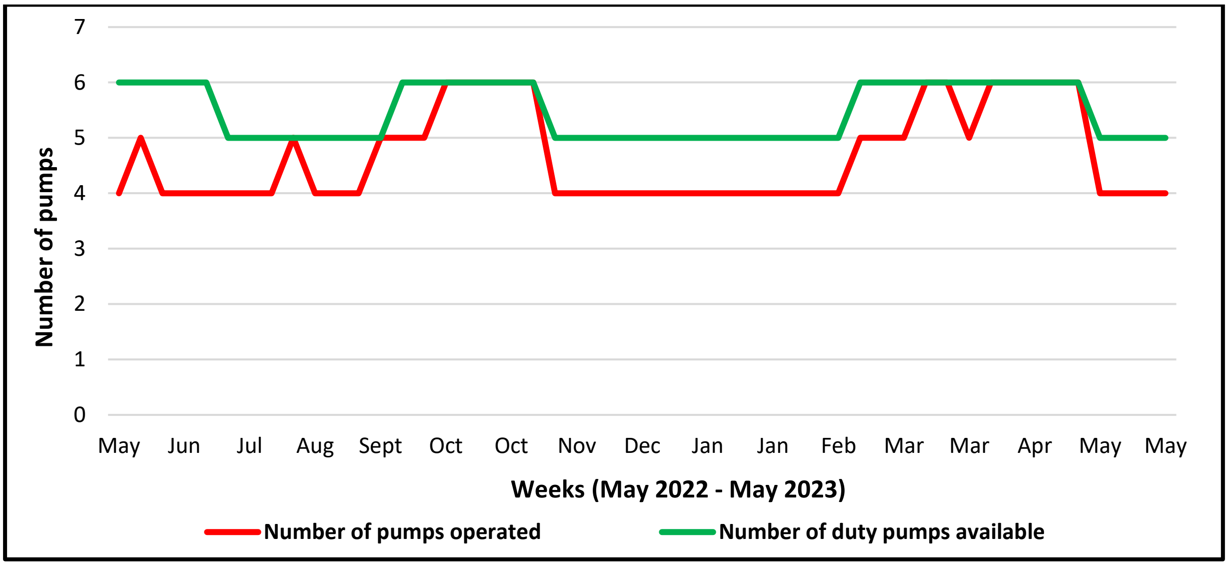


Figure 4-23: Number of duty pumps available vs operated at Jericho and Kliphoek

From Figure 4-23, it can be deduced that there were periods where the number of pumps used were less than those available. Table 4-2 showed that there is a direct correlation between the number of pumps operated and the flow rate delivered from the pump station, whereby, the more pumps operated, the higher the flow rate.

As such Figure 4-23 and Table 4-6 show that the pump station could have operated more pumps resulting in a higher flow rate and thereby reduce the pumping durations.

4.6.4 Pumping durations

An important aspect of the DWS policy is the use of optimal pump scheduling to minimize power costs by using off-peak hours. To determine whether this is adhered to at the Jericho pump station and Kliphoek booster pump station, the average daily pumping duration of each of the duty pumps based on the reported weekly pumping durations was determined for the study period and are depicted in Figure 4-24 and 4-25 respectively.

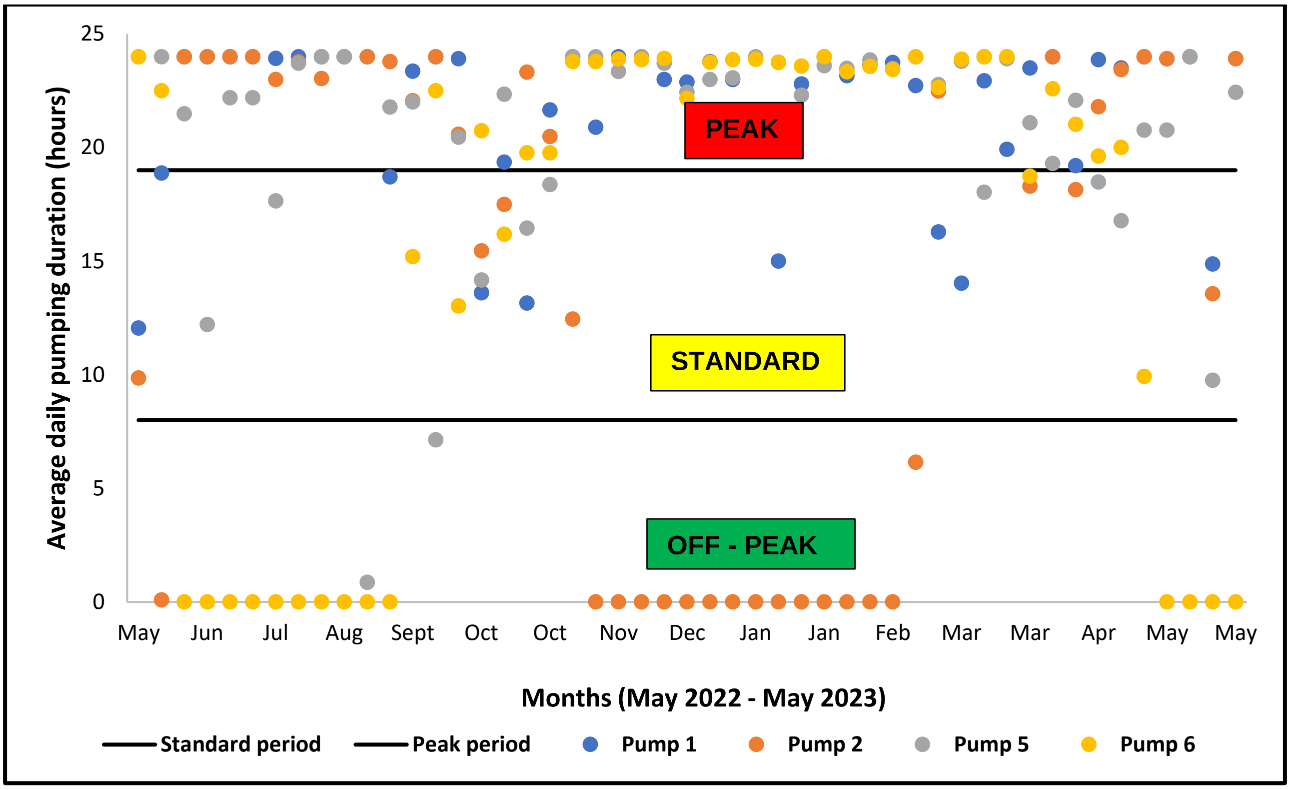


Figure 4-24: Average pumping durations of the Jericho duty pumps.

From Figure 4-24, it can be observed that most of the pumping durations extend into the peak region. This goes against the DWS policy of minimizing electricity costs by avoiding pumping during peak tariff periods. It should however be noted that the average pumping durations are not the actual daily pumping durations and are based on the weekly durations. This is because the pumps are often operated for multiple days without stopping, and as a result the operators record the time and day the pumps were switched on, and the day they are switched off in a week. When the pumps are operated throughout the week without stopping, the pumping durations are recorded as 168 hours.

Although the average daily pumping durations are only an approximation of the daily pumping durations, they are a conservative representation of the pumping duration as the pumps are operated continuously for multiple days and not intermittently. To further explain this, Pump 6 for 26 September to 3 October 2022 week in Appendix H, has a recorded pumping duration of 145.2 hours. This is equivalent to an average daily pumping duration of 20.7 hours, however, in actuality, the pump was operated 6 days continuously and switched off for one day. Consequently, using the average pumping durations, the number of hours when pumping occurred during peak periods is **8.5** hours, however, in actuality, the number of hours is **25** hours.

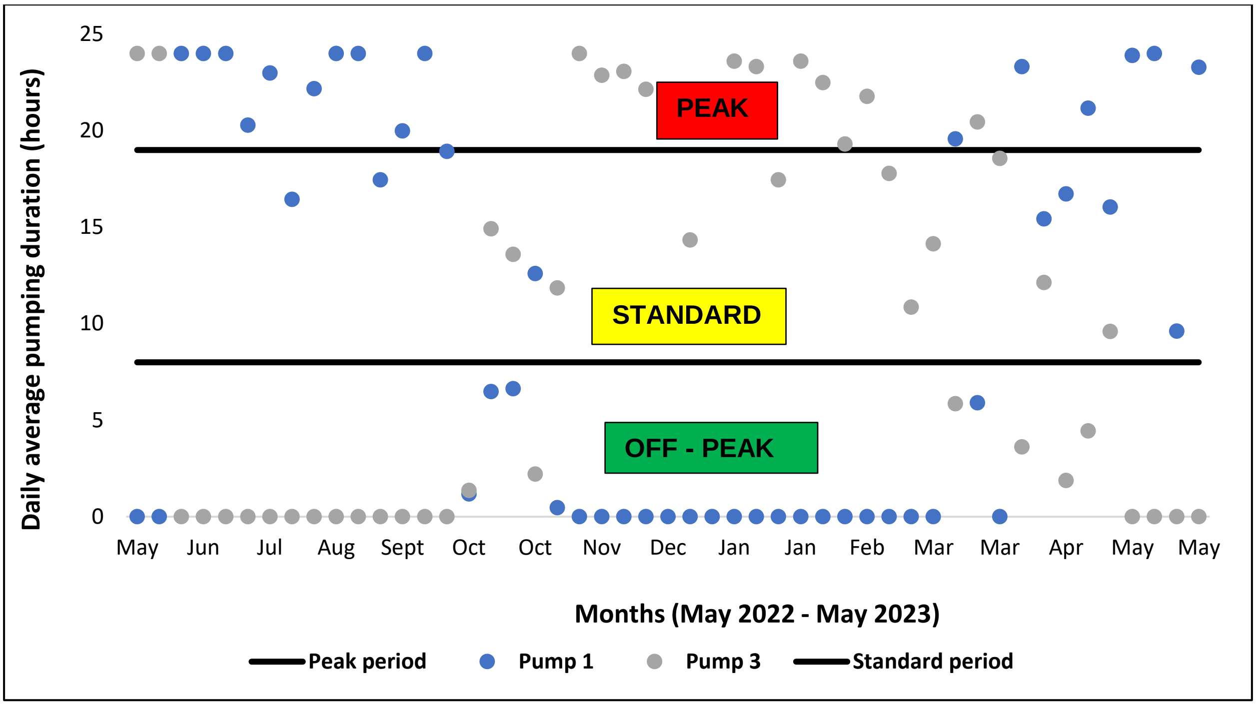


Figure 4-25: Average pumping durations of the Kliphoek duty pumps

Similarly, to the Jericho pump station, the duty pumps are also operated during peak periods, additionally, the pumping durations indicate that one duty pump is usually operated at a time. There are more instances where the average pumping durations are below the peak pumping period, than at Jericho. This is because the pumps at Kliphoek can only be operated if two pumps are operated simultaneously pumping into the same pipeline to ensure sufficient back pressure for the Kliphoek pumps as discussed in Section 4.1.

4.7 Pump operational data

4.7.1 Original performance data

The pumps in the Jericho pump station were originally commissioned with a duty flow rate of *972 l/s* (3500 m3/h) at a pressure head of *300 m* with a pumping efficiency of *88%*. The original control policy prior to the increases in demand and system upgrades, was to operate a single pump per rising main as discussed in Section 4.2.

The six pumps at Jericho pump station have identical pump curves and all operated at the same duty point. Figures 4-26 and 4-27 show the performance and efficiency curves of these installed pumps at the Jericho pump station, and Figure 4-28 shows the relation between the power consumption of the pump and the flow rate delivered by the pump.

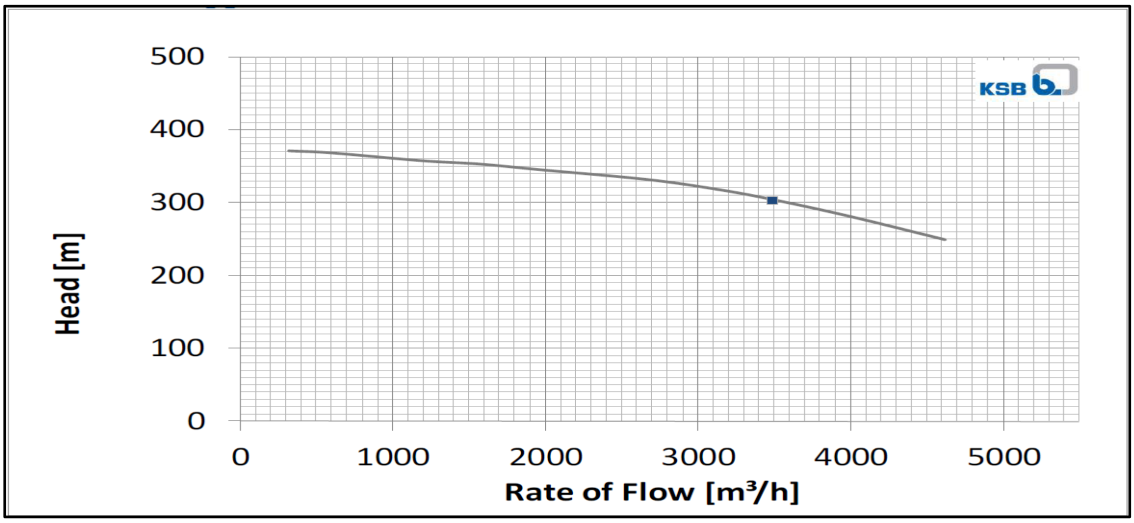


Figure 4-26: Pump performance curve and original duty point (KSB Service, 2013)

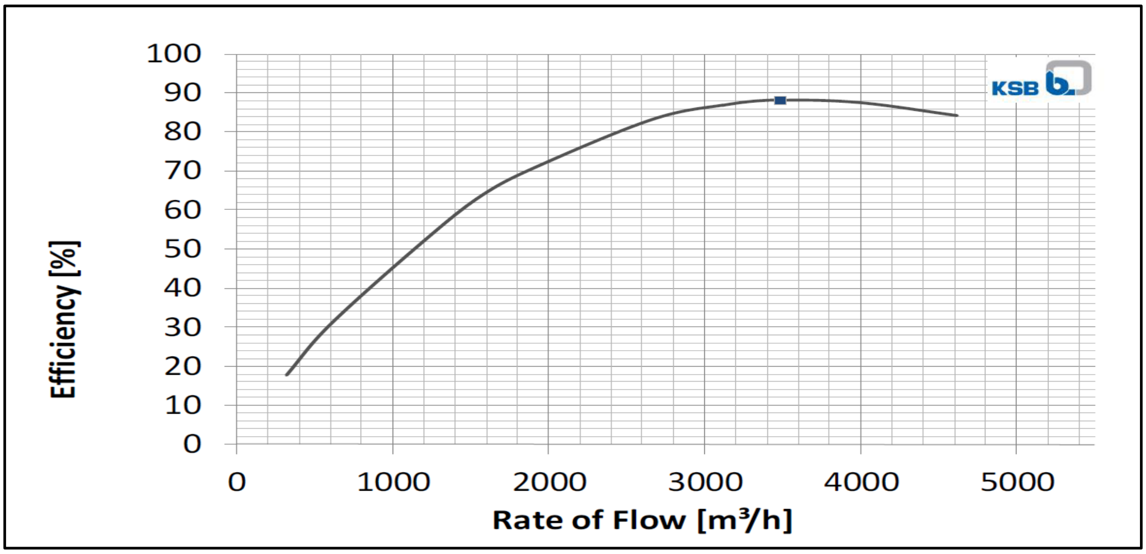


Figure 4-27: Efficiency curve of the installed pump (KSB Service, 2013)

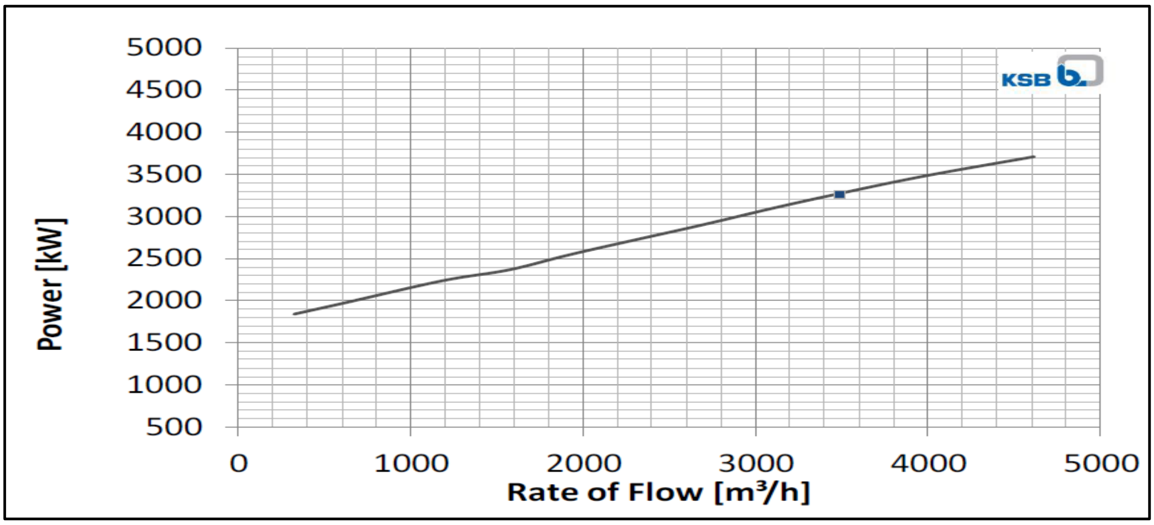


Figure 4-28: Power consumption curve for installed pumps (KSB Service, 2013)

The original pump and efficiency curves of the Kliphoek pump station could not be obtained. However, the original duty point of the installed pumps was obtained from DWS records and the pump curve was generated through pump testing in a DWS report (Niebuhr, 2015). The pump station was commissioned with a duty flow rate of 1680 l/s at a head of 114 m.

4.7.2 Change in system characteristic curve

As detailed in Section 4.2, the pipelines from Jericho to the Onverwacht reservoirs were re-lined with cement mortar in 2002. The re-lining significantly reduced the internal pipe diameter which drastically changed the system characteristic curve. Figure 4-29 shows the system curves before and after the re-lining of the pumps, as well as the pump curves for: single operation at the Jericho pump station, parallel combination two pumps pumping into one pipeline at Jericho, and a parallel combination of the two pumps at Jericho in conjunction with a booster pump at Kliphoek in one pipeline.

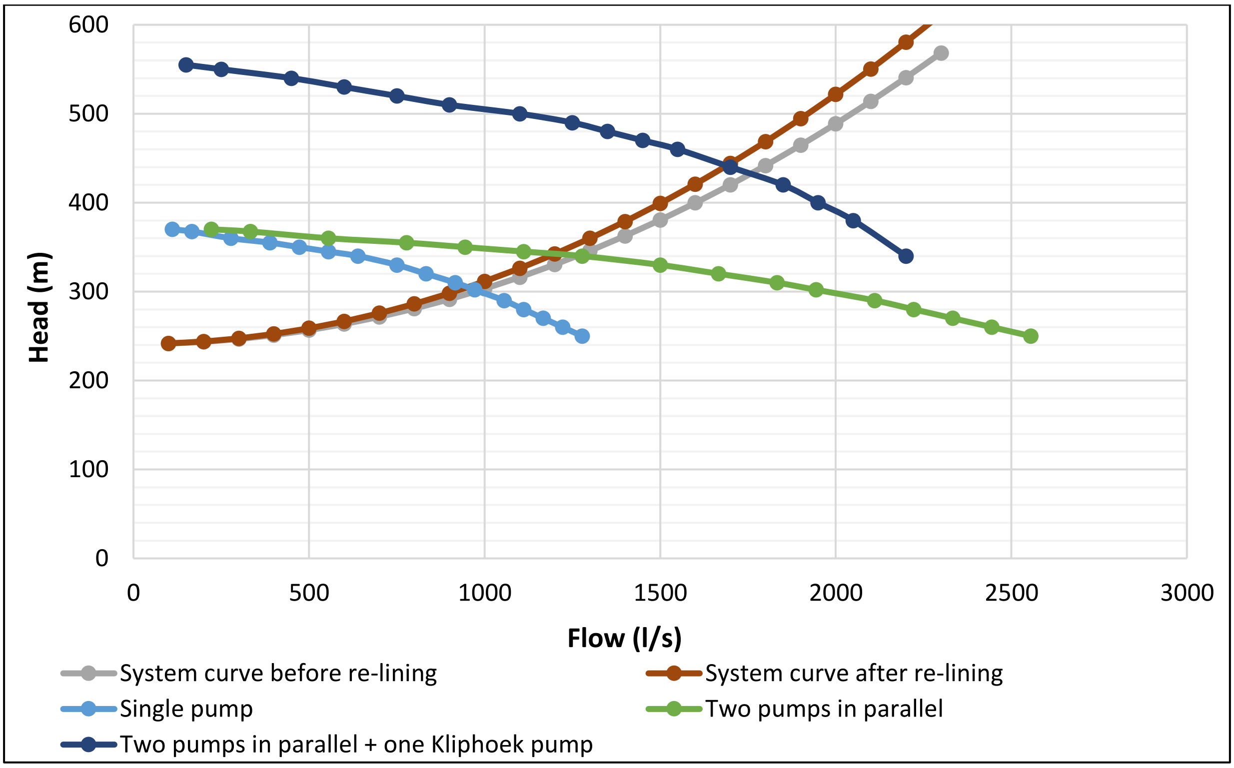


Figure 4-29: Jericho pump station system curves and pump curves.

The lining of pipeline generally deteriorates over long periods of time increasing the pipe surface roughness, resulting in increased frictional losses. This has an impact in the system curve of the pumping system; however, this impact is usually minimal and taken into consideration in the design phase as the gradual increase in pipe roughness over time is generally known.

Figure 4-29 shows that the change in the system curve due to the re-lining resulted in a drop of flow rate from 1770 l/s to 1650 l/s when two pumps are operated in parallel in conjunction with one pump at Kliphoek. This drop in flow rate can be quantified as a 6.8 % decline for each pipeline after the pipeline relining. Consequently, less flow is pumped at a given time leading to an increase in pumping durations to meet the required demand. The increased pumping durations result in more operational costs and potentially operations during peak periods.

4.7.3 Effect of Kliphoek booster pump station on Jericho pumping operations

As described in Section 4.1, water pumped from Jericho pump station to the Onverwacht reservoirs can pass through Kliphoek booster pump station or bypass it. The booster pumps at Kliphoek increase the discharge pressure and the flow rate being pumped, as per Table 4-1. When Jericho and Kliphoek are operated in conjunction with two pumps at Jericho and one pump at Kliphoek, the pumping dynamics are as shown in Figure 4-30 with the Kliphoek pump curve adapted from Niebuhr (2015) and the Jericho pump curves adapted from Figure 4-26.

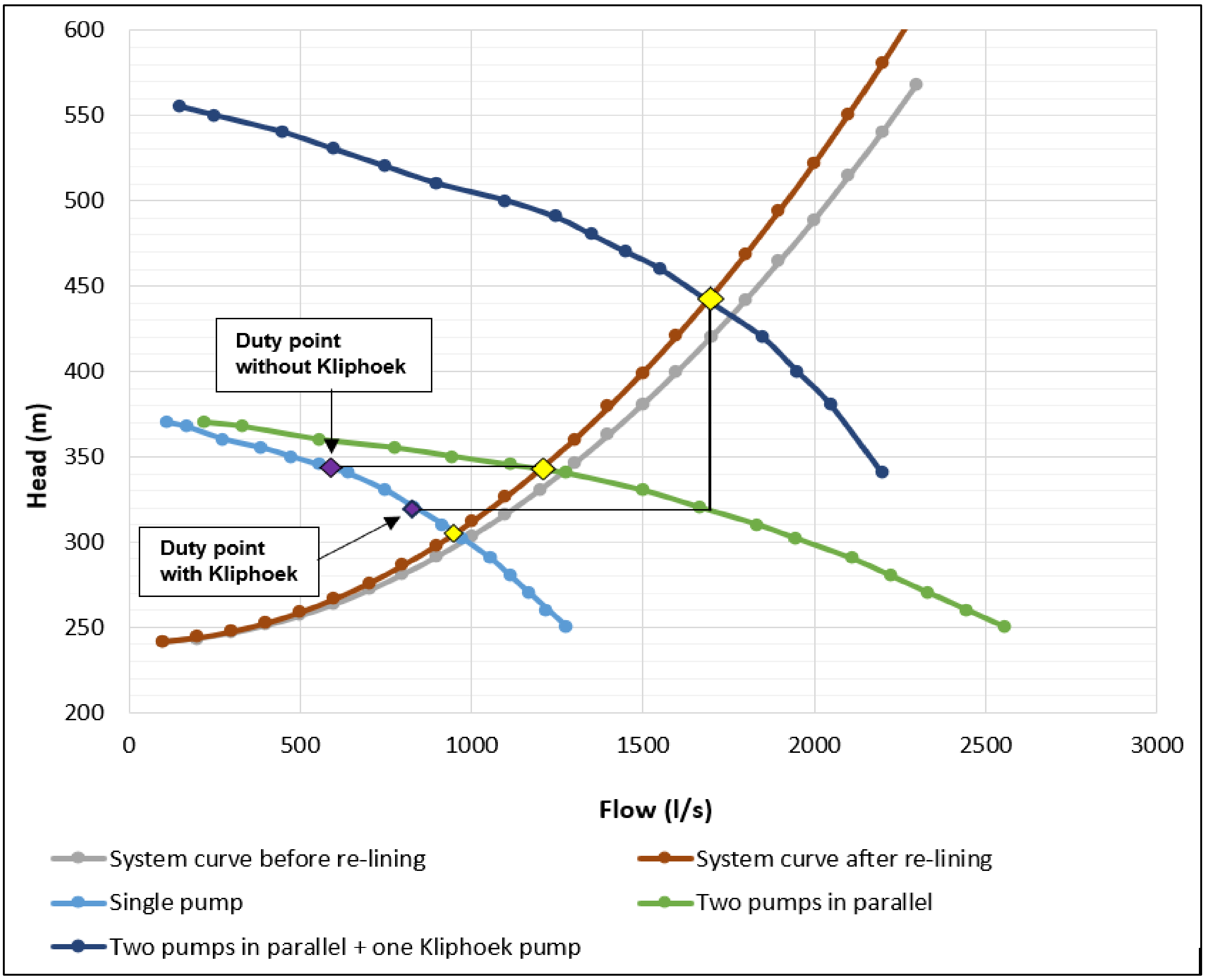


Figure 4-30: Effect of Kliphoek pump station on the Jericho pump curve and flow rate

Figure 4-30 shows that the addition of Kliphoek indeed does not only increases the system discharge pressure but also increases the delivered flow rate from 1135 l/s to 1650 l/s. This is because the addition of Kliphoek pump station reduces the pumping head on the Jericho pumps, resulting in the duty point on the pump curve moving to the right increasing the pumped flow rate as shown in Figure 4-30.

4.7.4 Power consumption data

Assessment of a pump's energy use is based on its hydraulic power consumption which is dependent on the pressure head, the flow delivered and the pumping efficiency. The hydraulic power consumption of each of the pumps at Jericho pump station for each pumping combinations listed in Table 4-1 were determined using the pump delivery flow and the pumping efficiency at the pumping duty, using Figure 4-30. The power consumption of the Kliphoek booster pump station was reported to be 2134 kW (Hatch, 2017a). Table 4-7 and 4-8 shows the power consumption values for the individual pumps at Jericho and Kliphoek in each of the modes of operation and of the different pumping combinations respectively.

Table 4-7: Power consumptions of Jericho pumps in the different operational modes

Mode of operation	**Power consumption (kW)**
Single operation	3200
In parallel combination	2600
In parallel combination + Kliphoek pump	3050

From Table 4-7, its shown that the pumps at the Jericho pump station consume the most power when operated individually and consume the least power when operated in parallel without the Kliphoek pumps operating. This is because the Jericho pumping system was originally designed to operate one pump individually, and as a result the pumps deliver the most flow when run individually and consequently consume the most power. When two pumps are operated in parallel, each pump delivers considerably less flow due to the steep system curve as shown in Figure 4-30, and as a result consume less power.

The addition of the Kliphoek pump operating in conjunction with two pumps operating in parallel at Jericho, increase the delivered flow for each pump at Jericho as shown in Figure 4-30. Consequently, the pumps at Jericho consume more power when operated in conjunction with Kliphoek than without as shown in Table 4-7.

Table 4-8: Total power consumption of the pumping combinations

Pump combination	Jericho pump station		Kliphoek pump station		Total power consumption (kW)
	No. of pumps operating	Power consumption (kW)	No. of pumps operational	Power consumption (kW)	
A	1	3200	0	0	3200
B	2	6400	0	0	6400
C	2	5200	0	0	5200
D	3	8400	0	0	8400
E	4	10400	0	0	10400
F	2	6100	1	2134	8234
G	3	9300	1	2134	11434
H	4	11300	1	2134	13434
I	4	12200	2	4268	16468

Table 4-8 shows that the power consumptions of the two commonly used pumping combinations (G and H) are considerably high compared to the rest of the combinations which involve less pumps operating. Furthermore, as detailed in Table 4-7 the pumps at Jericho consume more power when operated individually than in parallel, which is shown as pumping combination B (two pumps run individually in two different pipelines) consumes more power than C (two pumps run in parallel into one pipeline).

4.8 Conclusion to the Data collection

The Jericho pump station has had to manage various demands and changes throughout its operational life. The effect of these demand increases, and changes have resulted in the pump station undergoing various upgrades and modifications and changes in its operational policies.

4.8.1 Control policy

There currently isn't a document detailing the control policy of the pump station as the policy has changed several times due to the upgrades and system changes. The current policy is to simply meet the daily water demands using the minimum required number of pumps. This is further seen in the weekly pump performance reports detailed in Section 4.6, which show that there is not a fixed pumping combination used, with the pumping combinations primarily dependent on the daily water demand.

A correlation between the pump availability at the Jericho pump station and Kliphoek booster pump station and the pumping combination used was also analysed in Section 4.6.3, and although the pump availability played a factor on which pumping combinations could be used, pump availability was determined to not be a limiting factor on the pumping operations.

Water availability was shown to have affected the Jericho pump station's transfer capacity during dry seasons, where the pumping capacity was reduced due to significant drops in the Jericho dam storage. As for the study period between May 2022 and May 2023, the storage levels in the Jericho dam remained fairly high and there was no impact on the pumping operations, as detailed in Section 4.6.2.

4.8.2 Limitations on data collection

As detailed in Section 4.5.4, the actual daily pumping durations could be obtained, and the average daily pumping durations are based off the weekly durations that the operators record weekly. Consequently, the average daily pumping durations were used to assess the adherence of the Jericho pump station to the DWS policy. Information on the pumping efficiencies of the Kliphoek pumps could not be obtained.

4.8.3 Demand growth and system changes

There has been considerable growth in the water demand managed by the Jericho pump station primarily due to the growing need for electricity in the South Africa population and the growth in the recipient municipalities of the pump station. These increases resulted in upgrades to the pump station, which resulted in changes in the control policy and pumping operations.

Aside from the pump station, the Onverwacht reservoirs have also been affected by the growth in water demand as more water must be supplied from the reservoirs. Furthermore, the reservoirs cannot be allowed to drop below 60%, consequently they now have shorter periods of storage availability without inflow coming from the Jericho pump station due to the increased demand.

The deterioration of the pipeline lining resulted in the use of cement mortar lining in the pipelines. This reduced the transfer capacity of the pumping system as a result of the increased frictional losses and resulted in increased pumping durations, affecting the control policy with regards to how the pump station is operated.

Chapter 5 : Assessment and quantification of the effects of demand and system changes

In this chapter, the effects of the demand changes and uncertainties on the Jericho pump station are assessed and quantified. Four ways are used to assess the effects of demand changes and uncertainties on the operational performance of Jericho pump station, namely:

- Adherence to the control policy.
- The operational performance of the pump station.
- The energy costs associated with the current operational control policy.
- Energy costs associated with the uncertainties that affected the pump station.

5.1 Adherence to the control policy

Currently, there is no official document on the control policy of the Jericho pump station. The pump station and bulk water transfer system have undergone several changes in relation to the demand throughout their operational lives, which has resulted in changes in how they're operated and as a consequence the original control policy has become redundant.

Currently, operators run the minimum number of pumps required to fill the Onverwacht reservoirs. There is no consideration of power supply peak periods as the pumps were run continuously to meet the demand. It should be noted that although the AOA (Annual Operating Analysis) of the Integrated Vaal River System provides annual demand targets to be met, which are used to guide operators at Jericho on the target volumes they must provide, there is no guidance provided on how the task of meeting target volume must be accomplished.

5.1.1 Pump scheduling

The analysis of the recorded weekly pumping durations of the installed pumps at the Jericho pump station from May 2022 to May 2023 in Section 4.6 showed the following:

- Figure 4-23 and 4-24 showed that at least three pumps at the Jericho pump station and one pump at Kliphoek were operated throughout the peak tariff periods daily.
- There were no restrictions on the transfer capacity of the pump station due to water availability in the Jericho dam.
- There were periods when the pump station operated below the available transfer capacity resulting in increased pumping durations.
- As a result of the continuous pumping throughout the week, the pumps were operated throughout the peak tariff periods.

Using the recorded pumping durations of the individual pumps during which they were operated for the weeks between May 2022 and May 2023, the average weekly pumping duration for the duty pumps at Jericho and Kliphoek were determined. Considering the operator's reports that the pumps are operated continuously and stopped during periods of low demands which is usually weekends, and an additional pump at Jericho is added when required during periods of high demand. The weekly pumping durations are as depicted in Figure 5-1.

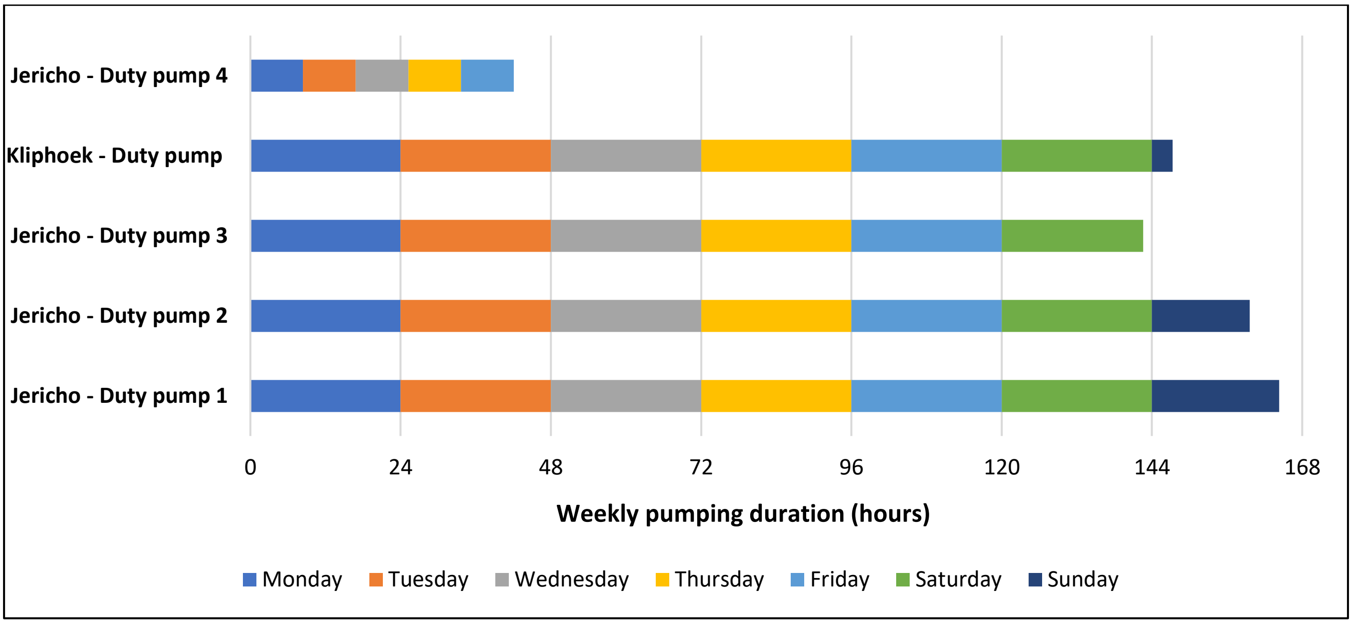


Figure 5-1: Average weekly pumping durations for the Jericho and Kliphoek pumps

Figure 5-1 shows that the average pumping durations of duty pumps 1 - 3 at Jericho and duty pump 1 at Kliphoek extend throughout the week and only stop during weekends when the demand has reduced. During the week, these pumps operate throughout the peak periods due to the continuous pumping operations. This aligns with pumping combination G, which was the most used pumping combination as determined in Figure 4-20 of Section 4.6.1.

Duty pump 4 at Jericho has a considerably less average pumping duration and was operated during periods of high demand. For the purposes of this study, the pumping duration in which duty pump 4 at Jericho was operated is assumed to be spread evenly during the week. Considering that the primary end users of the pumped water are Eskom power stations, it can be deduced that periods of high demands are peak and standard periods. As it can be assumed that these pumps were operated during these periods.

Figure 5-1 also shows that only one pump is primarily operated at a time at Kliphoek despite the pump station having been designed for and with the capacity to operate two duty pumps.

The optimal period to operate a pump is during off-peak period which is eight (8) hours in total, and if required also during standard period which is eleven (11) hours in total. This gives a total of 19 hours where cost-effective pumping operations can be done. As discussed in Section 2.3.2 and depicted in Figure 2-7, peak periods are only applicable during weekdays, with Saturday having a mix of standard and off-peak periods, and Sunday only having off-peak periods.

Therefore, pumping operations during peak periods can only be minimized during weekdays, and pump scheduling during Saturdays only involves standard and off-peak periods. To provide a clearer representation the average pumping durations during weekdays, Saturdays and Sundays must be assessed. Figure 5-2 shows a representation of the pump scheduling of the duty pumps at Jericho and Kliphoek during weekdays with Saturdays and Sundays excluded.

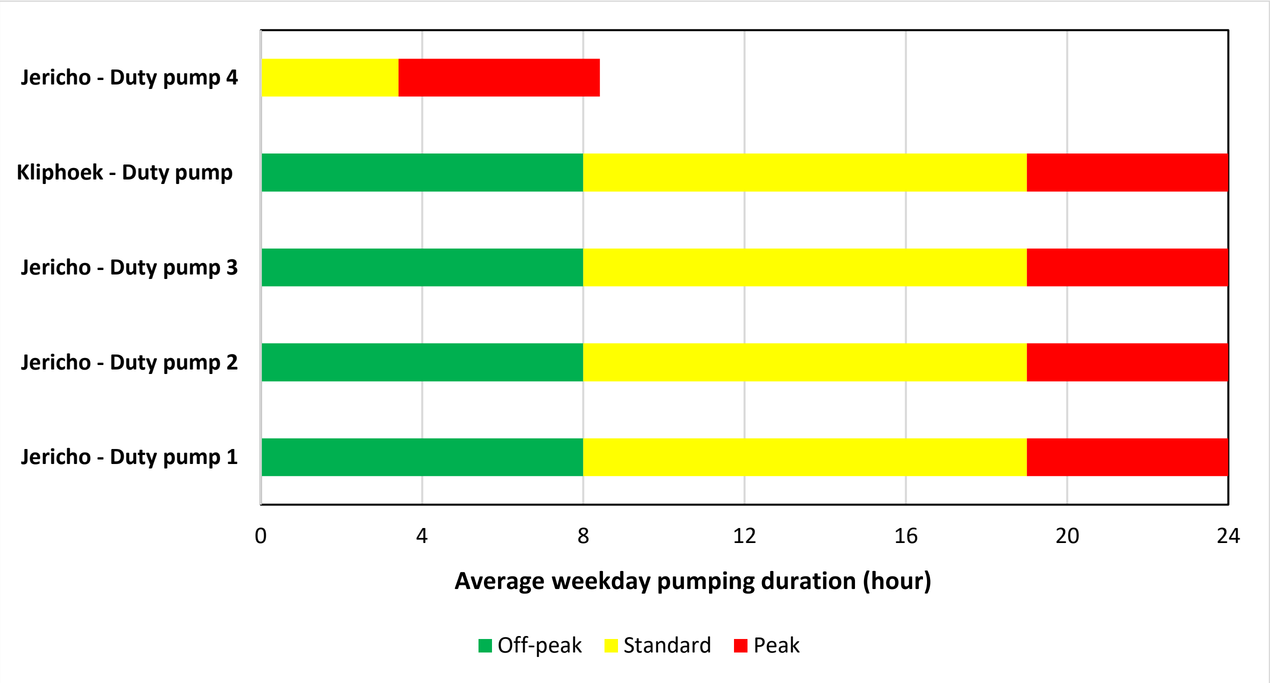


Figure 5-2: Average weekday pump scheduling of the Jericho and Kliphoek duty pumps

As Figure 5-2 is a clearer representation of what occurs on an average weekday at the Jericho and Kliphoek pump stations. It will be used as a basis in the quantification of the energy costs and the improvement of the pump scheduling. The Saturday and Sunday pump scheduling are depicted in Figures 5-3 and 5-4.

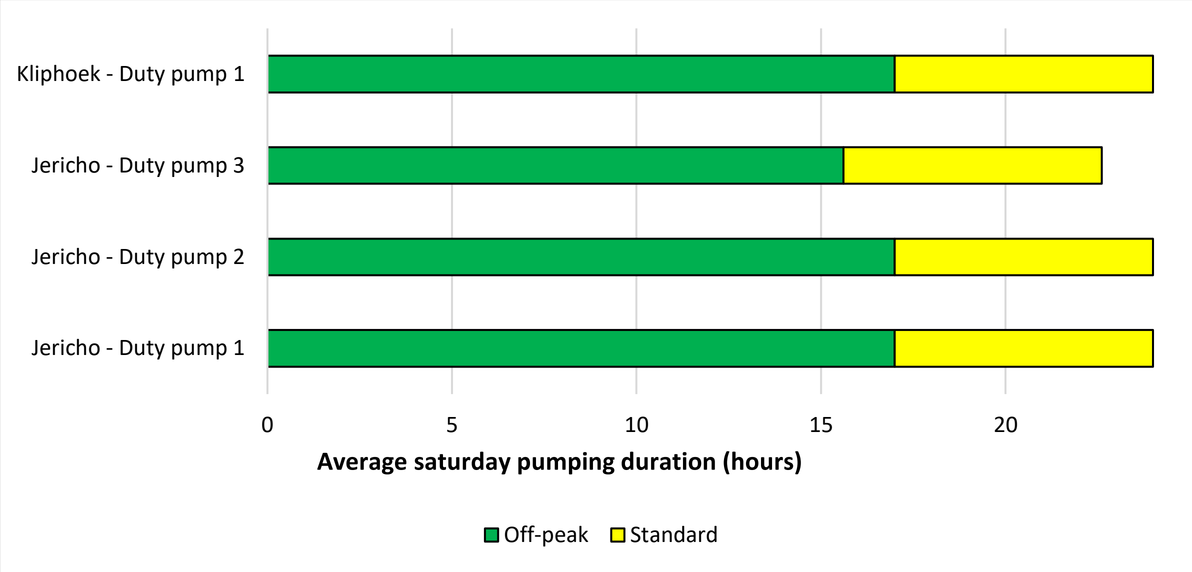


Figure 5-3: Average Saturday pump scheduling of the Jericho and Kliphoek duty pumps

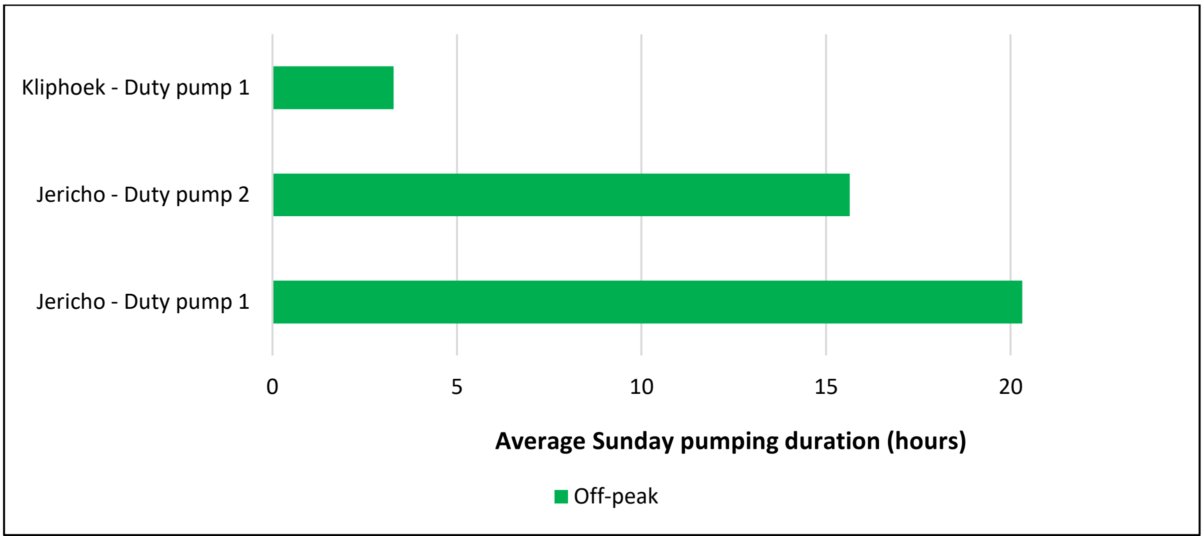


Figure 5-4: Average Sunday pump scheduling of the Jericho and Kliphoek duty pumps

In conclusion, it is clear that pumps are being operated at peak times, incurring high energy costs, and increasing demand that the power utilities must supply during peak times. It is also evident that additional off-peak period pumping could probably be done on Sundays if the storage capacity of the system is sufficient. The associated energy costs are quantified in Section 5.3. It is also evident that additional off-peak period pumping could probably be done on Sundays if the storage capacity of the system would enable that.

Therefore, in order to assess whether the current pump scheduling can be optimized to minimize the cost of the pumping operations, an analysis that relates; the supply from the pumps (based on pumping schedule), the demand from the system, and the storage capacity of the system needs to be done. This analysis that includes a mass balance of the system and identification of any constraints is done in Section 6.1.

5.1.2 Frequency of pump starts and pump throttling.

The Jericho pump station is operated on a continuous basis, where the primary duty pumps are operated for multiple days without being switched off. Therefore, in terms of frequency of pump starts, the pump starts are well below the recommended the number of pumps starts as per Section 2.3.3 and are therefore not shortening the life of the motor and the pump assembly.

The pumps at the Jericho pump station are not throttled during normal operations, and only throttled during filling of the pipelines after maintenance work on the pipelines. Therefore, in terms of pump throttling the Jericho pump station is adhering to the DWS policy.

5.1.3 Efficient operations and matching the target demand.

Based on the obtained data in Section 4.2, the re-lining of the rising main pipelines has had a detrimental effect on the pumping capacity of the installed pumps at Jericho. Additionally, the increase in demand has resulted in shorter periods of storage availability at the Onverwacht reservoirs, requiring more frequent pumping as the demand has increased and reservoirs are no longer allowed to draw below 60% capacity.

Section 4.5.1 also details how the Jericho pump station has not consistently met the Eskom demands. However, there are other factors such as water availability, maintenance downtime and dysfunctional infrastructure that have played a factor. As such to determine how the Jericho pump station is performing, an in-depth assessment will be performed on the study period (May 2022 - May 2023) for this research study, taking into consideration all the constraints that could have played a part. These are shown in Section 5.2

5.2 Performance and efficiency of operations

5.2.1 Demand targets

According to the DWS policy discussed in Section 2.3, pump stations should be operated so as to meet the required demand. The ability of a pump station to meet the required demand is dependent two factors, namely: the availability of a water resource with sufficient water and the pumping capacity capable of matching or exceeding the required demand.

The water resource must be capable of supplying the required yield, while ensuring that there is spare capacity for ecological needs, recreational needs and storage for low inflow periods. As a result, there is usually a constraint placed on the amount of water that can be drawn from a water resource. These constraints are provided on the Annual Operating Analysis (AOA) as operating rules which are obtained through optimization of the Water Resource Planning Model (WRPM) taking into account factors such as rainfall patterns and future demands as discussed in Section 3.3. The pumping capacity of a pump station is dependent on the number of pumps available and their individual and combined capacities. Using the weekly pump performance report which details the number of pumps available on a weekly basis and Section 4.2 with regards to flow rates of the various pump combinations, the maximum pumping capacity throughout the study period can be determined.

To ascertain how well the Jericho pump station has met the required demand, the weekly transferred volumes will be compared to the weekly transfer demand targets set during the study period. The maximum pumping capacity for each week, as well as the maximum allowable supply that can be drawn from the Jericho dam for each week will be taken into consideration. The maximum allowable supply from the Jericho Dam for each week and the weekly demand targets for the study period was obtained from the 2022/2023 AOA operating rules. The weekly transferred volumes during the study period were obtained from the Operator at the Jericho pump station. Figure 5-5 shows the comparison between the four aspects discussed above.

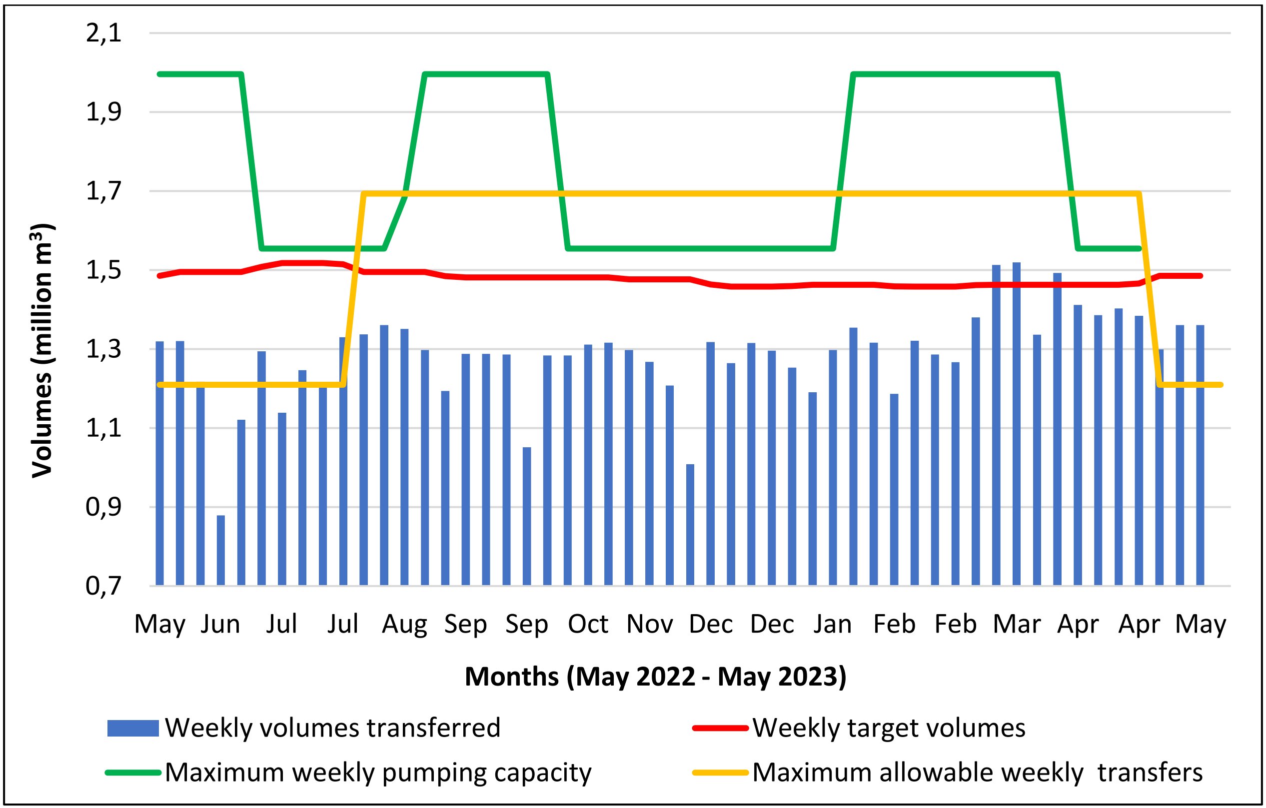


Figure 5-5: Performance metrics on the weekly transfers for the Jericho pump station during the study period.

Figure 5-5 shows that water transfer limits were placed on the Jericho pump station between May and July in 2022 and in May 2023, during which the weekly targets could not be met, however, the pump station failed to meet the weekly targets (See Appendix A) between August 2022 and April 2023 despite the both the weekly pumping capacity and maximum allowable weekly transfer as the AOA being above the weekly targets. To simplify and make the assessment of Figure 5-5 clearer, a performance indicator will be used.

The operational performance of the Jericho pump station will be quantified using a performance indicator, which will show how well the pump station manages its demand based on the information on Figure 5-5 and Equation 3-1 as described in Section 3.4.2.1. The results of the performance throughout the study period are depicted in Figure 5-6 where the values between 0 and 1 indicate how well the pump station has met the demand target.

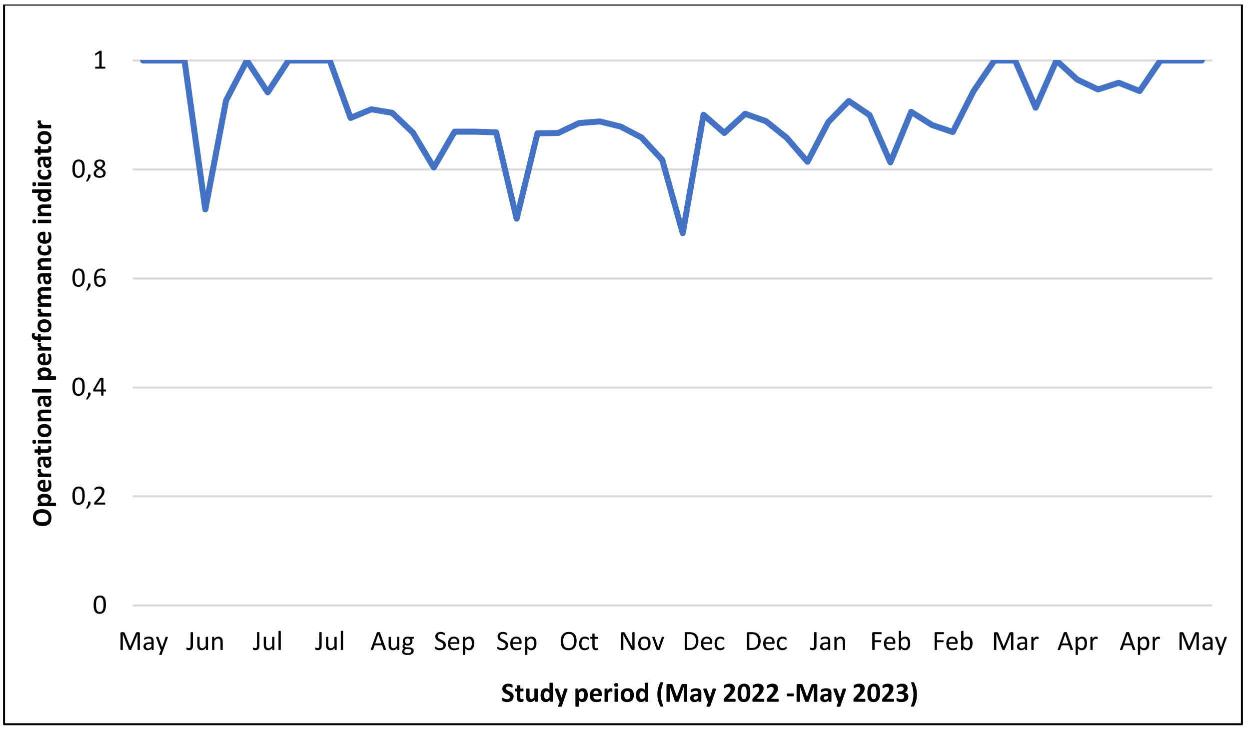


Figure 5-6: Jericho pump station operational performance during the study period

From the operational performance indicator in Figure 5-6, the Jericho pump station did not consistently meet the required demand particularly between August 2022 and February 2023 despite being capable of doing so as shown in Figure 5-5. The average performance of the pump station during the period is 0.906.

Although the pump station has not consistently met the demand within the study period, it has performed reasonably well.

5.2.2 Pumping efficiency

As detailed in Sections 2.4.1 and 2.5.3 of the literature study, the pumping efficiency plays a critical role in the energy costs of the operation and stable operations without unfavourable conditions such as noise, vibrations, and cavitation.

It should be noted that the pumping efficiencies are not only dependent on the pumping combinations, but also on the system characteristics. As discussed in Section 4.1, the rising mains were re-lined with cement mortar due to the deteriorated condition of the lining in the pipelines at the time, reducing the transfer capacity of the pump station and negatively affecting the pumping efficiencies.

From Figure 4-30 in Section 4.7.3, it can be observed that the system curve moved to the left following the re-lining, consequently, the duty points (intersection between system curve and pump curve) also moved to left resulting in a reduction of the flow rate being pumped. The reduction in flow rate means that the pumping duration must increase to compensate for the flow reduction.

Table 5-1 shows the flow rates of the pump in each of the pumping combinations and the corresponding pumping efficiency based of the efficiency curve of the installed pump in Section 4.7.1 (Figure 4-27), before and after the rising mains were re-lined.

Table 5-1: Pump combination flow rates and the Jericho pumping efficiency for each combination *(KSB Service, 2013)*

Pump combination	Pipeline	Prior to re-lining (< 2003)			After re-lining (> 2003)		
		Flow rate (l/s)	Individual Pumping efficiency (%)	Total Jericho pumping system efficiency (%)	Flow rate (l/s)	Individual pumping efficiency (%)	Total Jericho pumping system efficiency (%)
A	North	972	88	88	920	87.5	87.5
	South	0	-		0	-	
B	North	972	88	88	920	87.5	87.5
	South	972	88		920	87.5	
C	North	1270	77	77	1135	72	72
	South	0	-		0	-	
D	North	1270	77	82.5	1135	72	79.75
	South	972	88		920	87.5	
E	North	1270	77	77	1135	72	72
	South	1270	77		1135	72	
F	North	1770	86	86	1650	85	85
	South	0	-		0	-	
G	North	1770	86	87	1650	85	86.25
	South	972	88		920	87.5	
H	North	1770	86	81.5	1650	85	78.5
	South	1270	77		1135	72	
I	North	1770	86	86	1650	85	85
	South	1770	86		1650	85	

Table 5-1 shows that in terms of efficient operations, pump combination A, B, F, G and I are preferred. Pump combinations C, D, E and H are the least efficient of the pump combinations. Figure 5-7 shows graphical representation of the effect of the re-lining. Additionally, the three most frequent pumping combinations during the study period are shown ranked from the most frequent to the third most frequent.

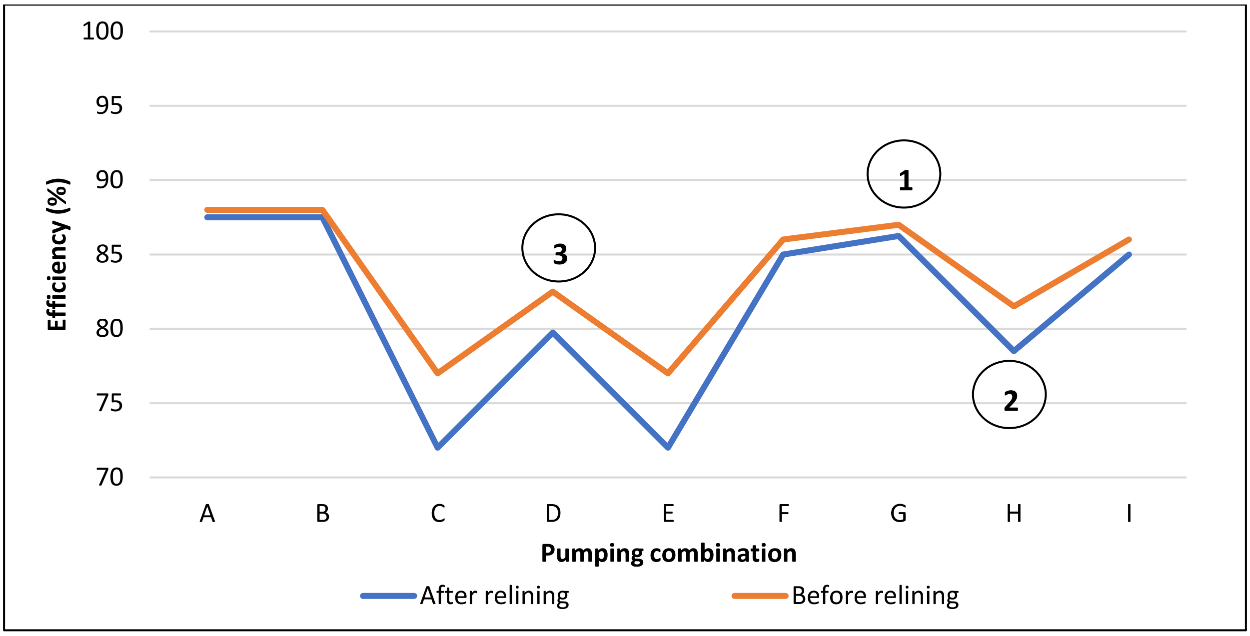


Figure 5-7: Pumping efficiencies before and after relining of the pipelines.

Figure 5-7 shows that the relining of the pipelines had a detrimental effect on the pumping efficiencies, particularly those belonging to pumping combination C, D, E and H. Based on the information discussed in Section 4.5.1, the most frequent pump combinations that were used during the study period, were G, H and D in that order. Pump combination H and D are among those negatively impacted by the re-lining of the pipelines.

Using Equation 3-2 (Section 3.4.2.2, Page 55) the efficiency losses for pumping combination C, D, E and H, were: 5%; 2.755%; 5% and 3% respectively.

As discussed in Section 4.7.1, the pump curves of the Kliphoek booster pump station could not be obtained and as result the pumping efficiency could not be obtained. However, using the installed flow meters, when operated each pump at Kliphoek delivers a flow rate of 1630 l/s which is a 3% reduction from the flow rate of 1680 l/s prior to the re-lining of the pipelines. Based on the information discussed above, it's clear that the relining had a negative impact on both the pumping efficiencies of the Jericho and Kliphoek pump stations.

5.3 Energy costs

To quantify the effects of the changes in demand on the energy costs, two aspects will be considered, namely: Time-of-Use (TOU) and the pumping efficiency.

5.3.1 Tariff charge profiles

Figure 5-8 shows the structure of the tariff charges throughout a normal weekday, with the peak, standard and off-peak hours indicated.

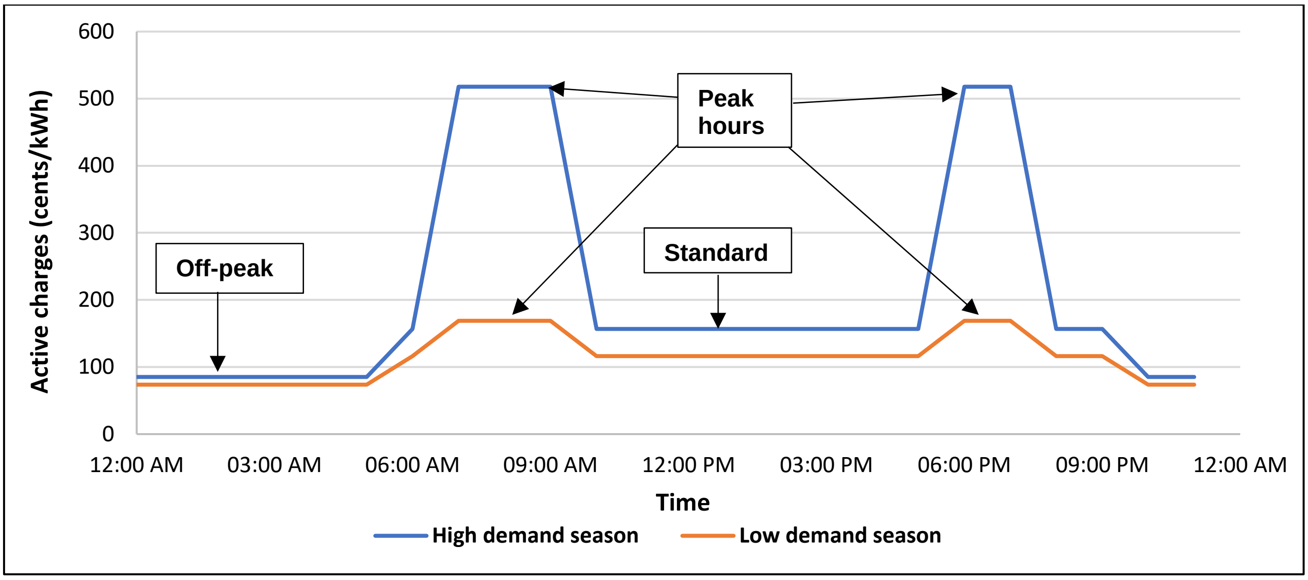


Figure 5-8: 2022 Eskom active tariff charges profile in a weekday

Figure 5-9 shows that the structure of the tariff charges throughout a weekend, with the standard and off-peak hours indicated. It should be noted that there are no peak hours during weekends.

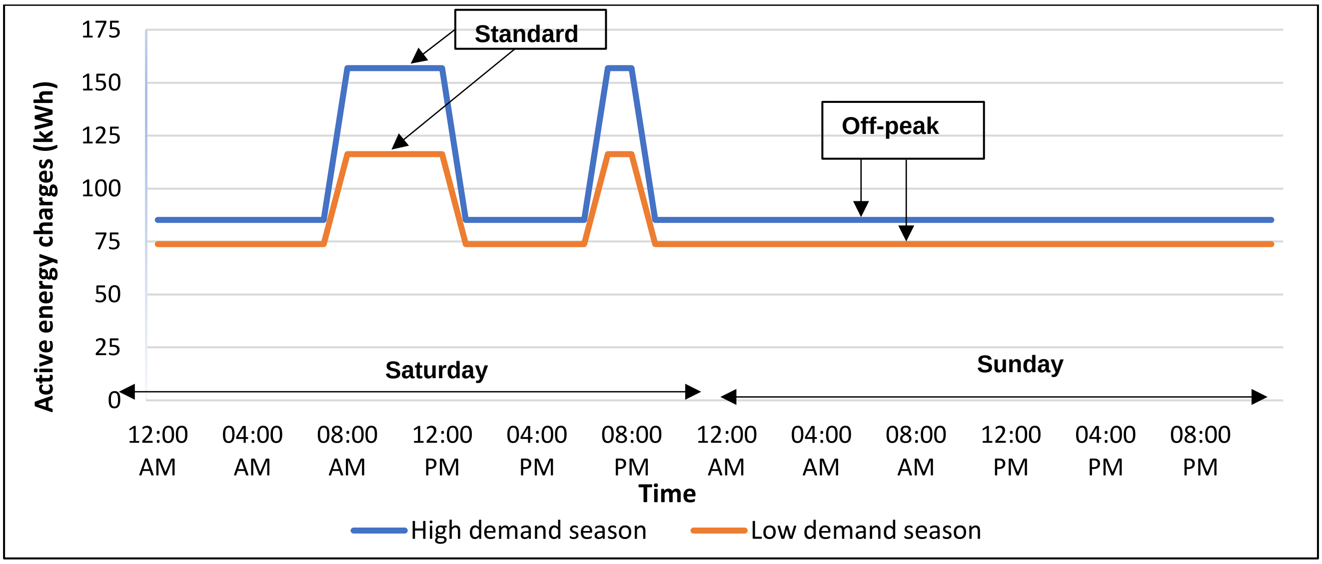


Figure 5-9: Eskom active tariff charges profile in a weekend.

5.3.2 Energy costs incurred during study period.

One of the requirements of the DWS policy is the avoidance of pumping operations during peak power supply periods, and as discussed in Chapter 1 one of the aims of this study is to assess the impact on the costs thereof. In this section the energy costs associated with the current pump station policy used during the study period are quantified.

The energy costs are calculated based on the weekly pumping durations for the pumps at the Jericho and Kliphoek pump stations. As discussed in Section 5.1.1, three pumps at Jericho and one at Kliphoek are operated continuously throughout the day during the weekdays, with an additional fourth pump at Jericho and second pump at Kliphoek added in periods of high demand. As the major end-users of the pumped water are Eskom power stations, periods of high demand can be deduced to be peak periods when electricity demand is high. Therefore, the additional pumps added throughout the week are be assumed to be added during peak periods and the remaining hours are attributed to standard periods.

The power consumption of the individual pumps is dependent on the pumping combination used as discussed in Section 4.7.4. Appendix C shows the calculation spreadsheets used to calculate the energy costs during peak, standard and off-peak periods considering the above. Figure 5-10 shows the weekly peak, standard and off-peak energy costs incurred throughout the study period.

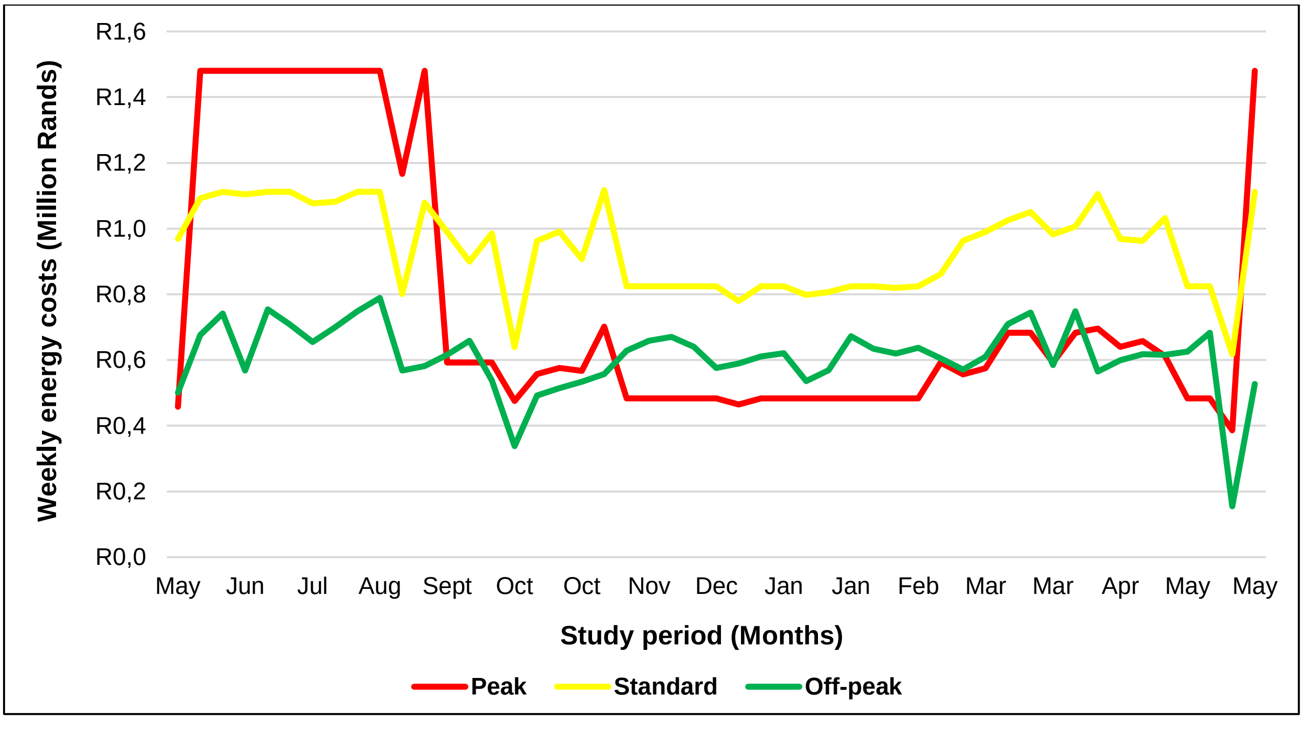


Figure 5-10: Weekly energy costs incurred during study period.

From Figure 5-10, the most peak energy costs were incurred during the winter months between May and September, which is to be expected as this is the high demand season when the peak TOU tariffs are at their highest as shown in Figure 5-8. During the low demand season, the highest energy costs occurred during the standard period.

The peak energy costs incurred during the study period were calculated to be **R 37 623 511.31** and the standard and off-peak energy costs were **R 46 030 675.22** and **R 29 862 642.82** respectively. The off-peak energy costs were the lowest despite majority of the pumping operations occurring during these periods, showing the advantage of pumping during these periods.

Figure 5-11 shows the average weekly energy costs for each pump at the Jericho and Kliphoek pump stations.

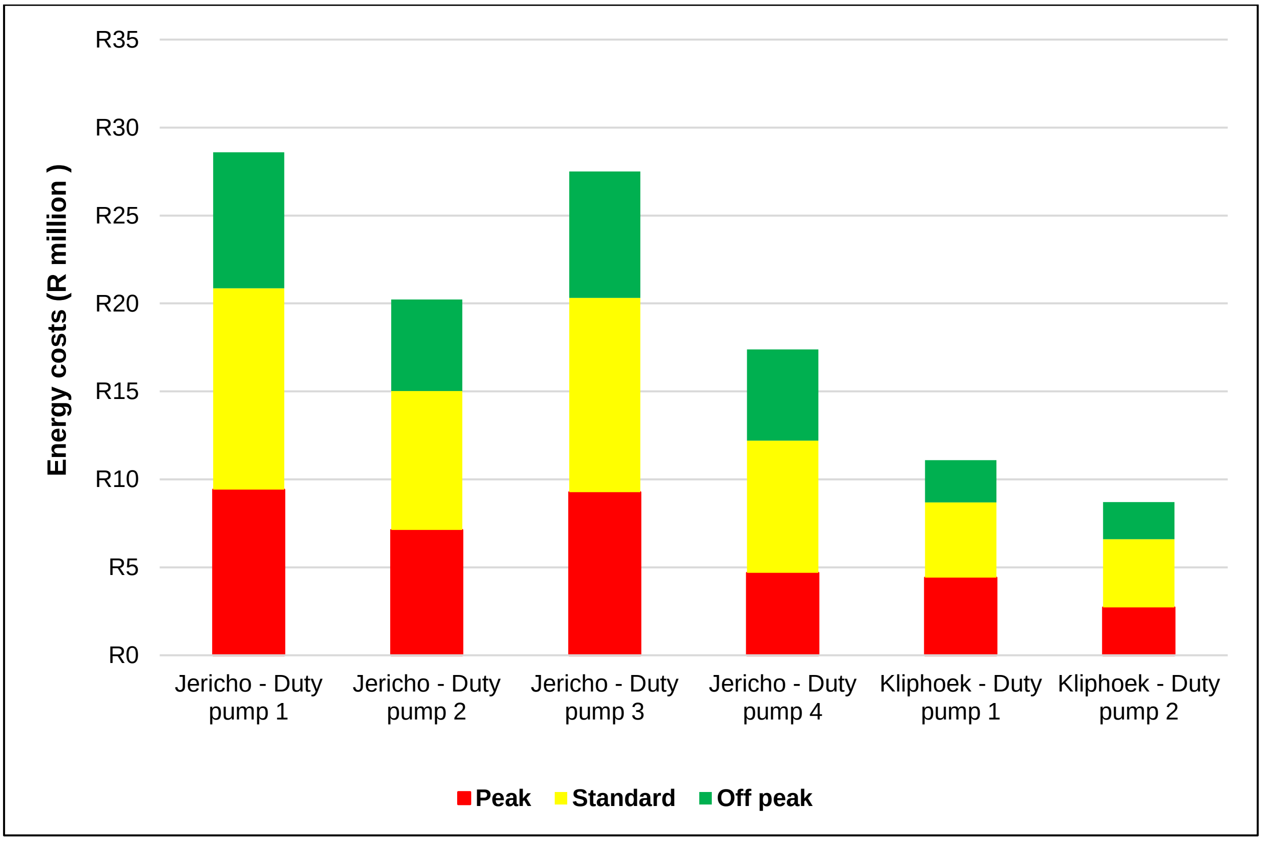


Figure 5-11:Energy costs per pump during study period

Figure 5-11 shows that peak energy costs have a considerable contribution to the energy costs despite only occurring for 25 out the 168 hours in a week. Furthermore, despite the Kliphoek pump being operated for a similar duration to the Jericho pumps, it has considerably lower energy costs. This is because the power consumption of the Kliphoek pumps is considerably lower than that of the Jericho pumps.

Figure 5-12 shows the comparison between the weekly average energy costs of weekdays and weekends.

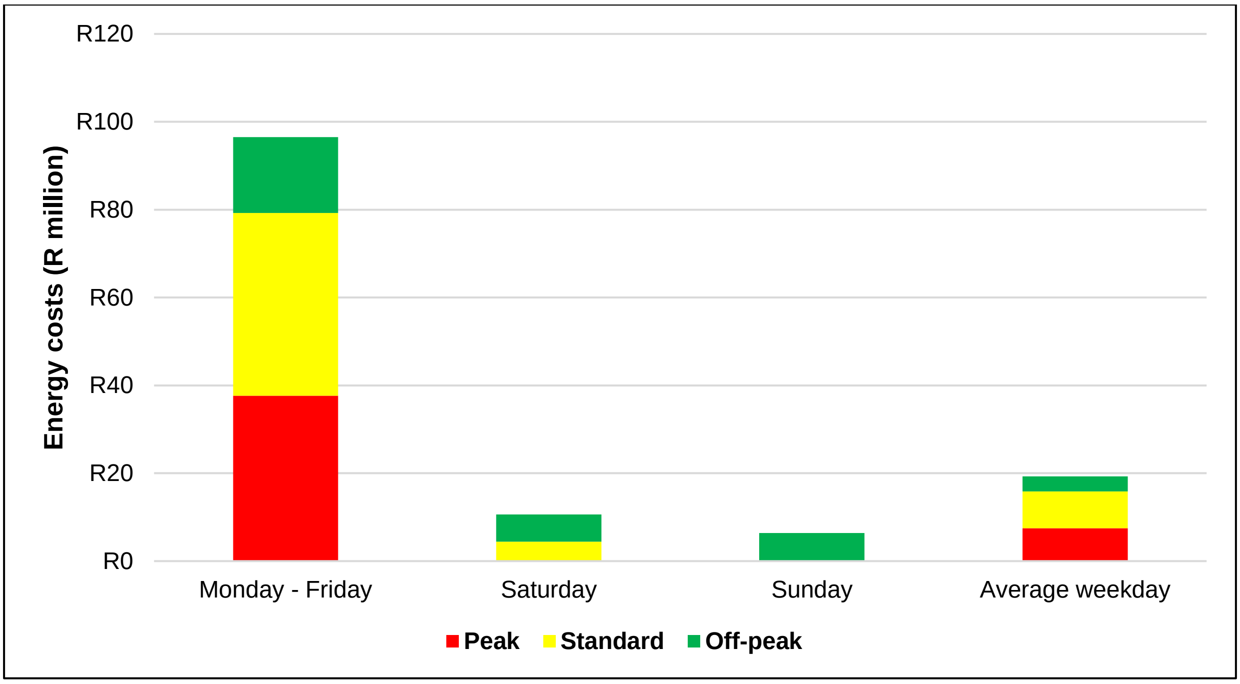


Figure 5-12: Energy costs for weekdays, Saturdays, and Sundays during the study period

From Figure 5-12, its clear that pumping during peak TOU periods has a considerable impact on the energy costs, as the energy costs for an average weekday are much higher than those of Saturdays and Sundays.

Figure 5-13 below shows the total energy costs throughout the study period, and for each of the TOU periods.

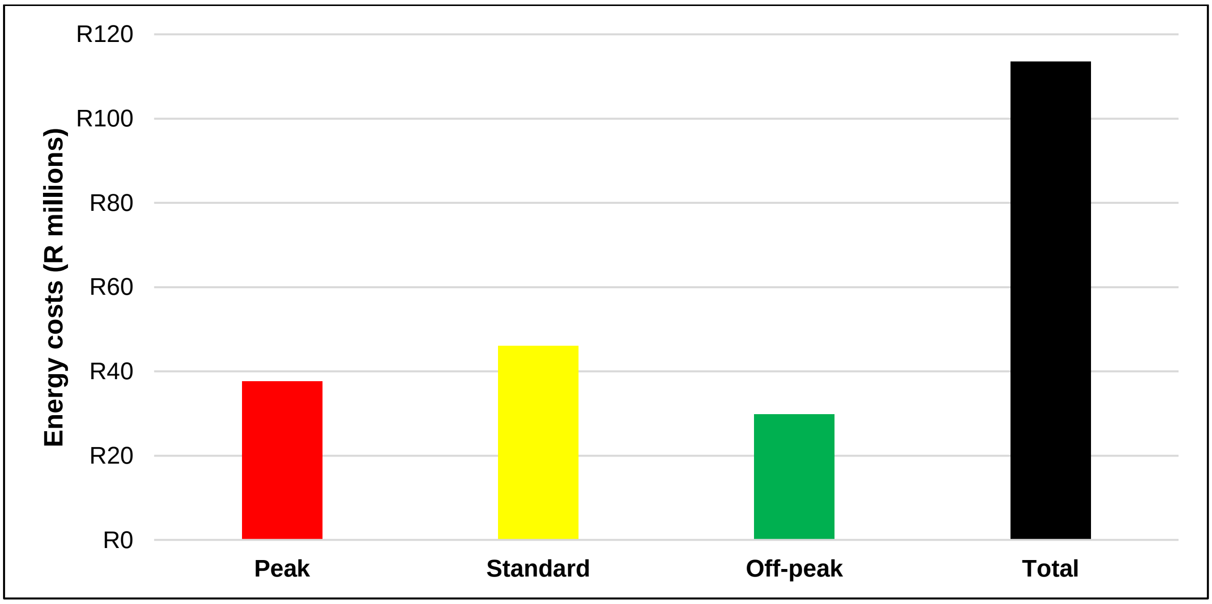


Figure 5-13: Total estimated energy costs throughout study period (May 2022 – May 2023)

Figure 5-13 shows that there is a case for the reducing the energy costs incurred, considering the energy costs associated with the peak and standard periods during the study period.

5.4 Conclusion to the assessment and quantification of costs

The pumps at the Jericho and Kliphoek pump stations are being operated at peak TOU periods, incurring high energy costs, and increasing demand that the power utilities must supply during peak times. There is no optimal pump scheduling being applied at the two pump stations.

In terms of operational performance, the Jericho pump station has struggled to meet the required demand during the study period, particularly between August 2022 and February 2023 despite there being sufficient water and pumping capacity to do so. This shows that a control policy on how to best use the available pumping capacity to meet the demand is required.

The pump station has undergone several upgrades and changes throughout its operational life, one which was the relining of the pipelines which had a negative impact on both the pumping efficiencies of the Jericho and Kliphoek pump stations.

Section 5-3 shows that there is an urgent need for optimal pump scheduling to minimize pumping operations during peak TOU periods, which could substantially reduce the energy costs. In terms of not adhering to the DWS policy, pump scheduling has had the most substantial negative impact on operational costs with the pumping operations during peak periods contributing to 33% of the estimated energy costs during the study period. Therefore, optimizing the pump scheduling requires the most attention.

Chapter 6 : Approaches to reduce the cost of the pumping operations.

In this Chapter, measures of reducing the energy consumption at the Jericho and Kliphoek pump stations are explored. This is mainly done seeking to minimize pumping operations during peak Time-Of-Use periods. Prior to searching for approaches for this, it is first necessary to understand the capacity and operational constraints of the system. As some of the proposals include could additions of infrastructure, the capital costs of such infrastructure are compared to the operational cost benefits to assess the financial viability.

6.1 Possible approaches for minimizing operational costs.

As detailed earlier in Chapter 4, the Jericho pump station pump station receives water from the Jericho dam, and the pumps water to the Onverwacht reservoirs with the option of pumping through the Kliphoek booster pump station. Figure 6-1 shows the schematic diagram of the system.

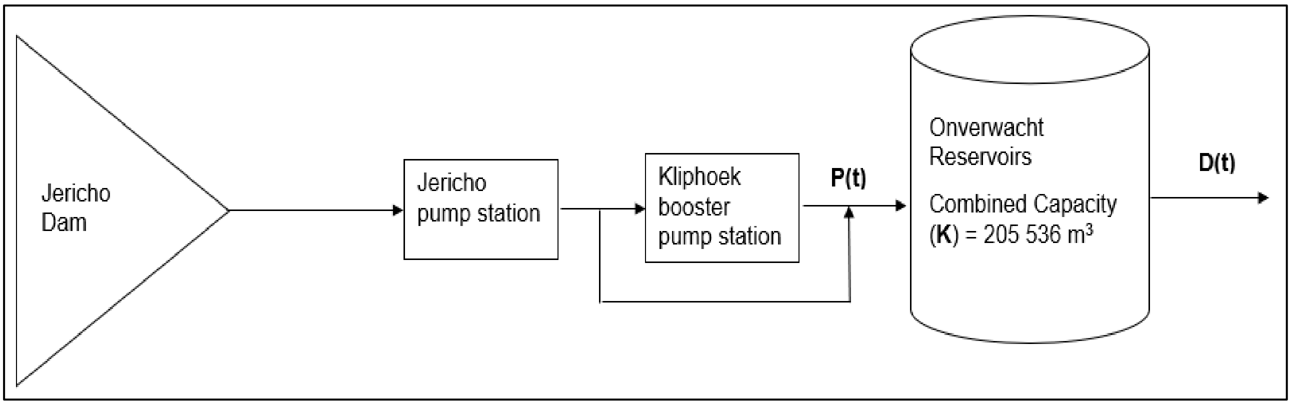


Figure 6-1: Schematic diagram of the Jericho pumping system (P(t) is the pumped volume from the Jericho pump station (with or without the Kliphoek pump station), D(t) is the demand to be supplied through the Onverwacht reservoirs.)

The system has a maximum pumping capacity of 3300 l/s, pumping 1650 l/s on each of two 900 mm rising mains to the Onverwacht reservoirs. The Onverwacht reservoirs have capacity of 205 536 m^3. From the Onverwacht reservoirs water gravitates to the recipient users.

6.1.1 Operational constraints

Onverwacht reservoirs - As discussed in Chapter 4, the water level in the Onverwacht reservoirs must not drop below 60% (3.6 m) as the pressure to gravitate to the required locations would not be sufficient. This places a considerable constraint on the system by reducing the time when the reservoir can continue supplying without incoming flow from the Jericho pump station.

Jericho-Kliphoek pumping system – The two pipelines from the Jericho pump station through Kliphoek pump station to the Onverwacht reservoirs have diameters of 900 mm, with internal diameters of 841.6 mm and 850.6 mm (van Vuuren & van Dijk, 2012). The relatively small pipeline diameters result in considerable frictional losses during pumping, which in addition to the static head of approximately 250 m, limits the maximum transfer capacity of the Jericho – Kliphoek pumping system to 3300 l/s, with 1650 l/s on each individual pipeline. The dynamics of the characteristic system and pump curves are shown in Section 4.7.2.

Water availability – The availability of sufficient water from the dam for the Jericho pump station could be constrained in periods of drought as discussed in Section 4.5 and 4.6.2 of Chapter 4.

6.1.2 Possible approaches for minimizing energy costs.

Four possible approaches were considered for the reduction of the energy costs incurred by the pumping operations. These were aimed at minimizing pumping during peak TOU periods:

A. **Increasing the transfer capacity of Jericho-Kliphoek pump stations** – This approach would ensure that more water is transferred during off-peak and standard periods, and thereby reducing pumping operations during peak periods. However, this approach would require additional pumps to be installed at the Jericho pump station. Furthermore, the flow velocities in the two pipelines from Jericho to the Onverwacht reservoirs are 2.966 m/s and 2.904 m/s respectively, at the current maximum transfer capacity. The maximum allowable flow velocity in rising mains is 3 m/s (Ekurhuleni Metropolitan, 2020). This limits additional flow that can be pumped in the pipelines and therefore necessitates an additional pipeline from Jericho to the Onverwacht reservoirs in this approach. Given the very high costs of installing new pipelines, the initial capital costs would be considerably high.
B. **The installation of a low-head high flow rate pumping station at the Onverwacht reservoirs –** This approach would substantially reduce the minimum allowable storage constraint at the Onverwacht reservoirs as water would be pumped to the recipient locations instead of gravitating. This would therefore increase the period of time that the Onverwacht reservoirs can supply water without requiring inflow from the Jericho pump station. This period can be scheduled to be during peak TOU periods. This option however includes the capital cost of the pumping station and operational costs during pumping.

C. **Optimized pump scheduling during Sundays** – From the weekly pump performance reports discussed in Section 4.6, pumping operations are reduced to one or two pumps during Sundays when the demand has reduced. To maximize the volume in storage for all the reservoirs in the system without incurring high energy costs, maximum pumping operations could be done during Sundays when the TOU is off-peak.
D. **The addition of a fourth Onverwacht reservoir** – This approach would increase the storage capacity of the Onverwacht reservoirs, and thereby increase the period of time that the Onverwacht reservoirs can supply water without requiring inflow from the Jericho pump station. The additional period of time can be scheduled for peak TOU periods. Although this approach would improve pump scheduling, it however, does not address the 60% minimum storage state constraint of the Onverwacht reservoirs (Department of Water & Sanitation, 2017).

Solution **A** would have the highest initial capital costs compared the other solutions. Although Solution **D** would reduce pumping operations during peak TOU periods, it however does not address the minimum storage capacity constraint. It should also be noted that these solutions can be used in combination with each other, e.g. Solutions **B** and **C** together, Solutions **B** and **D** together, Solutions **C** and **D** together, or Solutions **B**,**C** and **D** together. In order to accurately assess the financial viability of the four solutions, a comprehensive life cycle costing would have to be done for each solution. Considering the time constraints of the study, only Solution **B** in conjunction with **C**, were assessed for their feasibility in the reduction of the energy costs.

6.2 Mass balance of current system

To assess the constraints discussed in Section 6.1.1, a behaviour analysis method is used. The mass balance around the Onverwacht reservoirs is by Equation 6-1 below:

$$S_{t+1} = S_t + P_t - D_t - spill \qquad \textbf{Equation 6-1}$$

$\underline{Where}$:

S_t *is the reservoir storage*;

P_t *is the incoming flow into the reservoir*;

D_t *is the actual release from the reservoir*;

The following constraints are applicable to the system in Figure 6-1:

$$0.6K < S_t \leq K \quad , where\ K\ is\ the\ Dam\ storage\ capacity$$

$$if\ S_t > K, \quad then\ spillage\ will\ occur$$

$$\therefore spill = S_t - K$$

$$P_t \leq 3.3\ m^s/s$$

$$P_t \leq R_t$$

$$Where: R_t\ is\ the\ maximum\ allowable\ release\ from\ the\ Jericho\ Dam\ at\ each\ hour$$

The transfer constraints and demand targets for the study period are as per the 2022/2023 Annual Operating Analysis (Schlebusch, 2022). These are shown in Figure 6-2 where actual capacity is the maximum allowable transfer capacity and Target is the set demand targets for the year as per the Annual Operating Analysis.

Table 6-1: Study period demand targets as per the 2022/2023 Annual Operating Analysis (Schlebusch, 2022)

Description	Units	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	Annual Transfer
		31,00	30,00	31,00	31,00	30,00	31,00	30,00	31,00	31,00	28,25	31,00	30,00	365,25
Jericho to Onverwacht (Maximum transfer capacity is 2.8 m^3/s) - WRPM Channel 36 (Channels 27 and 39 transfers plus Channel 1425 transfer) (DWA Jericho pumped)														
Maximum Transfer Capacity	m^3/s	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	**2,80**
	Million m^3/m	7,50	7,26	7,50	7,50	7,26	7,50	7,26	7,50	7,50	6,83	7,50	7,26	**88,36**
	Cumulative	7,50	14,76	22,26	29,76	37,01	44,51	51,77	59,27	66,77	73,60	81,10	88,36	
Actual capacity	m^3/s	2,00	2,00	2,00	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	**2,60**
	Million m^3/m	5,36	5,18	5,36	7,50	7,26	7,50	7,26	7,50	7,50	6,83	7,50	7,26	**82,00**
	Cumulative	5,36	10,54	15,90	23,40	30,65	38,15	45,41	52,91	60,41	67,25	74,74	82,00	
Target	m^3/s	2,46	2,47	2,51	2,47	2,45	2,45	2,44	2,41	2,42	2,41	2,42	2,42	**2,44**
	Million m^3/m	6,58	6,41	6,72	6,62	6,35	6,56	6,33	6,46	6,48	5,88	6,48	6,27	**77,13**
	Cumulative	6,58	12,99	19,71	26,33	32,67	39,23	45,56	52,02	58,49	64,38	70,86	77,13	

6.2.1 Reservoir behaviour with current pump scheduling

The pumping rates and durations during as per Figures 5-2, 5-3 and 5-4 in Section 5.1.1 are used as representations of the current system's weekly operations. The daily demand target of the study period is 2.44 m^3/s as per average daily target in the 2022/2023 AOA shown in Table 6-1. However, it should be noted that the daily demand is constant as per the 2022/23 AOA. This assumption is not accurate as shown in the weekly electricity demand profile depicted in Figure 4-9 (Chikobvu & Sigauke, 2012) of Section 4.3.1, where the electricity demand varies throughout the week. Therefore, daily demands are adjusted in direct proportion to the indexes in Figure 4-9.

The initial storage volume of the Onverwacht reservoirs is assumed to be the minimum operating storage (60%). The hourly behaviour of the Onverwacht reservoir during the week was determined using the behaviour analysis method and is shown in Figure 6-2. Appendix D shows the computation on spreadsheet.

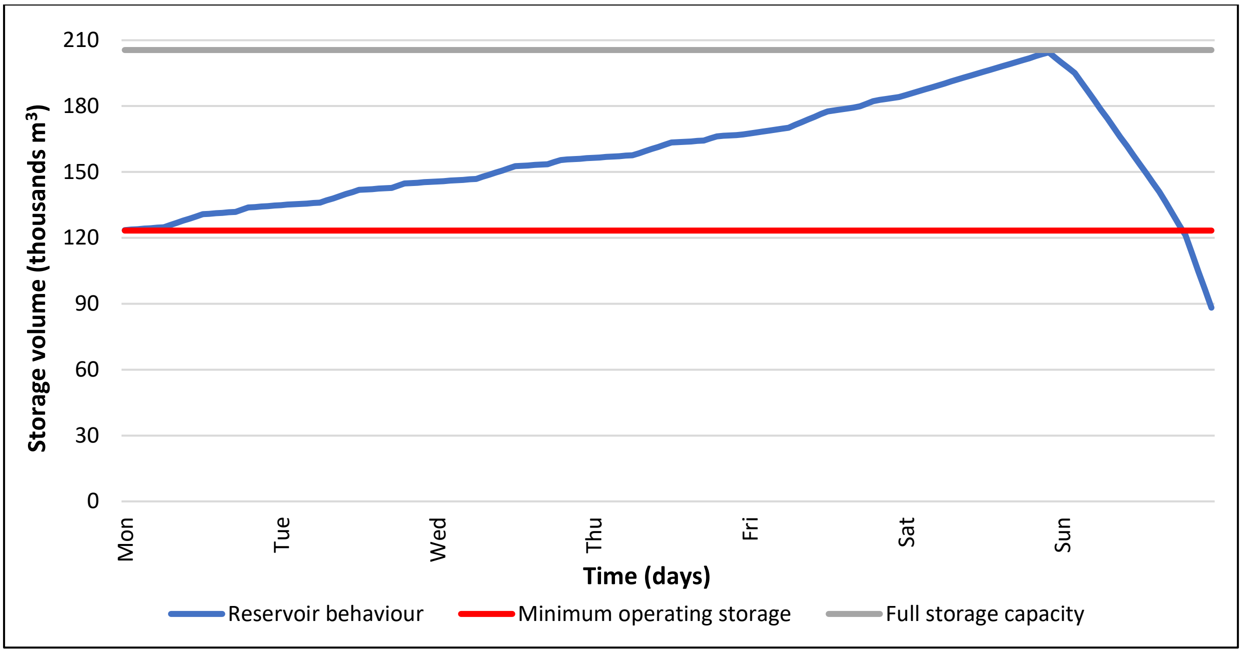


Figure 6-2: Onverwacht reservoir behaviour with average pumping rate and the current pump scheduling

Figure 6-2 shows that with the assumption of the initial storage capacity of 60%, the final storage capacity of the Onverwacht reservoir is well below the minimum storage capacity. The reservoirs do not spill during week, approaching the maximum storage capacity at the end of Saturday, and dropping as pumping operation are gradually stopped. The gradual reduction of pumping during the weekend results in the reservoir storage dropping. It is notable that additional pumping on Sunday, which is an off-peak TOU period, could help retain higher storage states.

6.2.2 Reservoir behaviour with Maximum allowable transfers with peak pumping excluded.

In this Section, the behaviour of the Onverwacht reservoirs and possibility of excluding pumping operation during peak periods are assessed when the pumping rate from the Jericho pump station is equal to either the maximum allowable transfer from the Jericho Dam or maximum transfer pumping capacity of the pump station, depending on which one is lower. Pumping is done during all the standard and off-peak TOU periods including weekends to maximise the reservoir storage, with no gradual reduction of pumping during weekends as is done with the current pump scheduling.

Although the maximum pumping capacity of the pump station is 3300 l/s, during the study period, the maximum allowable transfers from the dam, were 2000 l/s from May – July 2022 and May 2023, and 2800 l/s from August 2022 to April 2023. The behaviour of the reservoirs is assessed using the maximum allowable transfer rate of 2800 l/s, which is similar to the pumping combination H which has a pump flow rate of 2785 l/s.

To assess the feasibility of avoiding the high energy costs associated with peak TOU periods with the current system, the pumping operations are only done in standard and off-peak TOU periods with the maximum allowable transfer of 2785 l/s. The behaviour of the reservoir for this analysis with the assumption that the initial storage volume is the minimum operating storage of 60% is shown Figure 6-3.

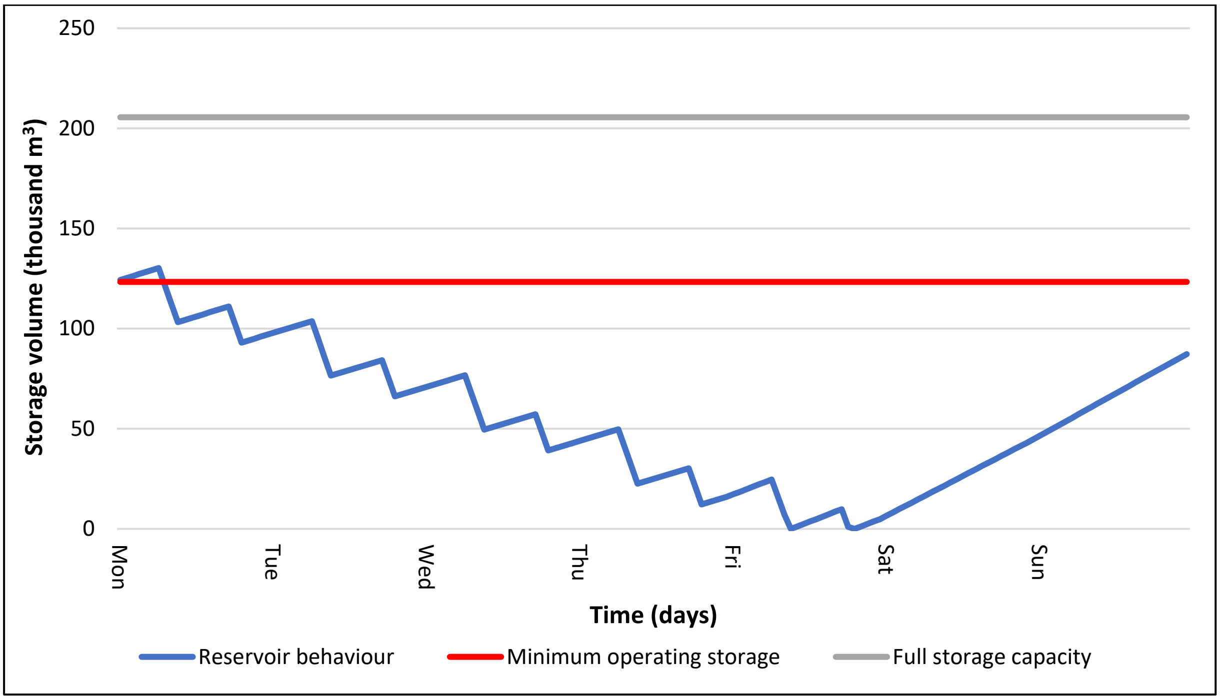


Figure 6-3: Onverwacht reservoir behaviour with pumping combination H without pumping during peak TOU periods.

Figure 6-3 shows the Onverwacht reservoirs fail to meet the minimum storage state when the pumping operations are entirely stopped during peak periods. The reservoir failed for a total of 161 hours out of the 168 hours in the week, which is equivalent to a 95.8 % probability of failure.

The reservoirs behaviour was also assessed assuming that the initial reservoir storage in the behaviour method analysis is at full reservoir capacity. Additionally, to ensure identical starting conditions in the following week, the final reservoir storage was iterated to be the same as the initial starting storage, by varying the number of peak period pumping hours. Once more the pumping rate is assumed to be equal to the maximum allowable transfer in the study period which is achieved by pumping combination H (2785 l/s). Pumping was done during all the standard and off-peak TOU periods including weekends to maximise the reservoir storage. This analysis is shown in Figure 6-4.

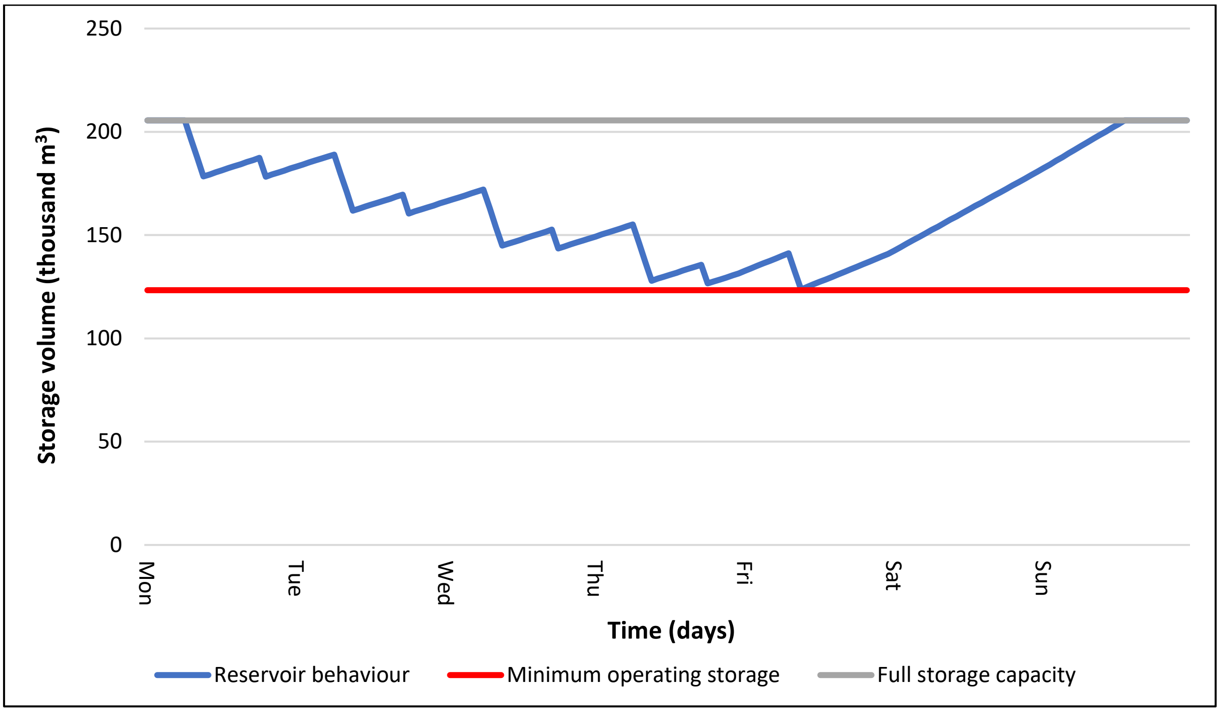


Figure 6-4:Onverwacht reservoir behaviour with both initial and final storages at full capacity

With the starting and final reservoir storages set at the full storage capacity and maximizing pumping operations during weekends, pumping operations during peak hours could be avoided for a total of 18 out of the 25 hours during the week without the reservoir failing with the final storage being the same as the initial storage.

This analysis shows that some measure of optimal scheduling is possible when the maximum allowable transfer is 2800 l/s within the current system. However, during the study period, the 2800 l/s flow was only allowable for 9 out of the 12 months, with the remaining 3 months having a maximum allowable transfer rate of 2000 l/s, which is even lower than the demand targets.

6.2.3 Reservoir behaviour with maximum pumping capacity

An ideal scenario was also analysed, where it is assumed that there is sufficient water in the Jericho dam to allow the Jericho pump station to pump at its maximum pumping capacity of 3300 l/s. The behaviour of the reservoir in this scenario assuming the initial storage volume to be the full reservoir capacity and minimum reservoir storage volume are shown in Figures 6-5 and 6-6 respectively.

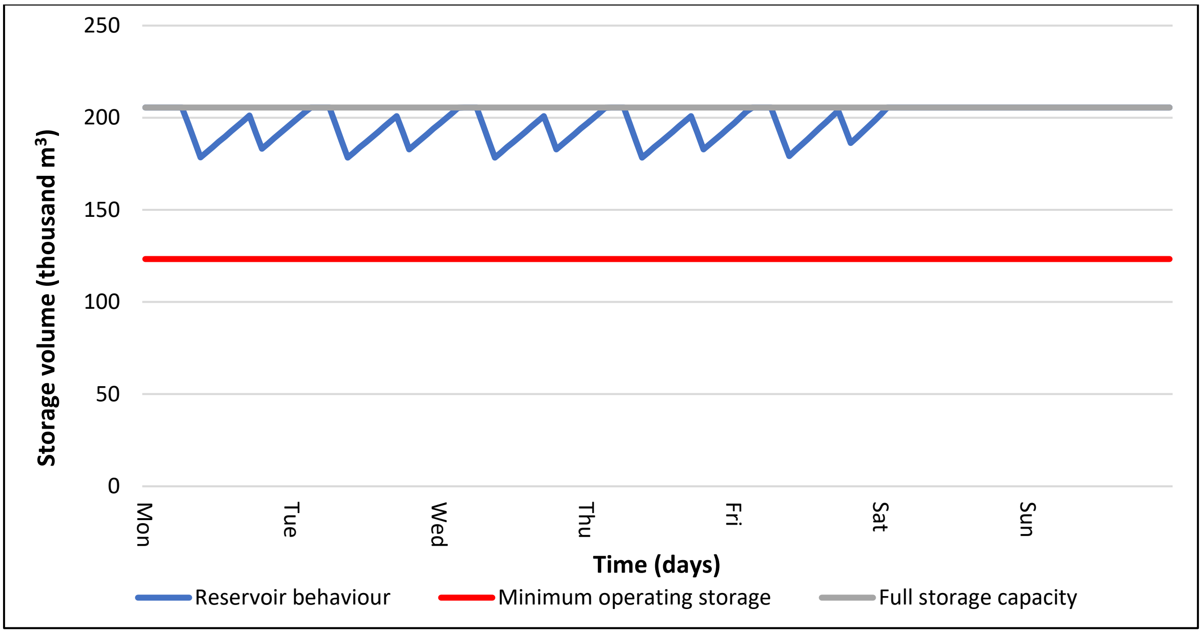


Figure 6-5: Onverwacht reservoir behaviour with maximum pumping capacity and peak pumping excluded and full storage as the initial storage.

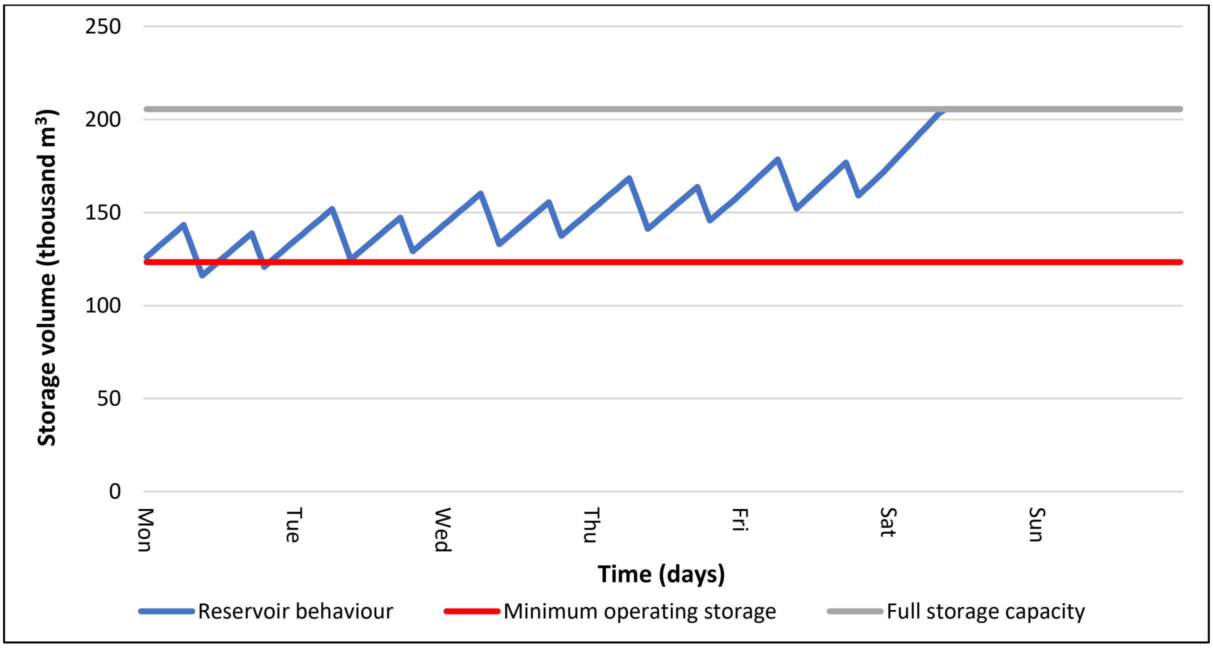


Figure 6-6: Onverwacht reservoir behaviour with maximum pumping capacity, peak pumping excluded, and minimum storage as the intial storage.

Figures 6-5 and 6-6 show that the final reservoir storage capacity is the full reservoir capacity in both cases, consequently, the reservoir does not fail in the next week and also has its final reservoir storage at full reservoir capacity perpetuating success in the following weeks.

It should be noted that this scenario is unrealistic in real life, since the highest maximum allowable transfer from the Jericho dam since the year 2010 is 2850 l/s (Department of Water Affairs, 2013) while this scenario uses the maximum transfer capacity of 3300 l/s.

6.2.4 Final assessment of current system

The current system is constrained significantly by the 60% minimum operating storage of Onverwacht reservoirs and consequently optimal pump scheduling to minimize pumping operations during peak TOU periods is possible for 9 out the 12 study period months when the maximum allowable transfer rate is 2800 l/s.

Approach C detailed in Section 6.1.2 involving maximizing pumping operations on Sundays to maximise the reservoir storage was able to improve the pump scheduling by reducing pumping operations during peak periods to 7 hours when the maximum allowable transfer rate is 2800 l/s. However, this allowable transfer is not always possible and to further improve the pump scheduling, Approach B in conjunction with C is considered in the following Section.

6.3. Proposed approaches to reduce energy costs.

As discussed in Section 4.2, the Onverwacht reservoirs must not drop below 60% storage capacity as the pressure to gravitate to the required locations would not be sufficient. This constraint directly impacts the pump scheduling at the Jericho pump station as there is limited downtime during peak periods without the reservoir falling the below the minimum storage capacity. Approaches B and C are considered to address the constraint discussed above.

6.3.1 Approach B – Onverwacht pump station

Approach B as discussed in Section 6.1.2, whereby a low-head high flow rate pump station would provide the required pressure to supply water to the required locations when the reservoirs are below the 60% storage capacity. Figure 6-7 shows a schematic diagram of how the Jericho pump system would change.

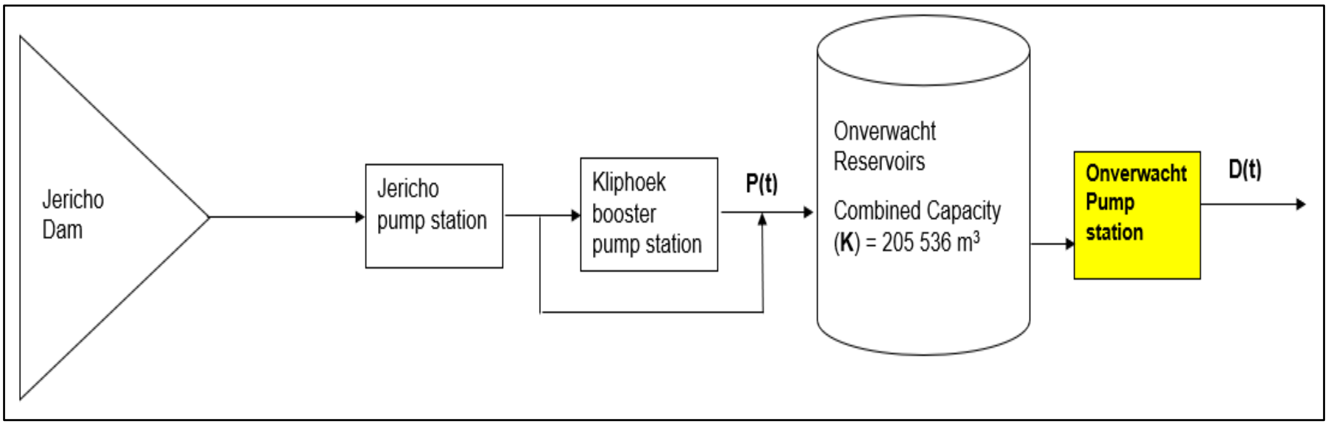


Figure 6-7: Proposed changes to the Onverwacht reservoirs

Currently, the water from the reservoirs gravitates over 17 km in three pipelines with diameters of 1092 mm, 1066 mm, and 1200 mm respectively to the raw water reservoir at Camden which has a storage capacity of 343 000 m^3. The Onverwacht reservoirs therefore act as a balancing facility for water supply to the Camden reservoir. The rate at which the water level in the Onverwacht reservoirs drops is dependent on the level of the Camden reservoir and demand of the Camden power station and other recipients (Department of Water & Sanitation, 2015).

During peak TOU periods, the demand at the power stations increases, resulting in the Onverwacht reservoirs dropping at a quicker rate, consequently, more flow is then required from the Jericho pump station to ensure the reservoir does not drop below the minimum storage capacity of 60% capacity.

The approach of adding a pump station at the Onverwacht reservoirs would ensure that the Camden reservoirs are supplied with sufficient flow so that pumping operations during peak TOU periods at the Jericho and Kliphoek pump stations can be minimized. The assessment of this option requires the determination of a hydraulically suitable pump, and the analysis for this is done in the following section.

6.3.1.1 Design parameters

The average daily required demand supplied by the Onverwacht reservoirs for the study period was 2.44 m^3/s as per the 2022/23 AOA. Within the past 10 years, the highest daily average demand to be supplied by the Onverwacht reservoirs has been 2.85 m^3/s, in the during the 2013/14 year (Department of Water & Sanitation, 2015). The highest maximum allowable transfer from the Jericho pump station since 2010 has also been 2.85 m^3/s. The design flow of the proposed pump station is therefore set at 2.85 m^3/s.

The pump head is dependent on the static head between the Onverwacht reservoirs and the Camden reservoirs, and frictional losses along the pipelines. The Onverwacht reservoirs are 6m in height and can only gravitate to the recipient location between heights 6 m and 3,6 m. Appendix I shows the illustration of this system. As the pump is only required when the storage is lower than 60% of the storage capacity, the static head required from the pump to gravitate to the required location should at least be **3.6 m**. To ensure that the reservoirs hydraulically perform as they would at Full Supply Level (FSL), the pump head should be equal to **6 m** minus the minimum allowable depth of the Onverwacht reservoirs. The minimum allowable depth of the reservoirs is determined in the following analysis.

The lowest operating level in the Onverwacht reservoirs is dependent on the minimum submergence required in the reservoir to avoid air entraining vortices (Ahmadi & Razavi, 2018). To determine the minimum water level (submergence) required to prevent air entrainment, Equations 6-2, 6-3 and 6-4 are used (Jones, et al., 2008).

$$v = \frac{Q}{A_{Bellmouth}}$$ **Equation 6-2**

Where:

v – Entrance velocity

Q – Flow rate

$A_{Bellmouth}$ - Area of Bellmouth (1.5 m x 1.5 m)

$$F_r = \frac{v}{\sqrt{gD}}$$ **Equation 6-3**

Where:

F_r – Froude number

D – Diameter of the suction pipe

$$S = D(1 + 2.3F_r)$$ **Equation 6-4**

Where:

S – Minimum submergence

Table 6-2: Summary of minimum submergence required in the Onverwacht reservoirs.

Pipeline Diameter (mm)	Entrance velocity (m/s)	Froude number	Minimum submergence (m)	Minimum storage (%)
1092	0.412	0.126	1.41	23.5
1066	0.402	0.124	1.37	22.8
1200	0.453	0.132	1.56	26

From Table 6-2, the minimum operating storage of the reservoirs with the proposed pump station is then the highest of the minimum storage capacities in Tabel 6-2 which is 26 % storage capacity. This is much lower than the current minimum storage constraint of 60%. Therefore, the pump head required considering the adopted minimum submergence in Table 6-2, is equal to **4.44 m.** To account for minor losses, a total pump head of **5 m** is used.

6.3.1.2 Pump selection

Pumps that could be used for this application were considered using pump selection software from KSB pumps (KSB Easyselect, 2024). Suitable centrifugal pumps were obtained with three pump pumping into the three pipelines. The 2850 l/s flow rate will then be split equally with each pipeline having a flow rate of 950 l/s. Figure 6-8 **shows that the performance curves of the suitable pump with a duty of: 5 m head and 950** l/s flow achieved in a parallel combination.

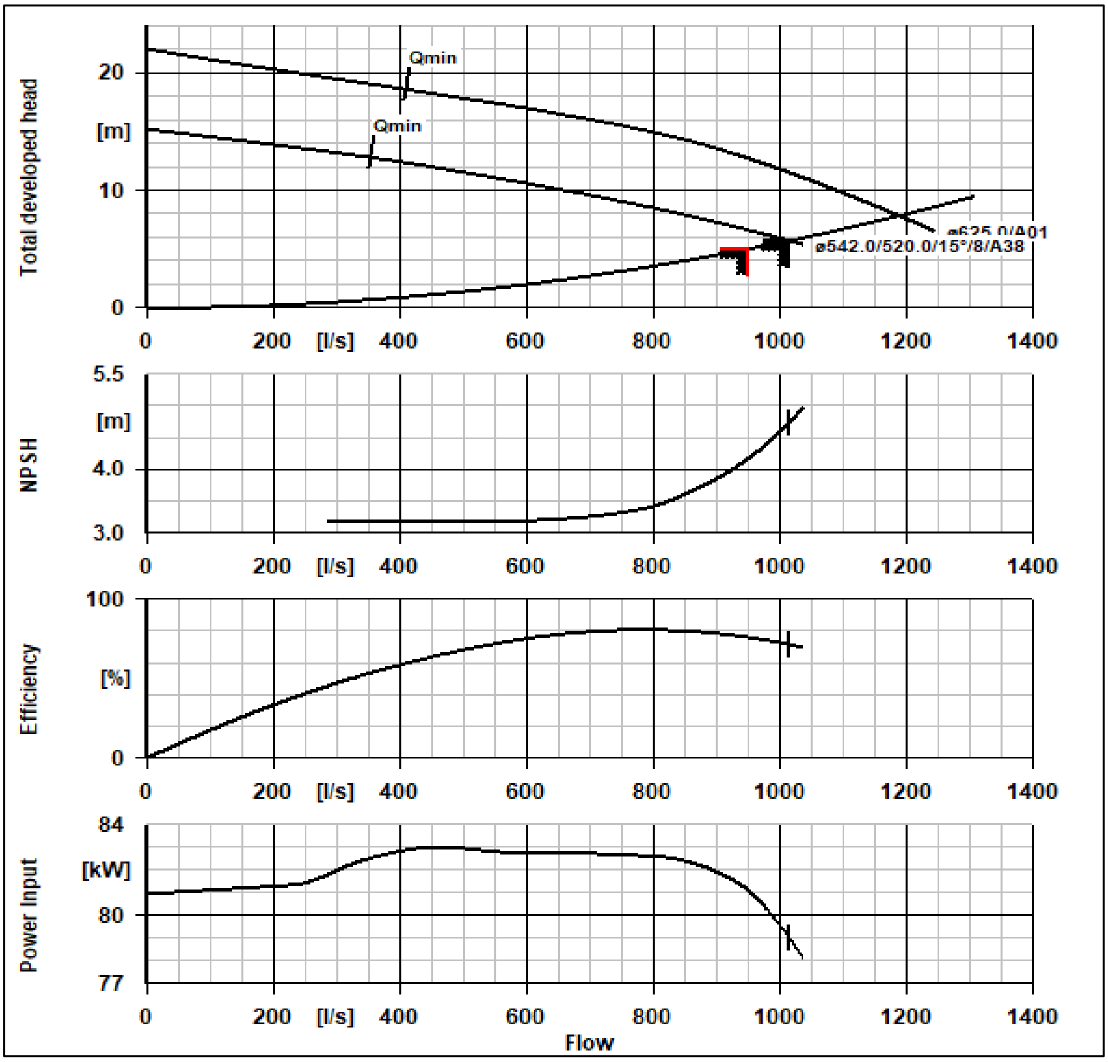


Figure 6-8: Performance curves of suitable pump for Approach B (KSB Easyselect, 2024)

Table 6-3 shows the performance information of the obtained suitable pump for Approach B from the KSB pump selection software.

Table 6-3: Summary of performance information of suitable pumps obtained (KSB Easyselect, 2024)

Pump	**Pump efficiency (%)**	**NPSH required (m)**	**Pump head (m)**	**Flow rate (l/s)**	**Power consumption (kW)**
RDLO 600-600 A	71.7	4.74	5.72	1015.75	79.17

The NPSH required refers to the height difference between the pump inlet and the lowest operating level in the reservoir. The total power consumption of all three pumps is therefore **237.51 kW**.

6.3.1.3 Capital costs

The capital costs of the proposed Onverwacht pump station are based on its maximum power consumption using the DWS Pump station cost estimation spreadsheet detailed in Section 3.5.1. and Figure 3-1. Using an average inflation since 2005 of 5.29% (World data.info, 2023) and an average of the pump station power consumption as per Table 6-2, the capital costs were obtained as shown in Table 6-3.

Table 6-4: Capital costs of the proposed Onverwacht pump station

Capacity of the pump station (kW)	**Total costs as of 2005 (R Million)**	**Total costs as of 2023 (R Million)**
254,96	4.244	10.73

6.3.2 Approach C - Optimized pump scheduling during Sundays

As discussed earlier in Section 6.1.2, Approach C involves the utilisation of the off-peak TOU period on Sundays to maximize the volume in storage for all the reservoirs in the system without incurring high energy costs. Figure 5-4 in Section 5.1.1 shows the average Sunday pump scheduling of the Jericho and Kliphoek duty pumps, whereby the pumps are gradually stopped during the day. In Approach C, the maximum number of pumps will be operated so as to maximize the storage of the Onverwacht and Camden reservoirs.

6.3.2.1 Reservoir behaviour for August to April with Approach C

During the months from August to April, the maximum allowable transfer is 2.8 m^3/s. Figure 6-4 shows the behaviour of the reservoir with the application of Approach C, whereby pumping combination H which has a total flow rate of 2750 l/s is used throughout the week, with the assumption that the initial reservoir storage is at full capacity. The final reservoir storage was iterated to be the same as the initial storage capacity. The analysis depicted in Figure 6-9 showed that pumping operations during peak periods only occurred in 7 out of the 25 hours during the week. The computation of the analysis is shown in Appendix E.

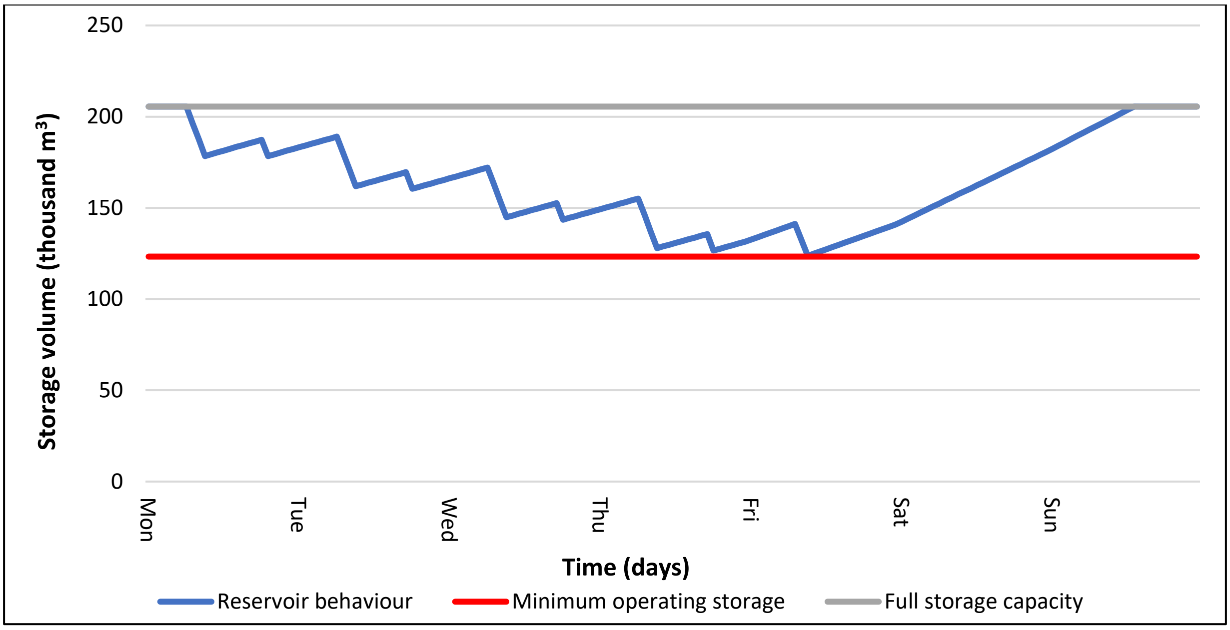


Figure 6-9: Analysis of reservoir behaviour for August to April with Approach C.

6.3.2.2 Reservoir behaviour for May, June, and July with Approach C

During the months of May, June and July, the maximum allowable transfer is 2 m^3/s. The demand targets for the May, June and July months are 2.46 m^3/s, 2.47 m^3/s, and 2.51 m^3/s for the respective months. As the demand targets are much higher than the allowable transfers, avoidance of pumping operations during peak periods would not be possible, and the reservoir would fail falling below the minimum storage capacity. Figure 10 illustrates this reservoir behaviour with the allowable transfer of 2 m^3/s between May and July, a mass balance was done assuming the initial storage to be at full reservoir capacity.

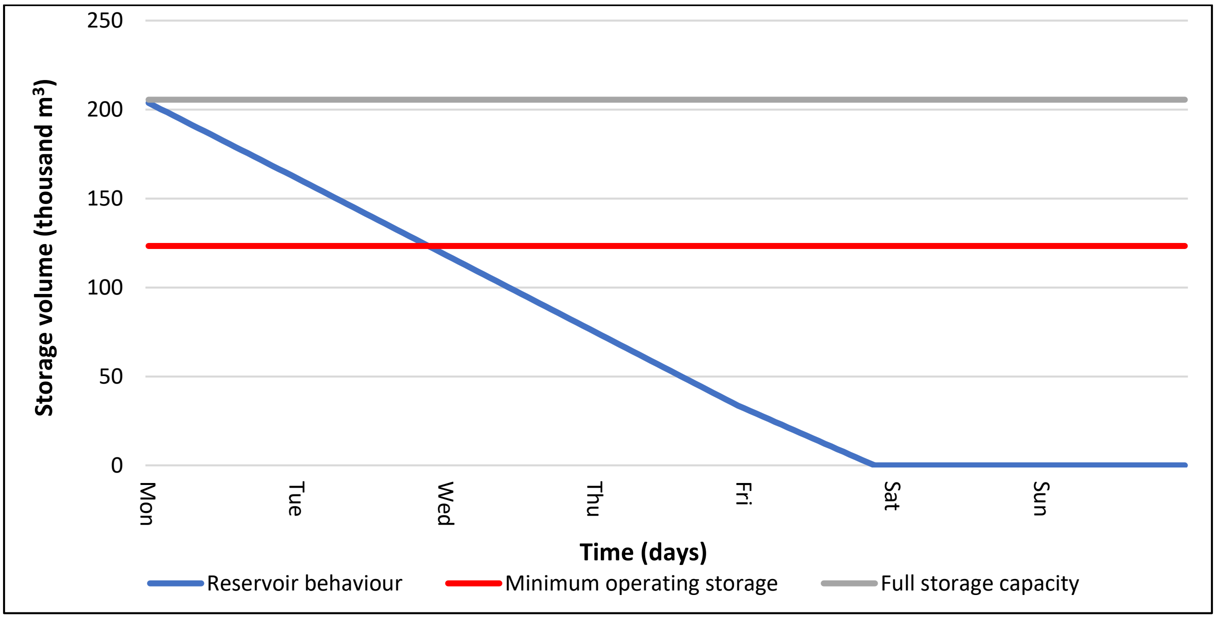


Figure 6-10: Analysis of reservoir behaviour for May, June, and July with Approach C

Figure 6-10 shows that the reservoir would indeed fail if it continued supplying the required demand despite there being pumping operations during peak periods. In this scenario, it would be more realistic to set the outflows from the Onverwacht reservoirs as equal to the maximum allowable transfer from the Jericho pump station.

To assess the behaviour of the Onverwacht reservoirs and whether pumping operations during peak periods can be avoided through the application of Approach C, a mass balance with these conditions is done as shown in Figure 6-11. Similar to Figure 6-10, the initial reservoir storage is assumed to be at full reservoir capacity, and to ensure identical starting conditions in the following week, the final reservoir storage was iterated to be the same as the initial starting storage. Transfers from the Jericho pump station are done using pumping combination D which has a total flow rate of 2055 l/s, which is closest to the allowable transfer.

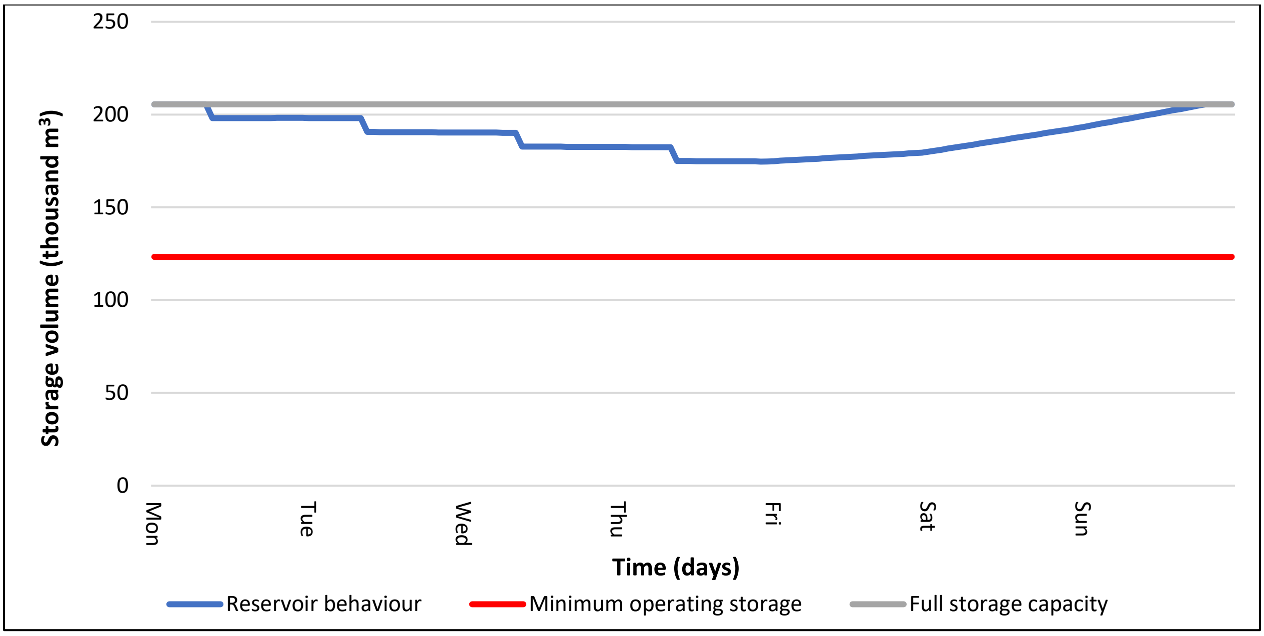


Figure 6-11: Analysis of reservoir behaviour for May, June, and July with Approach C and reduced demand targets

With the starting and final reservoir storages set at the full storage capacity, pumping operations during peak hours could only be avoided for a total of 4.5 out of the 25 hours during the week without the reservoir failing and with the final storage capacity being the same as the initial storage.

6.3.2.3 Summary of weekly cost saving of Approach C on pump scheduling

Table 6-4 shows the significant impact of Approach C on pump scheduling and the energy cost savings using the number of peak period hours avoided, the Eskom tariffs and the power consumption for the Pump combination D and H.

Table 6-5: Weekly cost savings of Approach C

Period	Maximum allowable transfer (m^3/s)	Peak period hours avoided (hours)	Weekly Cost savings during High demand season (Rands)	Weekly Cost savings during Low demand season (Rands)
May - July	2	4.5	R195 739.74	R63 844.20
Aug - April	2.8	18	R1 252 175.08	R408 420.47

6.3.3 Approach B in conjunction Approach C

As discussed in Section 6.1.2, Approach B can be used in conjunction with Approach C. The behaviour of the Onverwacht reservoirs and the pump scheduling at the Jericho pump station was analysed with the new minimum operating storage volume of 23.7 % and the utilisation of the off-peak TOU period on Sundays to maximize the volume in storage for all the reservoirs in the system.

6.3.3.1 August to April – Maximum allowable transfer (MAT) is 2.8 m^3/s.

The pumping combination H which has a total flow rate of 2750 l/s is used throughout the week, with the assumption that the initial reservoir storage is at full capacity. The final reservoir storage was iterated to be the same as the initial storage capacity. Figure 6-12 shows the behaviour of the Onverwacht reservoir with Approach B and C during this period.

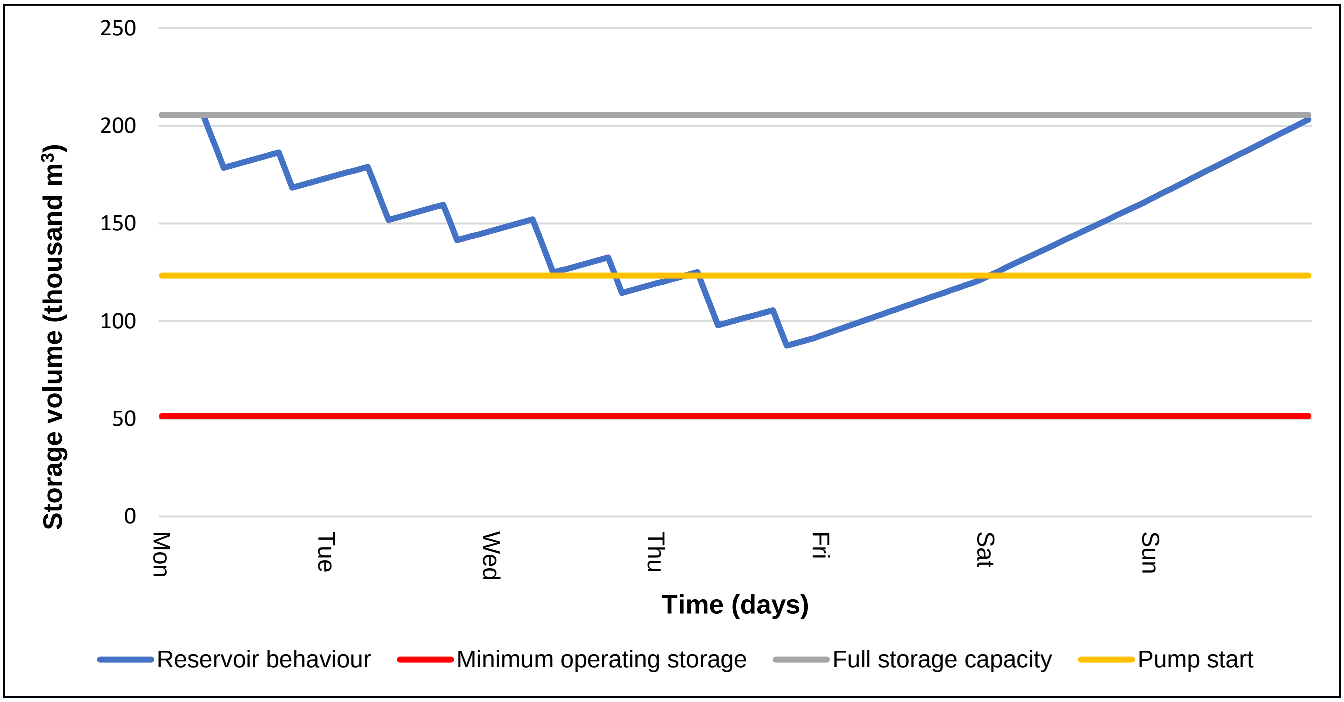


Figure 6-12:Onverwacht reservoir behaviour with Approach B and C with MAT of 2.8 m^3/s

The analysis showed that pumping operations at the Jericho pump station during peak periods only occurred for 3.8 hours out of the 25 hours during the week. Pumping operations of the Onverwacht pump station only occurred for 52 out of the 168 hours in a week, between Wednesday and Friday when the Onverwacht storage capacity was below the 60% capacity, where the flow could no longer be transferred through gravity and had to be pumped to the Camden reservoirs. Pumping operations for the Onverwacht pump station during peak periods only occurred for 11 of the 52 hours in the week.

6.3.3.2 May to July – Maximum allowable transfer is 2.0 m^3/s.

The pumping combination D which has a total flow rate of 2055 l/s is used throughout the week, with the assumption that the initial reservoir storage is at full capacity. The final reservoir storage was iterated to be the same as the initial storage capacity. As the demand targets are much higher than the allowable transfers, the outflows from the Onverwacht reservoirs are set as equal to the maximum allowable transfer from the Jericho pump station. Figure 6-13 shows the behaviour of the Onverwacht reservoir with Approach B and C during this period.

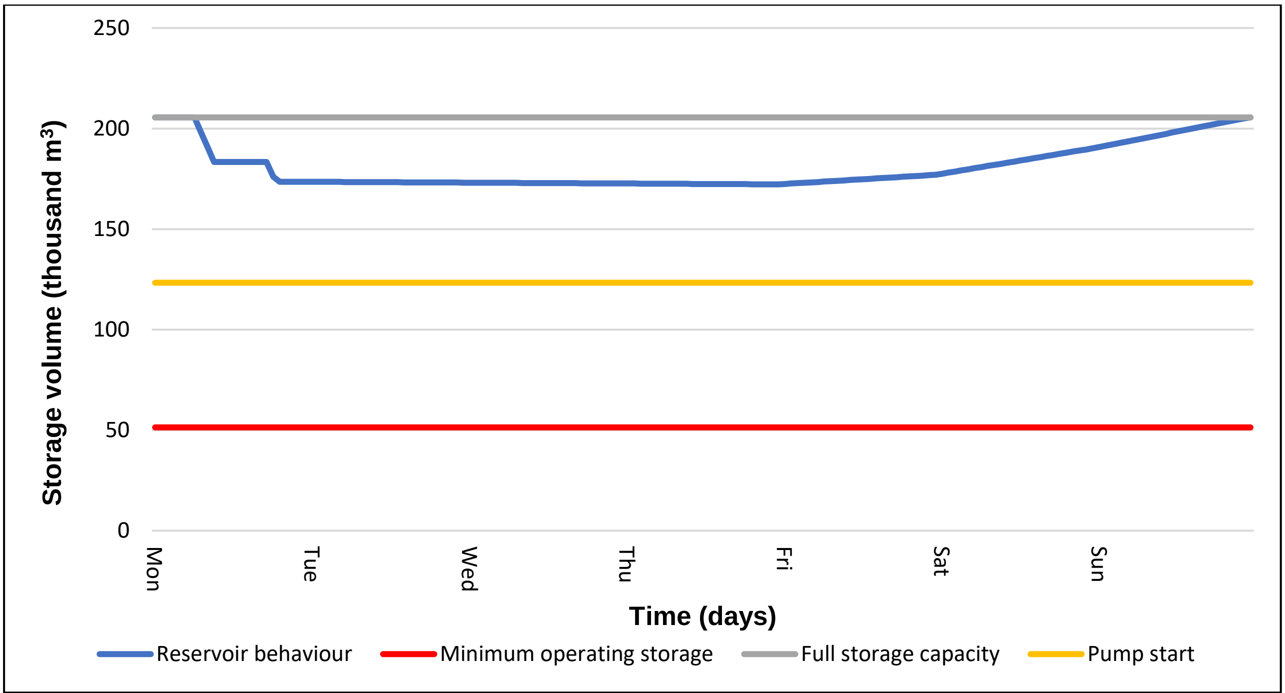


Figure 6-13: Onverwacht reservoir behaviour with Approach B and C with MAT of 2.0 m^3/s

Similar to Figure 6-11, the pumping operations during peak hours could only be avoided for a total of 4.5 out of the 25 hours during the week without the reservoir failing and with the final storage capacity being the same as the initial storage. Therefore, it’s clear that Approach B has no impact on the pumps scheduling as the inflows into the Onverwacht reservoirs are equal to the outflows.

6.3.3.3 Summary of weekly cost savings of Approach B & C on pump scheduling

Table 6-10 shows the impact of Approach B in conjunction with Approach C on pump scheduling and the energy cost savings using the number of peak period hours avoided, the Eskom tariffs and the power consumption for the Pump combination D and H.

Table 6-6: Weekly cost savings of Approach B & C

Period	**Maximum allowable transfer (m^3/s)**	**Number of peak period hours avoided (hours)**	**Weekly Cost savings during High demand season (Rands)**	**Weekly Cost savings during Low demand season (Rands)**
May - July	2	4.5	R195 739.74	R63 844.20
August - April	2.8	21.2	R1 474 783.98	R481 028.55

Table 6-10 shows that using Approach B in conjunction with Approach C yields less peak period pumping and therefore more weekly cost savings.

6.3.3.4 Weekly operational costs of the Onverwacht pump station

Table 6-11 shows the weekly energy costs associated with the Onverwacht pump station for high demand and low demand seasons as per Figures 6-12 and 6-13.

Table 6-7: Weekly operational costs of the Onverwacht pump station

Period	**TOU period**	**Pumping duration (hours)**	**Weekly operational costs during High demand season (Rands)**	**Weekly operational costs during Low demand season (Rands)**
August - April	Peak	11	R13 528.88	R4 412.70
	Standard	22	R8 196.80	R6 075.36
	Off-peak	19	R3 844.81	R3 328.56
	Total	52	**R25 570.49**	**R13 816.62**

6.4 Comparison of costs

To determine whether Approach B and C improve the system, a cost comparison between the two systems must be done. The total capital and operational costs of Approach B (Proposed Onverwacht pump station) and the operational costs of the Jericho and Kliphoek pump station with Approach C (Revised pump scheduling), are compared to the operational costs of the current system.

6.4.1 Operational costs for study period with Approach B and C

6.4.1.1 Jericho and Kliphoek pump stations

The peak energy costs incurred during the study period are calculated to be **R11 287 280.00** and the standard and off-peak energy costs are **R45 697 584.27** and **R36 659 212.73** respectively. Therefore, the total operational costs for the Jericho and Kliphoek pump stations in the proposed system during the study period are therefore **R93 644 076.99**. Appendix F shows the Excel calculation spreadsheet used to calculate the costs.

6.4.1.2 Onverwacht pump station

The peak energy costs incurred during the study period when the Onverwacht pump station was operational are calculated to be **R196 088.08** and the standard and off-peak energy costs are **R232 425.62** and **R125 015.23** respectively. Therefore, the total operational costs for the proposed Onverwacht pump station during the study period are therefore **R553 528.94**. Appendix G shows the Excel calculation spreadsheet used to calculate the costs.

6.4.2 Current system vs Proposed system.

Figure 6-14 shows the total energy costs throughout the study period, and for each of the TOU periods for the current and the proposed (Onverwacht + Jericho/Kliphoek) systems.

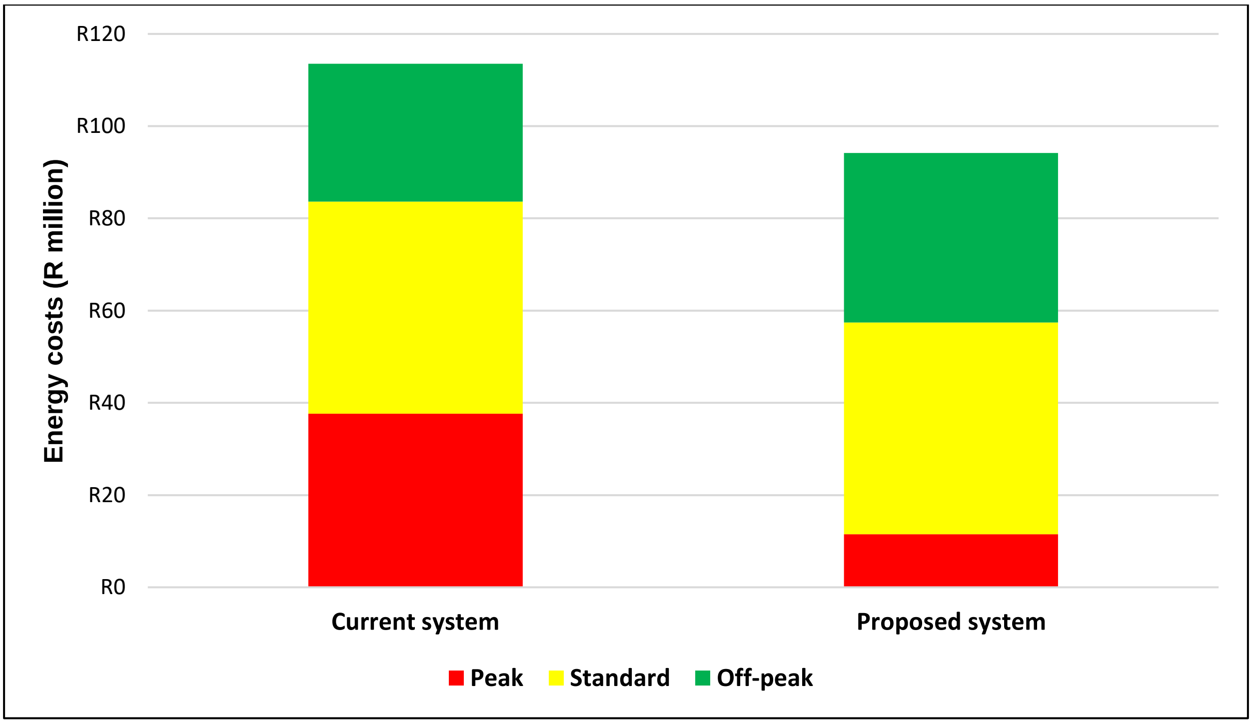


Figure 6-14: Energy costs for each TOU period for the current and proposed system

Figure 6-14 shows that, the proposed system has significantly less costs attributed to the peak periods due to the improved pump scheduling. Consequently, the proposed system has less energy costs throughout the study period. The difference between the energy costs of the current and proposed systems is **R19 319 223.42**, which is equivalent to a drop in costs of **17.02%**. Furthermore, the operational costs of the Onverwacht pump station have a contribution of **0.59%** in the total operational costs of the proposed system. Figure 6-15 shows the reduction in energy costs during the week with the proposed system.

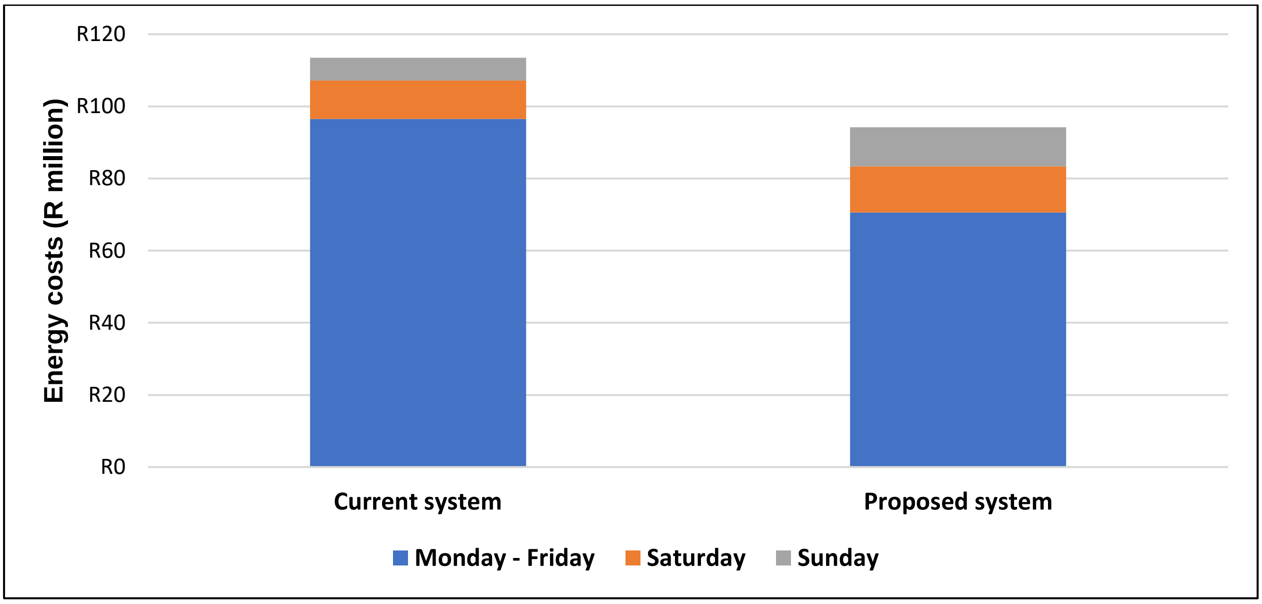


Figure 6-15: Energy costs for each day in the week for the current and proposed system

Figure 6-16 shows a comparison of the total costs associated with the current and proposed systems during the study period.

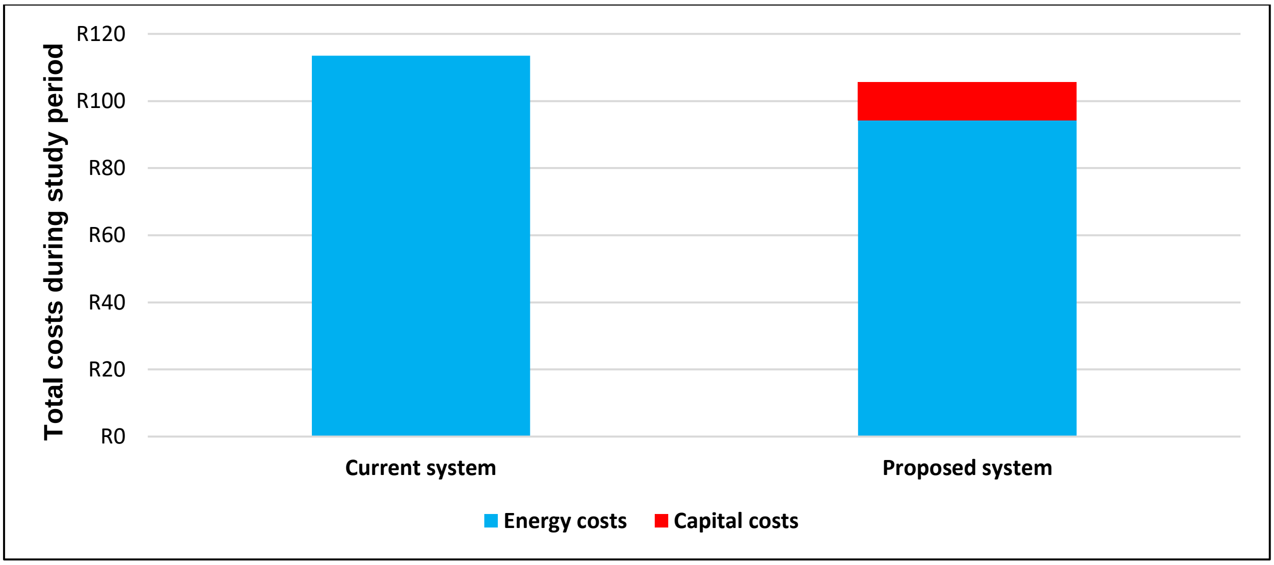


Figure 6-16: Comparison of the total costs of the proposed system and the current system

The total costs during the study period of the two systems shows that the proposed system has a lower cost despite also having capital costs, with a difference of **R8 585 732.34** which is equivalent to a **7.56 %** decrease in costs.

The energy costs of the proposed system and current system for the next 10 years further provides a clearer picture of the associated cost savings. To determine the growth rate of Eskom tariffs for the next 10 years, the growth rate of the last 10 years (2014 – 2023) is used. Using the tariffs from 2014 to 2023, the growth rate of the all the high and low demand seasons tariffs was determined to be **9.63 %**.

Using equation 3-4 and the growth rate of **9.63 %**, and assuming the demand targets and the maximum allowable transfers from the Jericho dam remain the same, the energy costs for the next 10 years are as shown in Figure 6-17.

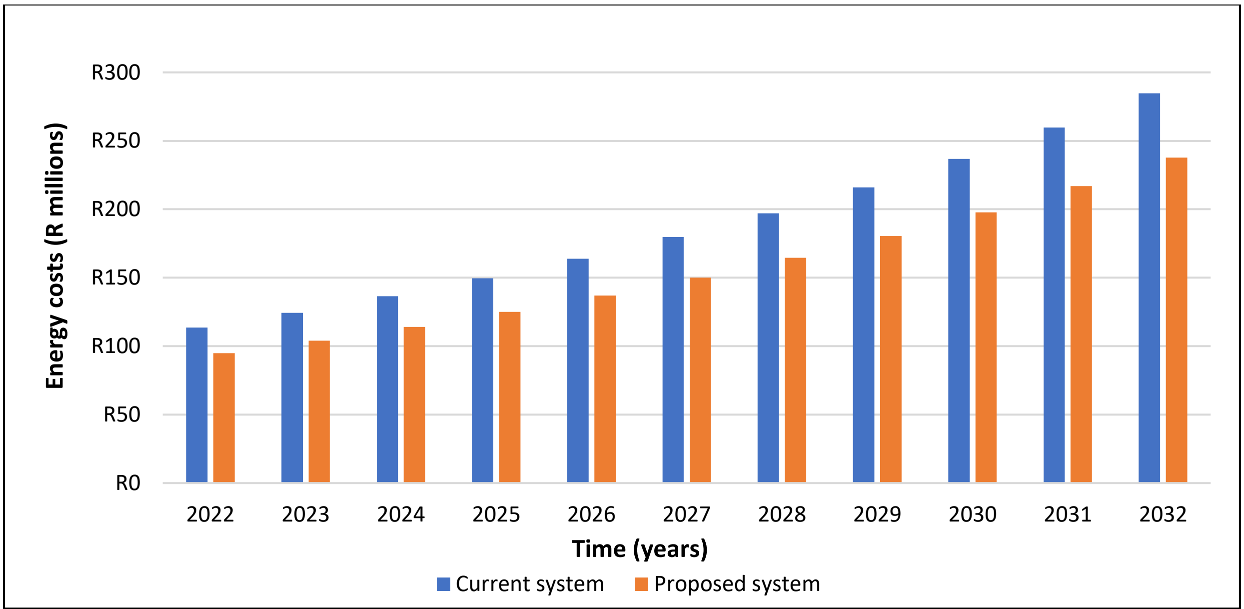


Figure 6-17: Energy costs for the proposed system and the current system for the next 10 years

From Figure 6-17, its clear that the proposed system would be provide energy costs savings for the foreseeable future as well.

6.5 Conclusion to the chapter

The mass balance of the Onverwacht reservoirs showed that the current system is constrained significantly by the minimum operating storage (60%) and the current pump scheduling makes minimization of pumping operations during peak TOU periods not possible.

Approach B which is a pump station to boost the supply from the Onverwacht reservoir is proposed to reduce the minimum required storage to 25%. Furthermore, the pump scheduling is improved through Approach C by maximizing pumping operations on Sundays during off-peak periods to maximize storage in the Onverwacht and Camden reservoirs.

The optimal pump scheduling will lead to two additional pump starts during weekdays for the peak periods in the mornings and evenings. As the maximum pump starts are between 8 and 10 as per Section 2.3.3, the additional pump stars should therefore not shorten the life of the motor and the pump assembly.

A comparison of the capital and operational costs of the proposed system with Approach B and C, and the current system showed that the energy costs of the proposed system are lower than the energy costs of the current system for the study period. Furthermore, using the proposed system would ensure a **17.02 %** saving in annual energy costs.

The total costs (operational and capital costs) of the proposed system are lower than those of the operational costs of the current system with percentage drop of **7.56 %** in total costs. Furthermore, it was showed that in the following ten years the annual savings in operational costs would be substantial. Overall, Approach B and C can significantly reduce the operational costs of the Jericho/Kliphoek/Onverwacht pumping system.

As discussed in Section 6.1.2, to accurately assess the financial viabilities of the four proposed solutions, a comprehensive life cycle costing would have to be done for each solution. Therefore, it should be noted that the other solutions and combinations could potentially also reduce the operational costs of the pumping Jericho/Kliphoek/Onverwacht system.

Chapter 7 : Conclusions, and Recommendations

As a contribution to the management of bulk water transfer schemes, this study aimed to determine the impact demand changes and uncertainties have on the adherence to operational policy, performance, and energy costs. Furthermore, this study aimed to propose approaches to mitigate the impact of these changes. The literature review showed that there was need to assess how bulk water transfer systems in South Africa are affected by demand changes and a suitable solution for managing the demands was also required.

Using the case study of the Jericho pumping system, adherence to DWS policy, the operations of a study period of 12 months from May 2022 to May 2023 were investigated in Chapter 4. The performance and operations were assessed in Chapter 5 and the pump station was determined to have substantial energy costs, due to the pumping operations in peak Time of Use (TOU) periods. Chapter 6 explored feasible approaches for reducing the operational costs at the pump station, and a more cost-effective approach was proposed.

7.1 Conclusions

7.1.1 Water demand variability and uncertainty in bulk water transfer schemes.

In the case study of the Jericho pump station, the water demand varied considerably because of the dynamic nature of Eskom power station operations, whose demand varied significantly throughout history, with Camden power station being a note-worthy example. This variability necessitated several changes in the transfer capacity of the Jericho pump station and constrained the pumping system at the Onverwacht reservoirs, resulting in optimal pump scheduling not being possible. The costs of operating during peak TOU periods were showed to be significant, contributing **33.1 %** of the total operational costs throughout the study period.

Additionally, the changes in the lining of the pipelines resulted in decreased pumping capacity and efficiency of the Jericho and Kliphoek pump stations resulting in longer pumping durations required to supply the target volumes. In terms of the control policy, the Jericho and Kliphoek pump stations were found to not be operated at full available pumping capacity in periods when there was sufficient water in the Jericho dam. These pumps were also being operated in peak TOU periods for considerable periods.

7.1.2 Capital investments and operational costs

One of the lessons that was learned from this study, was how capital investments into the improvement of operations of bulk water transfer pump stations and systems, can greatly reduce operational costs. The case study of the Jericho pump station showed that capital investment into reducing the minimum storage constraint at the Onverwacht reservoirs using a pump station could reduce the total costs of the entire pumping system. The energy costs of the proposed system compared to the current system were less by R 19.32 million which was equivalent to 17.06 % reduction in costs. The total costs of the proposed system compared to the operational costs of the current system were less by R 8.58 million which was equivalent to 7.56 % reduction. Therefore, the proposed system would lead to annual energy costs savings throughout the remaining operational life of the pump station.

For the purpose of the case study, the capital investment was into a booster pump station, in other bulk water transfer systems it could be an additional reservoir, pump or pipeline, that ensures pumping operations are done cost effectively while adhering to operational policies.

7.1.3 Optimal pump scheduling

The case study also showed that there were improvements that could be made on the current pump scheduling used by the operators at the Jericho pump station to reduce the energy costs through minimization of pumping operations during peak periods. Considering that there are other bulk water transfer pump stations in South Africa with outdated control and operational policies, revision of these could result in more optimal pump scheduling in the bulk water transfer systems.

7.2 Recommendations

7.2.1 Operations of bulk water transfer pump stations

To avoid the unnecessary costs associated with pumping operations during peak periods, operators should prioritise pumping the required volumes of water during non-peak periods. If required, the maximum number of pumps should be operated to ensure pumping is done during non-peak periods especially in the high demand seasons. Optimizing pump scheduling for the system studied would require two additional pump starts during weekdays for the peak periods in the mornings and evenings, therefore, operators must ensure that these below the minimum allowable pump starts per day.

Control and operational policies of bulk water transfer systems should continuously be reviewed and updated as required, especially with ever changing demands to ensure pumping operations remain cost effective and sustainable. Furthermore, consideration should be given to capital investments with regards to the improvement of pumping operations. Life cycle analysis of the pump stations or energy cost assessments can be used to indicate the benefit of cost-effective pumping operations especially with rapidly increasing electricity costs in South Africa, to inform decision-makers or source funding.

7.2.2 Future studies

This study was limited to only DWS bulk water transfer pump stations, and the assessment was based on a single case study. Other pump stations can be assessed to determine the impact demand variability and uncertainty have on the total costs and ability of the pump station to manage the demands.

Furthermore, only weekly pumping durations were recorded and made available for this study, consequently average daily pumping durations were used. A study with actual daily pumping durations would provide a more accurate assessment.

References

Ekurhuleni Metropolitan, 2020. *Guidelines and Standards for Planning and Design of Water and Sanitation Services,* Johannesburg: City of Ekurhuleni Metropolitan Municipality.

2030 Water Resources Group, 2009. *Charting Our Water Future: Economic frameworks to inform decision-making,* s.l.: Available at: https://www.2030wrg.org/wp-content/uploads/2014/07/Charting-Our-Water-Future-Final.pdf.

ABB, 2006. *Using variable speed drives (VSDs) in pump applications - Applications guide No. 2,* Helsinki, Finland: ABB.

Abdelazeem, A. A. & Hossam, A. G., 2021. Energy saving and management of water pumping networks. *Heliyon,* 7(8), p. e07820.

Absel.Sulzer.com, 2023. *Pump selection software,* Online software: Accessed at URL:https://absel.sulzer.com/PumpProdConfig.aspx.

Africa News, 2023. South Africa's economy at risk of stagnation, says IMF. *Africa News.com*, March, pp. https://www.africanews.com/2023/03/23/south-africas-economy-at-risk-of-stagnation-says-imf//.

Ahmadi, H. & Razavi, E., 2018. Determination of Submergence Depth to Avoid Vortices at Horizontal Intake Applying Flow-3D Software. *Journal of Civil Engineering Research,* 8(3), pp. 62-69.

Alabi, M. O., Telukdarie, A. & van Janse Rensburg, N., 2019. *Industry 4.0 and water industry: A South African perspective and readiness.* Johannesburg, American society for engineering management.

Andreu, J., Capilla, E. & Sanchis, E., 1996. A generalized decision-support system for water-resources planning and operational management. *Journal of Hydrology,,* 177(3-4), pp. 269-291.

Babayan, A. V., Kapelan, Z., Savic, D. A. & Walters, G. A., 2005. Least cost design of water distribution network under demand uncertainty. *Journal of Water Resource Planning and Management,* 131(5), pp. 375-382.

Babayan, A. V., Savic, D. A., Walters, G. A. & Kapelan, Z., 2007. Robust least-cost design of water distribution networks using redundancy and integration-based methodologies. *Journal of Water Resource Planning and Management,* 133(1), pp. 67-77.

Bagirov, A. M., Jetmarova, H. M., Nuaimat, A. A. & Ahmed, S. T., 2012. *Minimization of pumping costs in water distribution systems using explicit and implicit pump scheduling.* Sydney, Engineers Australia.

Barney, N., 2023. Load shedding. *TechTarget.com*, May, pp. https://www.techtarget.com/searchdatacenter/definition/load-shedding.

Basupi, I. & Kapelan, Z., 2015. Evaluating Flexibility in Water Distribution System Design under Future Demand Uncertainty. *Journal of Infrastructure Systems,* 21(2), pp. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000199.

Behandish, M. & Wu, Z., 2014. Concurrent pump scheduling and storage level optimization using meta-models and evolutionary algorithms. *Procedia Engineering,* 70(DOI:10.1016/j.proeng.2014.02.013), pp. 103-112.

Brown, C., 2010. The End of Reliability. *Journal of Water Resuorce Planning and Management,* 136(2), pp. 143-145.

Cardoso, P., Rato, R., Estrela, M. & and others, 2017. Assessment of pumps performance in water supply systems. *European Journal of Sustainable Development,* 6(2), pp. 217-226.

Chikobvu, D. & Sigauke, C., 2012. Regression-SARIMA modelling of daily peak electricity demand in South Africa. *Journal of Energy in Southern Africa,* 23(3), pp. 23-30.

CIWEM, 2023. *Bulk water transfers,* Accessed at URL: https://www.ciwem.org/assets/pdf/Policy/Policy%20Position%20Statement/Bulk-Water-Transfers.pdf: Chartered Institution of Water and Environmental Management.

Coward, S., 2018. 5 water industry challenges, and how industry 4.0 solves them. *Sage automation*, 3 December, pp. Accessed at URL: https://www.sageautomation.com/blog/5-water-industry-challenges-and-how-industry-4.0-solves-them, 9 May 2022.

Creaco, E., Franchini, M. & Walski, T. M., 2013. Accounting for phasing of construction within the design of water distribution networks. *Journal of Water Resource Planning and Management,* 140(5), pp. 598-606.

De Paola, F., Fontana, N., Giugni, M. & Marini, G., 2016. An Application of the Harmony-Search Multi-Objective (HSMO) Optimization Algorithm for the Solution of Pump Scheduling Problem. *Procedia Eng.,* 162(DOI:10.1016/j.proeng.2016.11.093), pp. 494 - 502.

Department of Water & Sanitation, 2015. *Onverwacht Reservoir - Operation and Maintenance manual,* Bloemfontein: Babereki Consulting Engineers.

Department of Water & Sanitation, 2015. *South Africa yearbook 2014/15,* Pretoria: DWS.

Department of Water & Sanitation, 2015. *VAAL RIVER SYSTEM 2014/2015 AOA,* Cape Town: Aurecon (SA) (Pty) Ltd.

Department of Water & Sanitation, 2015. *Vaal River System Annual Operating Analysis 2015/2016,* South Africa: Prepared by Aurecon in association with WRP as part of the Development of Operating Rules for the Integrated Vaal River System and Stand-alone Dams in the Catchment. DWS Report No. P RSA C000\00\21415.

Department of Water & Sanitation, 2017. *Operational philosophy meeting,* Jericho pump station: Department of Water and Sanitation - HATCH.

Department of Water & Sanitation, 2018. *Master plan Volume 1: Call to Action,* Pretoria: DWS.

Department of Water & Sanitation, 2020. *2019/20 Annual report,* Pretoria: Department of Water and Sanitation.

Department of Water & Sanitation, 2020. *Vaal River System: Annual Operating Analysis 2019/2020,* Pretoria: Directorate: Water Resources Planning Systems.

Department of Water Affairs and Forestry, 2009. *Pump station operation.* Pretoria: Department of Water Affairs and Forestry.

Department of Water Affairs, 1979. *Kriel, Camden, Matla power stations Raw water scheme - Diagrammatic layout,* Pretoria, South Africa: Department of Water Affairs.

Department of Water Affairs, 2011. *Classification of Significant Water Resources (River, Wetlands, Groundwater and Lakes) in the Upper, Middle and Lower Vaal Water Management Areas (WMA) 8, 9, 10: Water Water Resource Analysis Report - Report number:RDM/WMA8,9,10/00/CON/CLA/0411,* South Africa: Department of Water Affairs.

Department of Water Affairs, 2013. *Vaal River System - Annual Operating Analysis 2012/2013,* Pretoria: Department of Water Affairs.

Department of Water Affairs, 2016. *Vaal River System Annual Operating Analysis 2016/2017,* Cape Town: Aurecon (SA) (Pty) Ltd .

Director General of Environmental Affairs, 1982. *Komati - Usutu Rivers link system government water scheme - Second supplementary report,* Pretoria: Director General of Environmental Affairs.

Douglas, J. F., Gasiorek, J. M., Swaffield, J. A. & Jack, L. B., 2011. *Fluid Mechanics.* 6th ed. Harlow: Pearson Education Limited.

Duvenhage, D. F., 2015. *Integration of DSM into bulk water transfer strategies, M(Eng) thesis,* Potchefstroom: North West University.

DWA, 1981. *Report on the proposed Usutu-vaal government water scheme,* Pretoria: Department of water affairs, forestry and environmental conservation.

DWA, 2012. *Overview of the South African water sections,* s.l.: Accessed at URL: https://www.dws.gov.za/IO/Docs/CMA/CMA%20GB%20Training%20Manuals/gbtrainingmanualchapter1.pdf.

DWAF, 2000. *Overview of the South African water sector: Governing board induction manual,* Pretoria: Department of Water and Foresty.

DWAF, 2001. *Design of a decision support system and scenario generator for the assessment of land use impacts on water resources within an water management area,* Pretoria: DWS.

DWAF, 2003. *STRATEGIC FRAMEWORK FOR WATER SERVICES,* South Africa: Accessible at URL:https://www.gov.za/documents/other/strategic-framework-water-services-01-sep-2003,.

DWS - Hydrological Services, 2023. *Hydrological Services - Surface Water (Data, Dams, Floods and Flows),* Department of Water and Sanitation: Accessed at URL:https://www.dws.gov.za/Hydrology/Default.aspx,.

DWS: Water Services Macro Planning, 2017. *STRATEGIC OVERVIEW OF THE WATER SECTOR IN SOUTH AFRICA 2017,* s.l.: Available at: http://ws.dwa.gov.za/downloads/WS/P_I/Adhoc/AWensley/2017%20SOWS_A6_12%20Oct%202017_print%20crop.pdf.

DWS, 2015. *Jericho pump station - Draft report on design considerations,* Pretoria: DWS.

DWS, 2015. *STRATEGIC OVERVIEW OF THE WATER SERVICES SECTOR IN SOUTH AFRICA,* Pretoria: Accessed at URL: http://rnd.zednet.co.za/Training/B_learning_material/knowledge/3%20Legal%20Thompson/STRATEGIC%20OVERVIEW%20OF%20THE%20WATER%20SERVICES%202015%20(A6%20Booklet).pdf.

DWS, 2016. *Vaal river system 2015/2016 AOA: Main report,* Pretoria: Department of Water and Sanitation.

DWS, 2023. *Reconciliation strategy for the vaal river system,* Pretoria: Accessed at URL: https://www.dws.gov.za/iwrp/Vaal/#:~:text=The%20Integrated%20Vaal%20River%20System%20(IVRS)%20is%20the%20most%20important,and%2033%25%20of%20the%20population..

Eberhard, A., 2005. From State to Market and Back Again: South Africa's Power Sector Reforms. *Economic and political weekly,* 40(50), pp. 5309 - 5317.

Eck, B., McKenna, S., Akrhiev, A. & Kishimoto, A., 2014. *Pump scheduling for uncertain electricity prices.* Dublin, World Environmental and Water Resources Congress.

Ertin, E., Dean, A. N., Moore, M. L. & Priddy, K. L., 2001. Dynamic optimization for optimal control of water distribution systems.. *In Applications and Science of Computational Intelligence IV,* 4390(https://doi.org/10.1117/12.421163), pp. 142-149.

Eshragh, F., Pooyandeh, M. & Marceau, J. D., 2015. Automated negotiation in environmental resource management: Review and assessment. *Journal of Environmental Management,* 162(1), pp. 148-157.

Eskom , 2022. *Week-on-Week Dispatchable Generation Peak Demand: Weekly System Status,* South Africa: Accessed at URL: https://www.eskom.co.za/wp-content/uploads/2022/12/Weekly_System_Status_Report_2022_w51.pptx,.

Eskom, 1991. *Eskom tariff history: 1973 - 1991,* South Africa: Eskom.

Eskom, 2013. *History in the decades,* South Africa: Accessed at URL: https://www.eskom.co.za/heritage/history-in-decades/.

Eskom, 2018. *Water reuse and recycle practices at Eskom Power Plants - Fact sheet,* South Africa: Accessible at URL: https://www.eskom.co.za/wp-content/uploads/2021/03/ENV0003WaterRe-UseRecyclePowerPlants.pdf,.

ESKOM, 2021. *Tariffs and Charges Booklet - 2020/2021,* South Africa: website: www.eskom.co.za/tariffs. .

Eskom, 2022. *SCHEDULE OF STANDARD PRICES FOR ESKOM TARIFFS - 2022/23,* South Africa: Accessed at URL: https://www.eskom.co.za/distribution/wp-content/uploads/2022/03/Schedule-of-standard-prices-2022_23.pdf, 28 April 2022.

Eskom, 2022. *Tariffs and charges booklet,* South Africa: Eskom - www.eskom.co.za/tariffs.

Fan, Y., Hao-ru, Z. & Chao, L., 2016. Improvement of the Efficiency of the Axial-Flow Pump at Part Loads due to Installing Outlet Guide Vanes Mechanism. *Mathematical Problems in Engineering,* 2016(6), pp. 1-10.

Finnan, K., 2002. Water Security: The Role of the SCADA system. *Automation.com*, 10 March, pp. Accessed at URL: https://www.automation.com/en-us/articles/2017/water-security-the-role-of-the-scada-system, 06 May 2022.

Garcia-Lopez, M., Montano, B. & Melgarejo, J., 2022. The Tariff Structure in the Tagus-Segura Water Transfer. *Water,* 14(3), p. https://doi.org/10.3390/w14030413.

Gencoglu, G. & Merzi, N., 2016. Trading-off constraints in the pump scheduling optimization of water distribution networks. *Journal of Urban and Environmental Engineering,* 10(1), pp. 135-143.

Georgescu, S. C. & Georgescu, A. M., 2015. PUMPING STATION SCHEDULING FOR WATER DISTRIBUTION NETWORKS IN EPANET. *UPB Scientific Bulletin, Series D: Mechanical Engineering,* 77(2), pp. 235 - 246.

Giliomee, G. J., 2016. *Quantifying the cost of pump efficiency decay on the Department of Water and Sanitation, M(Eng) thesis, North University,* North West: Accessed at URL: https://dspace.nwu.ac.za/bitstream/handle/10394/26092/Giliomee_GJ_2017.pdf?sequence=1&isAllowed=y, 26 April 2022.

Goulter, I., 1995. Analytical and simulation models for reliability analysis in water distribution systems. *Improving Efficiency and Reliability in Water Distribution Systems,* Volume DOI:org/10.1007/978-94-017-1841-7_10, pp. 235-266.

Guyer, P., 2012. *Introduction to Pumping Stations for Water Supply Systems,* New York: CED engineering.com.

Hatch, 2017a. *DWS: Extension and Rehabilitation of the Existing Jericho Pump Station and Associated Work (WP0485) - Inception Report,* Pretoria: Accessed at URL: https://www.hatch.com/-/media/Hatch-Corporate/PDF/Jericho-Pump-Station/Inception-Report.pdf?la=en, 26 April 2022.

Hatch, 2017b. *Extension and rehabilitation of the existing Jericho pump station and Associated works - Review of preliminary design,* Pretoria: DWS.

Herstein, L. M., Filion, Y. R. & Hall, K. R., 2009. Evaluating environmental impact in water distribution system design. *Journal of Infrastructure Systems,* 15(3), pp. 241-250.

Hydraulic Institute & U.S. Department of Energy, 2006. *Improving Pumping System Performance.* 2nd ed. Washington, DC: Hydraulic Institute & U.S. Department of Energy.

Illemobade, A. A., Manson, N. J. & Stephenson, D., 2005. Pump and reservoir system operational optimisation using a non-linear tool. *Journal of the South African Institution of Civil Engineering,* 47(4), pp. 2-11.

info, W. d., 2023. *Inflation rates in South Africa,* s.l.: Accessed at URL:https://www.worlddata.info/africa/south-africa/inflation-rates.php.

Jaminet, M., 2003. Defining off-peak performance - AOR and POR. *Flygt*, 2 September, pp. 1-9.

Jones, G., Sanks, R., Tchobanoglous, G. & Bosserman, B., 2008. *Pump station design.* 3rd ed. s.l.:Elsevier.

Jung, D., Kang, D., Kang, M. & Kim, B., 2015. Real time pump scheduling for water transmission sytems: case study. *KSCE Journal of Civil Engineering,* 19(7), pp. 1-7.

Jung, D., Kang, D. & Kim, H. J., 2014. Robustness-Based Design of Water Distribution Systems. *Journal of Water Resources Planning and Management,* 140(11), pp. DOI:10.1061/(ASCE)WR.1943-5452.0000421.

Jung, D., Lansey, K. E., Choi, Y. H. & Kim, J. H., 2016. Robustness-based optimal pump design and scheduling for water distribution systems. *Journal of Hydroinformatics,* 18(3), pp. 500-513.

Jung, D., Lee, S. & Kim, J. H., 2019. Robustness and Water Distribution System: State-of-the-Art-Review. *Water,* 11(974), p. doi:10.3390/w11050974.

Kotzen, K., 2014. *A Perspective on Distributed Generation in Municipal Networks - The revenue impact of Solar Generation.* Midrand, Conference: 64th AMEU Convention - DOI: 10.13140/2.1.2914.0803.

KSB Easyselect, 2024. *Pump selection software,* Online software: Accessed at URL:https://www.ksb.com/easyselect/app/?n=ext_vst.

KSB Service, 2013. *System analysis of Water Pump WL 400/2 at Jericho Dam,* Johannesburg: KSB Pumps and Valves (Pty) Limited.

KSB, 2021. *Life cycle costs,* Accessed at URL: https://www.ksb.com/centrifugal-pump-lexicon/life-cycle-costs/192314/: KSB - Centrifugal Pump Lexicon.

Larralde, E. & Ocampo, R., 2010. Centrifugal pump selection process. *World Pumps,* 2010(2), pp. 24-28.

Lawens, M. & Mutsvangwa, C., 2018. Application of multiple regression analysis in projecting the water demand for the City of Cape Town. *Water Practice and Technology,* 13(6), p. doi: 10.2166/wpt.2018.082.

López-Ibáñez, M., Prasad, T. D. & Paechter, B., 2008. Ant Colony Optimization for Optimal Control of Pumps in Water Distribution Networks. *Journal for Water Resource Planning and Management,* 134(4), pp. 337-346.

Loucks, D. P. & van Beek, E., 2017. *Water resource systems planning and management.* 1st ed. ISBN 978-3-319-44234-1 (eBook): Deltares & UNESCO-IHE.

Mackle , G., Savic, D. & Walters, G., 1995. Application of genetic algorithms to pump scheduling for water supply. *First International Conference on Genetic Algorithms in Engineering Systems: Innovations and Applications,* Volume doi: 10.1049/cp:19951082., pp. 400-405.

Macleod, S. P. & Filion, Y. R., 2011. Issues and implications of carbon-abatement discounting and pricing for drinking water system design in Canada. *Water Resource Management,* 26(1), pp. 44-61.

Macrotrends, Accessed on 9 November 2023. *South Africa Inflation Rate 1960-2023,* s.l.: Accessed at URL: https://www.macrotrends.net/countries/ZAF/south-africa/inflation-rate-cpi.

Manson, N. J., 1998. *Reservoir system operational optimisation,* Johannesburg: Water Systems Research Group - University of Witwatersrand.

Markus, E. D., 2018. A critical Analysis of Water Resource in South Africa's Thermoelctric Power Sector. *Journal of Computational and Theoretical Nanoscience,* 24(14), pp. 8992-8996.

Matchaya, G., Nhamo, L., Nhlengethwa, S. & Nhemachena, C., 2019. An Overview of Water Markets in Southern Africa: An Option for Water Management in Times of Scarcity. *MDPI: Water,* 11(5), p. 1006.

Menke, R., Abraham, E., Parpas, P. & Stoianov, I., 2016. Exploring Optimal Pump Scheduling in Water Distribution Networks with Branch and Bound Methods. *Water Resource Management,* 30(14), pp. 5333-5349.

Mkhize, T. & Meyer, A., 2011. *Alternative funding model for water conservation.* Midrand, Accessed at URL:https://www.slideserve.com/simone/alternative-funding-model-for-water-conservation.

Moolman, S., 2021. 2022 update: Eskom tariff increases vs inflation since 1988 (with projections to 2024). *Poweroptimal.com*, 1 August, pp. Accessed at URL:https://poweroptimal.com/2021-update-eskom-tariff-increases-vs-inflation-since-1988/.

Mudau, T. D., 2018. *Report on the performance test of Pump 3 at Jericho pump station,* Pretoria: DWS: Directorate - Mechanical & Electrical Engineering.

Negishi, S. & Ikegami, T., 2021. Robust scheduling for pumping in a water distribution system under the uncertainty of activating regulation reserves. *Energies,* 14(2), p. 302.

Negm, A.-A. M., Shouman, M. A. & Abdel-Gawad, A. F., 2004. *PERFORMANCE EVALUATION OF ARTIFICIAL NEURAL NETWORKS SOFTWARES IN PREDICTION OF HYDRAULIC DATA.* Zagazig, 4 World Scientific Publishing Company, ISBN 981-238-787-0.

Ngancha, P. B., Kusakana, K. & Markus, E. D., 2022. Optimal pumping scheduling for municipal water storage systems. *Energy reports,* Volume 8, pp. 1126-1137.

NRCS, 2010. *Variable Speed Drives for Irrigation Pumping,* Montana, US: Natural Resources Conservation Services - Engineering Technical Note No. MT-14.

Official Inflation Data, Alioth Finance, 13 Aug 2023. *R100 in 2005 → 2023 | South Africa Inflation Calculator.,* s.l.: Accessed at URL:https://www.officialdata.org/south-africa/inflation/2005?amount=100..

ORASECOM, 2013. *Zaaihoek transfer scheme,* South Africa: The Orange–Senqu River Basin Infrastructure Catalogue.

Pandey, P., Dongre, S. & Gupta, R., 2020. Probabilistic and fuzzy approaches for uncertainty consideration in water distribution networks – a review. *Water Supply,* 20(1), pp. 13-27.

Papa, F., Radulj, D. & Fund, C., 2013. Thermodynamic method used for pump performance and efficiency testing program. *Environmental Science & Engineering Magazine*, March, pp. 44-48.

Pouris, A. & Thopil, G. A., 2015. *Long term forecasts of water usage for electricity generation: South Africa,* Pretoria: Institute for Technological Innovation, University of Pretoria.

Puccini, G. D., Blaser, L. E., Bonetti, C. A. & Butarelli, A., 2016. Robustness-based design of water distribution networks. *Water Utility Journal,* Volume 13, pp. 13-28.

Pulido-Calvo, I., Gutierrrez-Estrada, J. C. & Asensio-Fernandez, R., 2006. Optimal design of pumping stations of inland intensivge fishfarms. *Aquacultural Engineering,* 35(3), pp. 283-291.

Pumps & System, 2012. Pump efficiency - what is efficiency ?. *pumpsandsystems.com*, 20 January, pp. Accessed at URL: https://www.pumpsandsystems.com/pump-efficiency-what-efficiency.

Ramos, H. M., Kenov, K. N. & Vieira, F., 2011. Environmentally friendly hybrid solutions to improve the energy and hydraulic effciency in water supply systems.. *Energy Sustain Dev,* 15(4), pp. 436-442.

Reis, A. L., Lopes, M. A., Andrade-Campos, A. & Antunes, C. H., 2023. A review of operational control strategies in water supply systems for energy and cost efficiency. *Renewable and Sustainable Energy Reviews,* Volume 175, p. https://doi.org/10.1016/j.rser.2022.113140.

Rousseau, P., 2015. *MEC 3033F Thermofluids II - Fluid mechanics,* Cape Town: Department of Mechanical Engineering, University of Cape Town.

Sarbu, I., 2016. A study of Energy Optimization of Urban Water Distribution Systems Using Potential Elements. *Water,* 8(12), p. 593.

Scheepers, C., Bolt, G. & Kleingeld, M., 2013. *Energy management challenges in the automation of a water transfer pumping station.* Cape Town, 2013 Proceedings of the 10th Industrial and Commercial Use of Energy Conference, pp. 1-4.

Schlebusch, J., 2022. *Usutu River: Pump performance reports,* Amsterdam, Mpumalanga: DWS: Jericho Dam Office (Usutu River central operations).

Simonovic, S. P., 2009. *Managing Water Resources: Methods and Tools for a Systems Approach.* 1st ed. Paris: UNESCO.

Snaddon, C. D., Davies, B. R. & Wishart, M. J., 1999. *A Global Overview of Inter-Basin Water Transfer Schemes, with an Appraisal of Their Ecological, Socio-Economic and Socio-Political Implications,and Recommendations for Their Management ,* Pretoria: Water Research Commission.

Stokes, C. S., Simpson, A. R. & Maier, H. R., 2014. The cost–greenhouse gas emission nexus for water distribution systems including the consideration of energy generating infrastructure: an integrated conceptual optimization framework and review of literature. *Earth Perspectives,* 1(9), pp. https://doi.org/10.1186/2194-6434-1-9.

Sulzer, 2023. *Axial flow pump type Ensival Moret CAHR,* Europe: Accessed at URL: https://www.sulzer.com/en/shared/products/axial-flow-pump-type-ensival-moret-cahr.

Tolvanen, J., 2007. Life cycle energy cost savings through careful system design and pump selection. *World Pumps,* 2007(490), pp. 34-37.

Tsekoa, K., 2017. *An analysis of challenges in Implementing an equipment reliability improvement strategy.,* Pretoria: Accessed at URL: https://repository.up.ac.za/bitstream/handle/2263/62797/Tsekoa_Analysis_2017.pdf?sequence=1&isAllowed=y.

Van Niekerk, P. H., 2013. *Hydrologic-economic appraisal of inter-basin water transfer projects - Dissertation presented for the degree of Doctor of Philosophy,* Stellenbosch: Accessed at URL: https://core.ac.uk/download/pdf/37410606.pdf.

Van Niekerk, P. H. & Du Plessis, J. A., 2013. Hydrologic-economic appraisal of life-cycle costs of inter-basin water transfer projects. *Water SA,* 39(4), p. http://dx.doi.org/10.4314/wsa.v39i4.13.

van Vuuren, S. J. & van Dijk, M., 2012. *Determination of the change in Hydraulic Capacity in Pipelines,* Pretoria: Water Research Commission - WRC Report No. 1820/1/12.

Van Zyl, J. E., Savic, D. & Walters, G. A., 2004. OPERATIONAL OPTIMIZATION OF WATER DISTRIBUTION SYSTEMS USING A HYBRID GENETIC ALGORITHM. *Journal of Water Resuorce Planning and Management,* 130(2), pp. 160-170.

Vertommen, I., van Laarhoven, K. & da Conceicao Cunha, M., 2021. Robust Design of a Real-Life Water Distribution Network under Different Demand Scenarios. *Water,* 13(753), p. 10.3390/w13060753 .

Waide, P. & Brunner, C. U., 2011. *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems.* 1 ed. Paris: International Energy Agency (IEA) - Energy Efficiency Series.

Walters, G. & Savic, D., 1996. Recent applications of genetic algorithms to water system design. *HYDRAULIC ENGINEERING SOFTWARE VI,* pp. 143-152.

World data.info, 2023. *Inflation rates in South Africa,* Online source accessed on 9 November 2023: Accessed on URL: https://www.worlddata.info/africa/south-africa/inflation-rates.php.

World Population Review, 2021. *South Africa Population 2021,* Accessed at URL: https://worldpopulationreview.com/countries/south-africa-population: World Population Review.

WRC, 2013. Apprasing the lifecycle cots of SA's interbasin water transfer projects. *Water resource development*, Accessed at URL:https://www.wrc.org.za/wp-content/uploads/mdocs/09%20IBT%20p%2028-31.pdf December, pp. 28-31.

WRP Consulting Engineers, 2019. *2019/2020 Annual Operating Analysis: WRPM Scenarios - Compiled for the Deparment of Water and Sanitation,* Pretoria: Accessed at URL: http://rnd.zednet.co.za/Vaal/Vaal%20AOA/2019/Vaal_AOA_2019_Working_Document_v7.pdf, 28 April 2022.

Wu, Z. & Behandish, M., 2012. *Real time pump scheduling using genetic algorithm and artificial neural networks based on graphis processing unit.* Adelaide, Australia, 14th Water Distribution Systems Analysis Conference, pp 1088 - 1099.

Zhang, H., Xiaohua, X., Zhang, J. & Xia, X., 2012. OPTIMAL SIZING AND OPERATION OF PUMPING SYSTEMS TO ACHIEVE ENERGY EFFICIENCY AND LOAD SHIFTING. *Electric power systems research,* Volume 86, pp. 41-50.

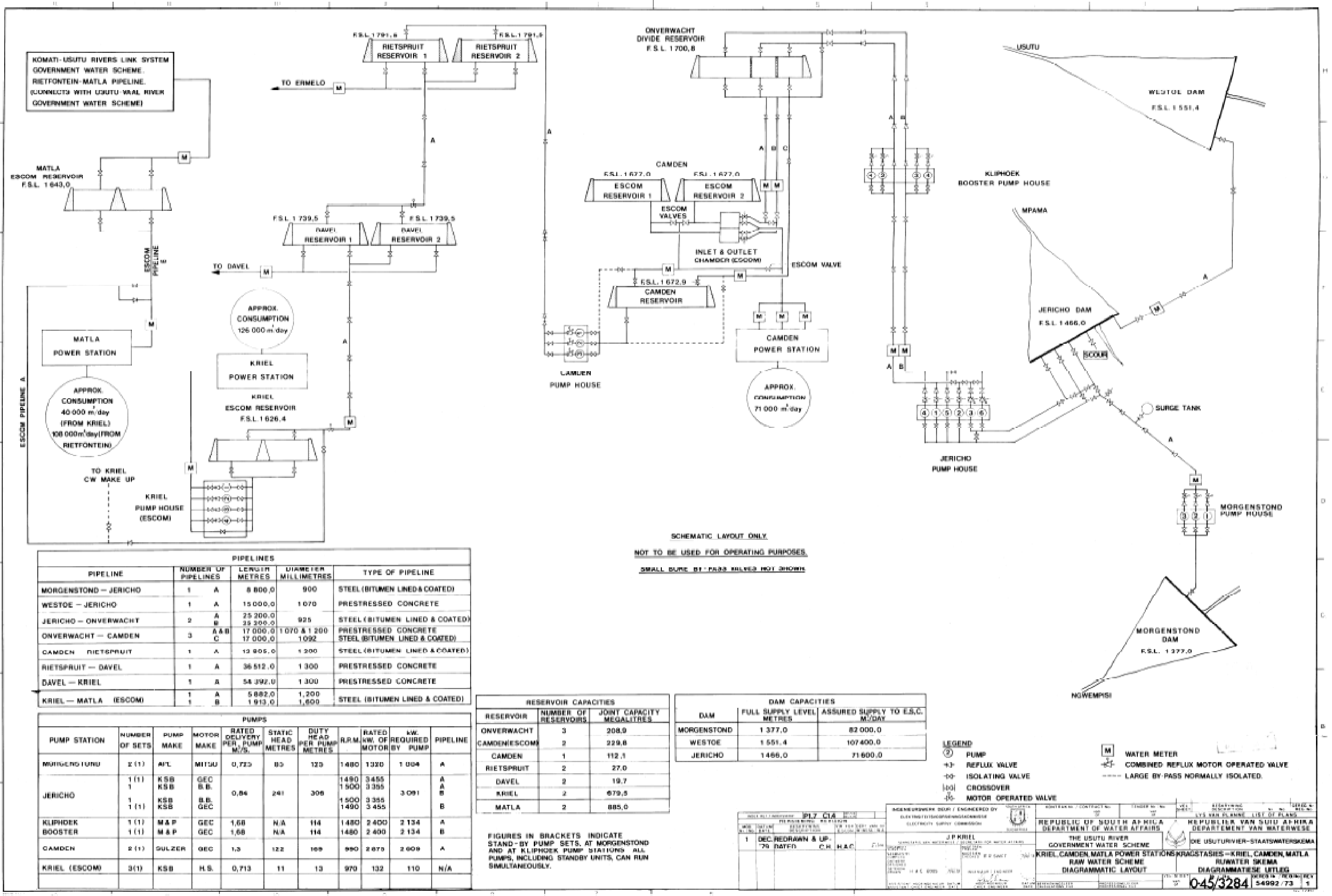
Appendices

Appendix A. AOA Targets – 2022/2023

Description	Units	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	Annual Transfer
		31,00	30,00	31,00	31,00	30,00	31,00	30,00	31,00	31,00	28,25	31,00	30,00	365,25

Jericho to Onverwacht (Maximum transfer capacity is 2.8 m^3/s) - WRPM Channel 36 (Channels 27 and 39 transfers plus Channel 1425 transfer) (DWA Jericho pumped)														
Maximum Transfer Capacity	m^3/s	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	**2,80**
	Million m^3/m	7,50	7,26	7,50	7,50	7,26	7,50	7,26	7,50	7,50	6,83	7,50	7,26	**88,36**
	Cumulative	7,50	14,76	22,26	29,76	37,01	44,51	51,77	59,27	66,77	73,60	81,10	88,36	
Actual capacity	m^3/s	2,00	2,00	2,00	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	**2,60**
	Million m^3/m	5,36	5,18	5,36	7,50	7,26	7,50	7,26	7,50	7,50	6,83	7,50	7,26	**82,00**
	Cumulative	5,36	10,54	15,90	23,40	30,65	38,15	45,41	52,91	60,41	67,25	74,74	82,00	
Target	m^3/s	2,46	2,47	2,51	2,47	2,45	2,45	2,44	2,41	2,42	2,41	2,42	2,42	**2,44**
	Million m^3/m	6,58	6,41	6,72	6,62	6,35	6,56	6,33	6,46	6,48	5,88	6,48	6,27	**77,13**
	Cumulative	6,58	12,99	19,71	26,33	32,67	39,23	45,56	52,02	58,49	64,38	70,86	77,13	

Appendix B: Usutu Vaal Layout



PIPELINES						
PIPELINE	NUMBER OF PIPELINES		LENGTH METRES	DIAMETER MILLIMETRES	TYPE OF PIPELINE
MORGENSTOND – JERICHO	1	A	8 800,0	900	STEEL (BITUMEN LINED & COATED)
WESTOE – JERICHO	1	A	15 000,0	1 070	PRESTRESSED CONCRETE
JERICHO – ONVERWACHT	2	A B	25 200,0 25 200,0	925	STEEL (BITUMEN LINED & COATED)
ONVERWACHT – CAMDEN	3	A & B C	17 000,0 17 000,0	1 070 & 1 200 1092	PRESTRESSED CONCRETE STEEL (BITUMEN LINED & COATED)
CAMDEN – RIETSPRUIT	1	A	12 905,0	1 200	STEEL (BITUMEN LINED & COATED)
RIETSPRUIT – DAVEL	1	A	36 512,0	1 300	PRESTRESSED CONCRETE
DAVEL – KRIEL	1	A	54 392,0	1 300	PRESTRESSED CONCRETE
KRIEL – MATLA (ESCOM)	1 1	A B	5 882,0 1 913,0	1,200 1,600	STEEL (BITUMEN LINED & COATED)

PUMPS										
PUMP STATION	NUMBER OF SETS	PUMP MAKE	MOTOR MAKE	RATED DELIVERY PER PUMP M³/S.	STATIC HEAD METRES	DUTY HEAD PER PUMP METRES	R.P.M.	RATED kW. OF MOTOR	kW. REQUIRED BY PUMP	PIPELINE
MORGENSTOND	2 (1)	APL	MITSU	0,723	83	123	1480	1320	1 004	A
JERICHO	1 (1) 1 1 1 (1)	KSB KSB KSB KSB	GEC B.B. B.B. GEC	0,84	241	306	1490 1 500 1 500 1490	3 455 3 355 3 355 3 455	3 091	A A B B
KLIPHOEK BOOSTER	1 (1) 1 (1)	M & P M & P	GEC GEC	1,68 1,68	N/A N/A	114 114	1480 1480	2 400 2 400	2 134 2 134	A B
CAMDEN	2 (1)	SULZER	GEC	1,3	122	169	990	2 875	2 609	A
KRIEL (ESCOM)	3(1)	KSB	H.S.	0,713	11	13	970	132	110	N/A

RESERVOIR CAPACITIES		
RESERVOIR	NUMBER OF RESERVOIRS	JOINT CAPACITY MEGALITRES
ONVERWACHT	3	208,9
CAMDEN(ESCOM)	2	229,8
CAMDEN	1	112,1
RIETSPRUIT	2	27,0
DAVEL	2	19,7
KRIEL	2	679,5
MATLA	2	885,0

DAM CAPACITIES		
DAM	FULL SUPPLY LEVEL METRES	ASSURED SUPPLY TO E.S.C. M³/DAY
MORGENSTOND	1 377,0	82 000,0
WESTOE	1 551,4	107 400,0
JERICHO	1466,0	71 600,0

FIGURES IN BRACKETS INDICATE STAND-BY PUMP SETS. AT MORGENSTOND AND AT KLIPHOEK PUMP STATIONS ALL PUMPS, INCLUDING STANDBY UNITS, CAN RUN SIMULTANEOUSLY.

Appendix C: Actual energy costs of pumping operations for peak, standard and off-peak periods during study period

	No.	Reporting period (May 2022 and	Jericho Pump Station				Kliphoek pump statio		Pump consumption (kW)						Peak (hours)						kWh	Peak energy costs (Rands)						Total weekly costs (Rands)
			Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/2	Pump 3/4	Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/2	Pump 3/4	Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/2	Pump 3/4		Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/2	Pump 3/4	
May	1	23 - 30 May	84,4	69	168	168	0	168	2600	2600	3050	3050	0	2134	18	7	25	25	0	25	270850	79045	30740	128786	128786	0	90108,15	R457 465,65
Jun	2	6 - 13 June	132,15	0,67	168	157,5	0	168	3200	2600	3050	3050	0	2134	25	0	25	25	0	25	285850	414264	0	394845	394845	0	276262,3	R1 480 217,06
Jun	3	13 - 16 June	168	168	150,45	0	168	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Jun	4	20 - 27 June	168	168	85,45	0	168	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Jul	5	27 June - 4 July	168	168	155,3	0	168	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Jul	6	4 - 11 July	168	168	155,3	0	142	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Jul	7	18 - 25 July	167,5	161	123,55	0	161	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Jul	8	25 July - 1 Aug	168	166,4	166	0	115,15	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Aug	9	1 - 8 Aug	168	161,25	168	0	155,3	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Aug	10	8 - 15 Aug	168	168	168	0	168	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Aug	11	22 - 29 Aug	168	168	6,09	0	168	0	3050	3050	3200	0	2134	0	25	25	6,09	0	25	0	225338	394845	394845	100915	0	276262,3	0	R1 166 867,77
Sept	12	29 Aug - 5 Sept	131	166,5	152,45	0	122,2	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
Sept	13	5 - 12 Sept	163,55	154,4	154,05	106,4	140	0	3050	3050	3200	2600	2134	0	25	25	25	25	25	0	350850	128786	128786	135120	109785	90108,15	0	R592 585,65
Sept	14	12 - 19 Sept	168	168	50	157,47	168	0	3050	3050	2600	3200	2134	0	25	25	25	25	25	0	350850	128786	128786	109785	135120	90108,15	0	R592 585,65
Sept	15	19 - 26 Sept	167,4	144,05	143,2	91,2	132,5	0	3050	3050	3200	2600	2134	0	25	25	25	25	25	0	350850	128786	128786	135120	109785	90108,15	0	R592 585,65
Oct	16	26 Sept - 3 Oct	95,25	108,15	99,15	145,2	8,3	9,5	2600	2600	2600	3200	2134	2134	20	23	20	25	8,3	9,5	281785,2	87828	101002	87828	135120	29915,91	34241,1	R475 935,20
Oct	17	3 - 10 Oct	135,55	122,5	156,45	113,35	50,85	104,45	2600	2600	3050	3050	2134	2134	25	25	25	23	5	20	329750	109785	109785	128786	118483	18021,63	72086,52	R556 947,75
Oct	18	10 - 17 Oct	92,1	163,2	115,15	138,4	51,95	95,2	3050	3200	3050	3050	2134	2134	20	25	23	25	6	19	340750	103029	135120	118483	128786	21625,96	68482,19	R575 526,75
Oct	19	17 - 24 Oct	151,55	143,35	128,55	138,35	100,45	15,45	3050	3050	2600	2600	2134	2134	25	25	25	25	20	5	335850	128786	128786	109785	109785	72086,52	18021,63	R567 250,65
Oct	20	24 - 31 Oct	168	87,2	168	166,5	61,45	83	3200	3050	3050	3050	2134	2134	25	25	25	25	25	25	415450	135120	128786	128786	128786	90108,15	90108,15	R701 695,05
Nov	21	31 Oct - 7 Nov	146,22	0	168	166,5	0	168	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Nov	22	7 - 14 Nov	168	0	163,45	167,3	0	160,15	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Nov	23	21 - 28 Nov	168	0	168	167,05	0	161,55	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Dec	24	28 Nov - 5 Dec	161	0	166	167,45	0	155	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Dec	25	5 - 12 Dec	160,2	0	157	155,1	0	145,55	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Dec	26	12 - 19 Dec	166,5	0	161	166,3	0	100,35	3200	0	3050	3050	0	2134	25	0	25	25	0	20	275180	135120	0	128786	128786	0	72086,52	R464 779,02
Dec	27	19 - 26 Dec	161	0	161,5	167,1	0	143,45	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Jan	28	26 Dec - 2 Jan	144	0	168	167,2	0	165,25	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Jan	29	2 - 9 Jan	105	0	166,3	166,15	0	163,3	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Jan	30	9 - 16 Jan	159,55	0	156,1	165,15	0	122,25	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Jan	31	16 - 23 Jan	168	0	165,2	168	0	165,2	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Jan	32	23 - 30 Jan	162,1	0	164,4	163,3	0	157,45	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Feb	33	30 Jan - 6 Feb	165,45	0	167	165,05	0	135,2	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Feb	34	6 - 13 Feb	166,2	0	164,3	164	0	152,5	3200	0	3050	3050	0	2134	25	0	25	25	0	25	285850	135120	0	128786	128786	0	90108,15	R482 800,65
Feb	35	13 - 20 Feb	159,1	43,05	168	168	0	124,55	3200	2600	3050	3050	0	2134	25	25	25	25	0	25	350850	135120	109785	128786	128786	0	90108,15	R592 585,65
Feb	36	20 - 27 Feb	114	157,45	159,4	158,45	0	76	2600	3200	3050	3050	0	2134	25	25	25	25	0	15	329510	109785	135120	128786	128786	0	54064,89	R556 542,39
Mar	37	27 Feb - 6 Mar	98,25	167,15	166,55	167,15	0	99,05	2600	3200	3050	3050	0	2134	25	25	25	25	0	20	340180	109785	135120	128786	128786	0	72086,52	R574 564,02
Mar	38	6 - 13 Mar	160,55	168	126,25	168	137	41	3050	3050	2600	3200	2134	2134	25	25	25	25	25	25	404200	128786	128786	109785	135120	90108,15	90108,15	R682 693,80
Mar	39	13 - 20 Mar	139,45	168	167,4	168	41,3	143,25	2600	3200	3050	3050	2134	2134	25	25	25	25	25	25	404200	109785	135120	128786	128786	90108,15	90108,15	R682 693,80
Mar	40	20 - 27 Mar	164,55	128,15	147,6	131,15	0	130	3200	2600	3050	3050	0	2134	25	25	25	25	25	25	350850	135120	109785	128786	128786	0	90108,15	R592 585,65
Apr	41	27 Mar - 3 Apr	168	168	135,1	158,1	163,3	25,3	3050	3050	2600	3200	2134	2134	25	25	25	25	25	25	404200	128786	128786	109785	135120	90108,15	90108,15	R682 693,80
Apr	42	3 - 10 Apr	134,45	127,05	154,5	147,1	108	85	3050	3050	3050	3050	2134	2134	25	25	25	25	25	25	411700	128786	128786	128786	128786	90108,15	90108,15	R695 361,30
Apr	43	10 - 17 Apr	167,05	152,55	129,4	137,4	117,15	13,15	3050	3050	3200	2600	2134	2134	25	25	25	25	25	13,15	378912,1	128786	128786	135120	109785	90108,15	47396,89	R639 982,54
Apr	44	17 - 24 Apr	164,55	164,05	117,45	140	148,25	31,1	3050	3050	2600	2600	2134	2134	25	25	25	25	25	25	389200	128786	128786	109785	109785	90108,15	90108,15	R657 358,80
Apr	45	24 Apr - 1 May	168	168	145,35	69,55	112,4	67,25	3050	3050	3200	3050	2134	2134	25	25	25	25	20	5	362100	128786	128786	135120	128786	72086,52	18021,63	R611 586,90
May	46	1 - 8 May	167,35	167,35	145,35	0	167,35	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	128786	128786	135120	0	90108,15	0	R482 800,65
May	47	15 - 22 May	168	168	168	0	168	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	128786	128786	135120	0	90108,15	0	R482 800,65
May	48	22 - 29 May	104,1	95	68,35	0	67,35	0	3050	3050	3200	0	2134	0	20	20	20	0	20	0	228680	103029	103029	108096	0	72086,52	0	R386 240,52
May	49	29 May - 5 June	167,4	167,35	157	0	163	0	3050	3050	3200	0	2134	0	25	25	25	0	25	0	285850	394845	394845	414264	0	276262,3	0	R1 480 217,06
																												R37 623 511,31

	No.	Reporting period (May	Jericho Pump Station				iphoek pump stati		Pump consumption (kW)						Standard period (hours)						kWh	Standard energy costs (Rands)						Total weekly costs (Rands)
			Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/2	Pump 3	Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3	Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3/4		Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3	
May	1	23 - 30 May	84,4	69	168	168	0	168	2600	2600	3050	3050	0	2134	62	62	62	62	0	62	832908	187427	187427	219867	219867	0	153835	R968 422,13
Jun	2	6 - 13 June	132,15	0,67	168	157,5	0	168	3200	2600	3050	3050	0	2134	60	0	62	60	0	62	696408	301190	0	296641	287072	0	207552	R1 092 455,23
Jun	3	13 - 16 June	168	168	150,45	0	168	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	296641	296641	311230	0	207552	0	R1 112 063,98
Jun	4	20 - 27 June	168	168	85,45	0	168	0	3050	3050	3200	0	2134	0	62	62	60,45	0	62	0	703948	296641	296641	303449	0	207552	0	R1 104 283,23
Jul	5	27 June - 4 July	168	168	155,3	0	168	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	296641	296641	311230	0	207552	0	R1 112 063,98
Jul	6	4 - 11 July	168	168	155,3	0	142	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	296641	296641	311230	0	207552	0	R1 112 063,98
Jul	7	18 - 25 July	167,5	161	123,55	0	161	0	3050	3050	3200	0	2134	0	62	62	55	0	62	0	686508	296641	296641	276091	0	207552	0	R1 076 925,10
Jul	8	25 July - 1 Aug	168	166,4	166	0	115,15	0	3050	3050	3200	0	2134	0	62	62	62	0	53	0	689702	296641	296641	311230	0	177423	0	R1 081 935,53
Aug	9	1 - 8 Aug	168	161,25	168	0	155,3	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	296641	296641	311230	0	207552	0	R1 112 063,98
Aug	10	8 - 15 Aug	168	168	168	0	168	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	296641	296641	311230	0	207552	0	R1 112 063,98
Aug	11	22 - 29 Aug	168	168	6,09	0	168	0	3050	3050	3200	0	2134	0	62	62	0	0	62	0	510508	296641	296641	0	0	207552	0	R800 833,90
Sept	12	29 Aug - 5 Sept	131	166,5	152,45	0	122,2	0	3050	3050	3200	0	2134	0	60	62	62	0	55	0	687870	287072	296641	311230	0	184118	0	R1 079 061,67
Sept	13	5 - 12 Sept	163,55	154,4	154,05	106,4	140	0	3050	3050	3200	2600	2134	0	62	62	62	55	62	0	851908	219867	219867	230680	166266	153835	0	R990 513,43
Sept	14	12 - 19 Sept	168	168	50	157,47	168	0	3050	3050	2600	3200	2134	0	62	62	25	62	62	0	773908	219867	219867	75576	230680	153835	0	R899 822,83
Sept	15	19 - 26 Sept	167,4	144,05	143,2	91,2	132,5	0	3050	3050	3200	2600	2134	0	62	62	62	55	60	0	847640	219867	219867	230680	166266	148872	0	R985 551,03
Oct	16	26 Sept - 3 Oct	95,25	108,15	99,15	145,2	8,3	9,5	2600	2600	2600	3200	2134	2134	44	47,15	44	62	0	0	549790	133013	142535	133013	230680	0	0	R639 240,83
Oct	17	3 - 10 Oct	135,55	122,5	156,45	113,35	50,85	104,45	2600	2600	3050	3050	2134	2134	60	55	62	55	25,85	55	828384	181381	166266	219867	195043	64139	136466	R963 161,96
Oct	18	10 - 17 Oct	92,1	163,2	115,15	138,4	51,95	95,2	3050	3200	3050	3050	2134	2134	42	62	53	62	26,95	55	852131	148942	230680	187950	219867	66868	136466	R990 773,06
Oct	19	17 - 24 Oct	151,55	143,35	128,55	138,35	100,45	15,45	3050	3050	2600	2600	2134	2134	62	62	56,55	62	44	0	780326	219867	219867	170952	187427	109173	0	R907 285,04
Oct	20	24 - 31 Oct	168	87,2	168	166,5	61,45	83	3200	3050	3050	3050	2134	2134	62	62	62	62	36,45	55	960854	230680	219867	219867	219867	90440	136466	R1 117 185,29
Nov	21	31 Oct - 7 Nov	146,22	0	168	166,5	0	168	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Nov	22	7 - 14 Nov	168	0	163,45	167,3	0	160,15	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Nov	23	21 - 28 Nov	168	0	168	167,05	0	161,55	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Dec	24	28 Nov - 5 Dec	161	0	166	167,45	0	155	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Dec	25	5 - 12 Dec	160,2	0	157	155,1	0	145,55	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Dec	26	12 - 19 Dec	166,5	0	161	166,3	0	100,35	3200	0	3050	3050	0	2134	62	0	62	62	0	44	670496	230680	0	219867	219867	0	109173	R779 585,70
Dec	27	19 - 26 Dec	161	0	161,5	167,1	0	143,45	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Jan	28	26 Dec - 2 Jan	144	0	168	167,2	0	165,25	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Jan	29	2 - 9 Jan	105	0	166,3	166,15	0	163,3	3200	0	3050	3050	0	2134	55	0	62	62	0	62	686508	204635	0	219867	219867	0	153835	R798 202,85
Jan	30	9 - 16 Jan	159,55	0	156,1	165,15	0	122,25	3200	0	3050	3050	0	2134	62	0	62	62	0	55	693970	230680	0	219867	219867	0	136466	R806 878,92
Jan	31	16 - 23 Jan	168	0	165,2	168	0	165,2	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Jan	32	23 - 30 Jan	162,1	0	164,4	163,3	0	157,45	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Feb	33	30 Jan - 6 Feb	165,45	0	167	165,05	0	135,2	3200	0	3050	3050	0	2134	62	0	62	62	0	60	704640	230680	0	219867	219867	0	148872	R819 284,93
Feb	34	6 - 13 Feb	166,2	0	164,3	164	0	152,5	3200	0	3050	3050	0	2134	62	0	62	62	0	62	708908	230680	0	219867	219867	0	153835	R824 247,33
Feb	35	13 - 20 Feb	159,1	43,05	168	168	0	124,55	3200	2600	3050	3050	0	2134	62	18,1	62	62	0	55	741030	230680	54717	219867	219867	0	136466	R861 595,58
Feb	36	20 - 27 Feb	114	157,45	159,4	158,45	0	76	2600	3200	3050	3050	0	2134	55	62	62	62	0	51	828434	166266	230680	219867	219867	0	126541	R963 220,21
Mar	37	27 Feb - 6 Mar	98,25	167,15	166,55	167,15	0	99,05	2600	3200	3050	3050	0	2134	55	62	62	62	0	62	851908	166266	230680	219867	219867	0	153835	R990 513,43
Mar	38	6 - 13 Mar	160,55	168	126,25	168	137	41	3050	3050	2600	3200	2134	2134	62	62	55	62	60	16	881784	219867	219867	166266	230680	148872	39699	R1 025 250,26
Mar	39	13 - 20 Mar	139,45	168	167,4	168	41,3	143,25	2600	3200	3050	3050	2134	2134	61,45	62	62	62	16,3	62	903462	185765	230680	219867	219867	40444	153835	R1 050 455,50
Mar	40	20 - 27 Mar	164,55	128,15	147,6	131,15	0	130	3200	2600	3050	3050	0	2134	62	56,15	62	60	0	60	844530	230680	169743	219867	212774	0	148872	R981 935,03
Apr	41	27 Mar - 3 Apr	168	168	135,1	158,1	163,3	25,3	3050	3050	2600	3200	2134	2134	62	62	60	62	62	0,3	865548	219867	219867	181381	230680	153835	744,36	R1 006 372,89
Apr	42	3 - 10 Apr	134,45	127,05	154,5	147,1	108	85	3050	3050	3050	3050	2134	2134	60	55	62	62	47	57	950886	212774	195043	219867	219867	116616	141429	R1 105 595,15
Apr	43	10 - 17 Apr	167,05	152,55	129,4	137,4	117,15	13,15	3050	3050	3200	2600	2134	2134	62	62	57,4	60	54	0	833116	219867	219867	213565	181381	133985	0	R968 663,97
Apr	44	17 - 24 Apr	164,55	164,05	117,45	140	148,25	31,1	3050	3050	2600	2600	2134	2134	62	62	55	62	62	6,1	827725	219867	219867	166266	187427	153835	15135	R962 396,32
Apr	45	24 Apr - 1 May	168	168	145,35	69,55	112,4	67,25	3050	3050	3200	3050	2134	2134	62	62	62	44,55	40	42,25	887999	219867	219867	230680	157985	99248	104831	R1 032 476,44
May	46	1 - 8 May	167,35	167,35	145,35	0	167,35	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	219867	219867	230680	0	153835	0	R824 247,33
May	47	15 - 22 May	168	168	168	0	168	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	219867	219867	230680	0	153835	0	R824 247,33
May	48	22 - 29 May	104,1	95	68,35	0	67,35	0	3050	3050	3200	0	2134	0	55	44	43,35	0	42,35	0	531045	195043	156034	161290	0	105079	0	R617 445,91
May	49	29 May - 5 June	167,4	167,35	157	0	163	0	3050	3050	3200	0	2134	0	62	62	62	0	62	0	708908	296641	296641	311230	0	207552	0	R1 112 063,98
																												R46 030 675,22

	No.	ing period	Jericho Pump Station				›hoek pump stat		Pump consumption (kW)						Off peak (hours)						kWh	Peak energy costs (Rands)						Total weekly costs (Rands)
			Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3	Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3	Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3/4		Pump 1	Pump 2	Pump 3	Pump 4	Pump 1/	Pump 3	
May	1	23 - 30 M	84,4	69	168	168	0	168	2600	2600	3050	3050	0	2134	4,4	0	81	81	0	81	678394	8438,1	0	182224	182224	0	127497	R500 383,41
Jun	2	6 - 13 Jur	132,15	0,67	168	157,5	0	168	3200	2600	3050	3050	0	2134	47,15	0,67	81	72,5	0	81	793651	128550	1484,2	210487	188399	0	147272	R676 190,65
Jun	3	13 - 16 Ju	168	168	150,45	0	168	0	3050	3050	3200	0	2134	0	81	81	63,45	0	81	0	869994	210487	210487	172990	0	147272	0	R741 234,89
Jun	4	20 - 27 Jı	168	168	85,45	0	168	0	3050	3050	3200	0	2134	0	81	81	0	0	81	0	666954	210487	210487	0	0	147272	0	R568 244,81
Jul	5	27 June -	168	168	155,3	0	168	0	3050	3050	3200	0	2134	0	81	81	68,3	0	81	0	885514	210487	210487	186213	0	147272	0	R754 457,93
Jul	6	4 - 11 July	168	168	155,3	0	142	0	3050	3050	3200	0	2134	0	81	81	68,3	0	55	0	830030	210487	210487	186213	0	99999	0	R707 185,56
Jul	7	18 - 25 Jı	167,5	161	123,55	0	161	0	3050	3050	3200	0	2134	0	80,5	74	43,55	0	74	0	768501	209187	192296	118735	0	134544	0	R654 762,85
Jul	8	25 July -	168	166,4	166	0	115,15	0	3050	3050	3200	0	2134	0	81	79,4	79	0	37,15	0	821298	210487	206329	215386	0	67545	0	R699 745,98
Aug	9	1 - 8 Aug	168	161,25	168	0	155,3	0	3050	3050	3200	0	2134	0	81	74,25	81	0	68,3	0	878465	210487	192946	220838	0	124181	0	R748 451,92
Aug	10	8 - 15 Au	168	168	168	0	168	0	3050	3050	3200	0	2134	0	81	81	81	0	81	0	926154	210487	210487	220838	0	147272	0	R789 083,21
Aug	11	22 - 29 A	168	168	6,09	0	168	0	3050	3050	3200	0	2134	0	81	81	0	0	81	0	666954	210487	210487	0	0	147272	0	R568 244,81
Sept	12	29 Aug -	131	166,5	152,45	0	122,2	0	3050	3050	3200	0	2134	0	46	79,5	65,45	0	42,2	0	682270	119536	206589	178443	0	76727	0	R581 293,87
Sept	13	5 - 12 Se	163,55	154,4	154,05	106,4	140	0	3050	3050	3200	2600	2134	0	76,55	67,4	67,05	26,4	53	0	835350	172213	151628	158259	50629	83424	0	R616 153,79
Sept	14	12 - 19 Se	168	168	50	157,47	168	0	3050	3050	2600	3200	2134	0	81	81	0	70,47	81	0	892458	182224	182224	0	166332	127497	0	R658 277,02
Sept	15	19 - 26 S	167,4	144,05	143,2	91,2	132,5	0	3050	3050	3200	2600	2134	0	80,4	57,05	56,2	11,2	47,5	0	729548	180874	128344	132650	21479	74767	0	R538 114,24
Oct	16	26 Sept -	95,25	108,15	99,15	145,2	8,3	9,5	2600	2600	2600	3200	2134	2134	31,25	38	35,15	58,2	0	0	457680	59930	72875	67409	137371	0	0	R337 584,77
Oct	17	3 - 10 Oc	135,55	122,5	156,45	113,35	50,85	104,45	2600	2600	3050	3050	2134	2134	50,55	42,5	69,45	35,35	20	29,45	667096	96943	81505	156240	79526	31481	46355	R492 050,23
Oct	18	10 - 17 O	92,1	163,2	115,15	138,4	51,95	95,2	3050	3200	3050	3050	2134	2134	30,1	76,2	39,15	51,4	19	21,2	697609	67715	179856	88075	115634	29907	33370	R514 556,62
Oct	19	17 - 24 O	151,55	143,35	128,55	138,35	100,45	15,45	3050	3050	2600	2600	2134	2134	64,55	56,35	47	51,35	36,45	10,45	724540	145217	126769	90135	98477	57374	16449	R534 420,41
Oct	20	24 - 31 O	168	87,2	168	166,5	61,45	83	3200	3050	3050	3050	2134	2134	81	0,2	81	79,5	0	3	755737	191186	449,94	182224	178850	0	4722,1	R557 431,61
Nov	21	31 Oct - 7	146,22	0	168	166,5	0	168	3200	0	3050	3050	0	2134	59,22	0	81	79,5	0	81	851883	139778	0	182224	178850	0	127497	R628 348,90
Nov	22	7 - 14 No	168	0	163,45	167,3	0	160,15	3200	0	3050	3050	0	2134	81	0	76,45	80,3	0	73,15	893390	191186	0	171988	180649	0	115141	R658 964,17
Nov	23	21 - 28 N	168	0	168	167,05	0	161,55	3200	0	3050	3050	0	2134	81	0	81	80,05	0	74,55	909492	191186	0	182224	180087	0	117345	R670 841,45
Dec	24	28 Nov -	161	0	166	167,45	0	155	3200	0	3050	3050	0	2134	74	0	79	80,45	0	68	868235	174664	0	177725	180987	0	107035	R640 409,77
Dec	25	5 - 12 De	160,2	0	157	155,1	0	145,55	3200	0	3050	3050	0	2134	73,2	0	70	68,1	0	58,55	780391	172775	0	157478	153203	0	92160	R575 616,18
Dec	26	12 - 19 De	166,5	0	161	166,3	0	100,35	3200	0	3050	3050	0	2134	79,5	0	74	79,3	0	36,35	799536	187645	0	166476	178400	0	57216	R589 737,68
Dec	27	19 - 26 D	161	0	161,5	167,1	0	143,45	3200	0	3050	3050	0	2134	74	0	74,5	80,1	0	56,45	828794	174664	0	167601	180199	0	88854	R611 318,68
Jan	28	26 Dec -	144	0	168	167,2	0	165,25	3200	0	3050	3050	0	2134	57	0	81	80,2	0	78,25	841046	134538	0	182224	180424	0	123169	R620 355,16
Jan	29	2 - 9 Jan	105	0	166,3	166,15	0	163,3	3200	0	3050	3050	0	2134	25	0	79,3	79,15	0	76,3	726097	59008	0	178400	178062	0	120099	R535 568,93
Jan	30	9 - 16 Jar	159,55	0	156,1	165,15	0	122,25	3200	0	3050	3050	0	2134	72,55	0	69,1	78,15	0	42,25	771434	171241	0	155453	175812	0	66503	R569 009,72
Jan	31	16 - 23 Ja	168	0	165,2	168	0	165,2	3200	0	3050	3050	0	2134	81	0	78,2	81	0	78,2	911639	191186	0	175925	182224	0	123090	R672 424,78
Jan	32	23 - 30 J	162,1	0	164,4	163,3	0	157,45	3200	0	3050	3050	0	2134	75,1	0	77,4	76,3	0	70,45	859445	177260	0	174125	171651	0	110891	R633 926,85
Feb	33	30 Jan -	165,45	0	167	165,05	0	135,2	3200	0	3050	3050	0	2134	78,45	0	80	78,05	0	50,2	840219	185167	0	179974	175588	0	79017	R619 745,76
Feb	34	6 - 13 Fel	166,2	0	164,3	164	0	152,5	3200	0	3050	3050	0	2134	79,2	0	77,3	77	0	65,5	863832	186937	0	173900	173225	0	103100	R637 162,48
Feb	35	13 - 20 F	159,1	43,05	168	168	0	124,55	3200	2600	3050	3050	0	2134	72,1	0	81	81	0	44,55	819890	170179	0	182224	182224	0	70123	R604 750,64
Feb	36	20 - 27 F	114	157,45	159,4	158,45	0	76	2600	3200	3050	3050	0	2134	34	70,45	72,4	71,45	0	10	773923	65204	166285	162877	160740	0	15740	R570 845,24
Mar	37	27 Feb -	98,25	167,15	166,55	167,15	0	99,05	2600	3200	3050	3050	0	2134	18,25	80,15	79,55	80,15	0	17,05	827400	34999	189180	178962	180312	0	26837	R610 290,02
Mar	38	6 - 13 Ma	160,55	168	126,25	168	137	41	3050	3050	2600	3200	2134	2134	73,55	81	46,25	81	52	0	961796	165464	182224	88696	191186	81850	0	R709 420,36
Mar	39	13 - 20 M	139,45	168	167,4	168	41,3	143,25	2600	3200	3050	3050	2134	2134	53	81	80,4	81	0	56,25	1E+06	101641	191186	180874	182224	0	88540	R744 465,21
Mar	40	20 - 27 M	164,55	128,15	147,6	131,15	0	130	3200	2600	3050	3050	0	2134	77,55	47	60,6	46,15	0	45	791978	183043	90135	136331	103823	0	70832	R584 162,60
Apr	41	27 Mar -	168	168	135,1	158,1	163,3	25,3	3050	3050	2600	3200	2134	2134	81	81	50,1	71,1	76,3	0	1E+06	182224	182224	96080	167819	120099	0	R748 445,82
Apr	42	3 - 10 Ap	134,45	127,05	154,5	147,1	108	85	3050	3050	3050	3050	2134	2134	49,45	47,05	67,5	60,1	36	3	766731	111247	105847	151853	135206	56665	4722,1	R565 540,79
Apr	43	10 - 17 Ap	167,05	152,55	129,4	137,4	117,15	13,15	3050	3050	3200	2600	2134	2134	80,05	65,55	47	52,4	38,15	0	812132	180087	147467	110935	100491	60050	0	R599 028,64
Apr	44	17 - 24 A	164,55	164,05	117,45	140	148,25	31,1	3050	3050	2600	2600	2134	2134	77,55	77,05	37,45	53	61,25	0	837408	174463	173338	71820	101641	96410	0	R617 671,77
Apr	45	24 Apr -	168	168	145,35	69,55	112,4	67,25	3050	3050	3200	3050	2134	2134	81	81	58,35	0	52,4	20	835322	182224	182224	137725	0	82480	31481	R616 133,21
May	46	1 - 8 May	167,35	167,35	145,35	0	167,35	0	3050	3050	3200	0	2134	0	80,35	80,35	58,35	0	80,35	0	848322	180762	180762	137725	0	126474	0	R625 722,23
May	47	15 - 22 M	168	168	168	0	168	0	3050	3050	3200	0	2134	0	81	81	81	0	81	0	926154	182224	182224	191186	0	127497	0	R683 131,19
May	48	22 - 29 M	104,1	95	68,35	0	67,35	0	3050	3050	3200	0	2134	0	29,1	31	5	0	5	0	209975	65466	69740	11802	0	7870,2	0	R154 877,56
May	49	29 May -	167,4	167,35	157	0	163	0	3050	3050	3200	0	2134	0	80,4	80,35	70	0		0	714288	180874	180762	165222	0	0	0	R526 858,46
																												R29 862 642,82

Appendix D: Mass balance of Onverwacht reservoir current system

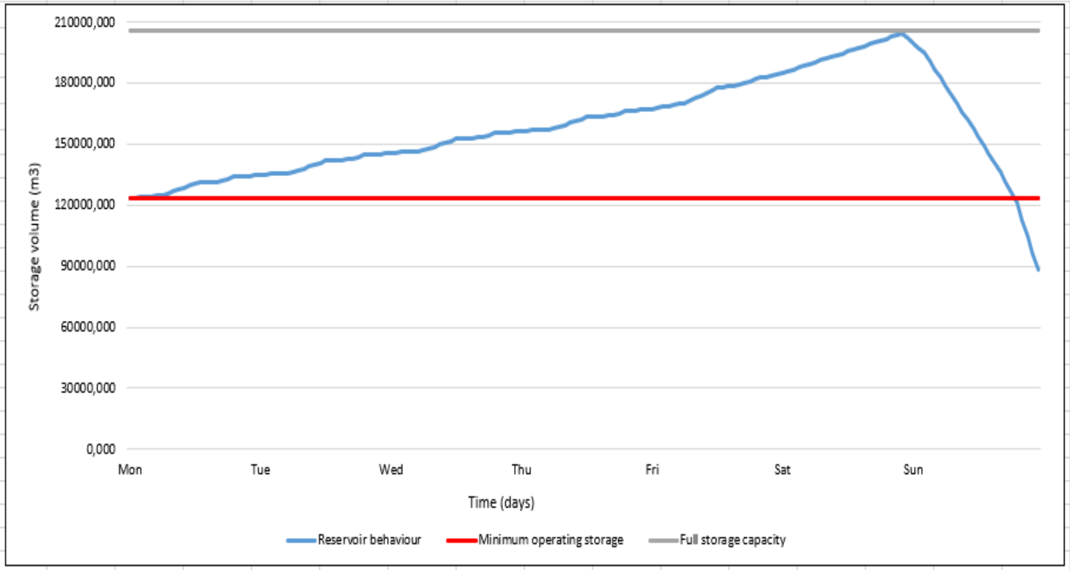
The Behaviour Analysis Method

Pumping combination C	=	1,135	m3/s	Pumping combination H	2,785	m3/s
Pumping combination A	=	0,92	m3/s	Pumping combination F	1,65	m3/s
				Pumping combination G	2,570	m3/s

de: demand/mean flow
ini: initial reservoir storage state
cap: reservoir capacity (Mm^3)
env: required environmental flow downstream (Mm^3/year)
fstate: reservoir storage state below which reservoir fails
pf: probability of failure

Min St	de	ini	cap	fstate	pf (%)
123321,600	2,444	205536,000	205536,000	123321,600	2,97619
				123321,600	

No.	Day	Time	Flows (m^3/hour)	Demand (m3/h)	Storage vol. (m^3)	spill (Mm^3)	Count of failure years	Failure line	Cap	Day	Index
					123321,600		0			Monday	1,027
1		12:00 am	9252	9034,971	123538,629	0,000	0	123321,600	205536,000	Tuesday	1,03
2		1:00 am	9252	9034,971	123755,658	0,000	0	123321,600	205536,000	Wednesda	1,03
3		2:00 am	9252	9034,971	123972,687	0,000	0	123321,600	205536,000	Thursday	1,03
4		3:00 am	9252	9034,971	124189,716	0,000	0	123321,600	205536,000	Friday	1
5		4:00 am	9252	9034,971	124406,746	0,000	0	123321,600	205536,000	Saturday	0,951
6		5:00 am	9252	9034,971	124623,775	0,000	0	123321,600	205536,000	Sunday	0,938
7		6:00 am	9252	9034,971	124840,804	0,000	0	123321,600	205536,000		
8		7:00 am	10026	9034,971	125831,833	0,000	0	123321,600	205536,000		
9		8:00 am	10026	9034,971	126822,862	0,000	0	123321,600	205536,000		
10		9:00 am	10026	9034,971	127813,891	0,000	0	123321,600	205536,000		
11		10:00 am	10026	9034,971	128804,920	0,000	0	123321,600	205536,000		
12	Mon	11:00 am	10026	9034,971	129795,949	0,000	0	123321,600	205536,000		
13		12:00 pm	10026	9034,971	130786,979	0,000	0	123321,600	205536,000		
14		1:00 pm	9252	9034,971	131004,008	0,000	0	123321,600	205536,000		
15		2:00 pm	9252	9034,971	131221,037	0,000	0	123321,600	205536,000		
16		3:00 pm	9252	9034,971	131438,066	0,000	0	123321,600	205536,000		
17		4:00 pm	9252	9034,971	131655,095	0,000	0	123321,600	205536,000		
18		5:00 pm	9252	9034,971	131872,124	0,000	0	123321,600	205536,000		
19		6:00 pm	10026	9034,971	132863,153	0,000	0	123321,600	205536,000		
20		7:00 pm	10026	9034,971	133854,182	0,000	0	123321,600	205536,000		
21		8:00 pm	9252	9034,971	134071,211	0,000	0	123321,600	205536,000		
22		9:00 pm	9252	9034,971	134288,241	0,000	0	123321,600	205536,000		
23		10:00 pm	9252	9034,971	134505,270	0,000	0	123321,600	205536,000		
24		11:00 pm	9252	9034,971	134722,299	0,000	0	123321,600	205536,000		
25		12:00 am	9252	9061,363	134912,936	0,000	0	123321,600	205536,000		
26		1:00 am	9252	9061,363	135103,572	0,000	0	123321,600	205536,000		
27		2:00 am	9252	9061,363	135294,209	0,000	0	123321,600	205536,000		
28		3:00 am	9252	9061,363	135484,846	0,000	0	123321,600	205536,000		
29		4:00 am	9252	9061,363	135675,483	0,000	0	123321,600	205536,000		



30		5:00 am	9252	9061,363	135866,120	0,000	0	123321,600	205536,000
31		6:00 am	9252	9061,363	136056,756	0,000	0	123321,600	205536,000
32		7:00 am	10026	9061,363	137021,393	0,000	0	123321,600	205536,000
33		8:00 am	10026	9061,363	137986,030	0,000	0	123321,600	205536,000
34		9:00 am	10026	9061,363	138950,667	0,000	0	123321,600	205536,000
35		10:00 am	10026	9061,363	139915,304	0,000	0	123321,600	205536,000
36	Tue	11:00 am	10026	9061,363	140879,940	0,000	0	123321,600	205536,000
37		12:00 pm	10026	9061,363	141844,577	0,000	0	123321,600	205536,000
38		1:00 pm	9252	9061,363	142035,214	0,000	0	123321,600	205536,000
39		2:00 pm	9252	9061,363	142225,851	0,000	0	123321,600	205536,000
40		3:00 pm	9252	9061,363	142416,488	0,000	0	123321,600	205536,000
41		4:00 pm	9252	9061,363	142607,124	0,000	0	123321,600	205536,000
42		5:00 pm	9252	9061,363	142797,761	0,000	0	123321,600	205536,000
43		6:00 pm	10026	9061,363	143762,398	0,000	0	123321,600	205536,000
44		7:00 pm	10026	9061,363	144727,035	0,000	0	123321,600	205536,000
45		8:00 pm	9252	9061,363	144917,671	0,000	0	123321,600	205536,000
46		9:00 pm	9252	9061,363	145108,308	0,000	0	123321,600	205536,000
47		10:00 pm	9252	9061,363	145298,945	0,000	0	123321,600	205536,000
48		11:00 pm	9252	9061,363	145489,582	0,000	0	123321,600	205536,000
49		12:00 am	9252	9061,363	145680,219	0,000	0	123321,600	205536,000
50		1:00 am	9252	9061,363	145870,855	0,000	0	123321,600	205536,000
51		2:00 am	9252	9061,363	146061,492	0,000	0	123321,600	205536,000
52		3:00 am	9252	9061,363	146252,129	0,000	0	123321,600	205536,000
53		4:00 am	9252	9061,363	146442,766	0,000	0	123321,600	205536,000
54		5:00 am	9252	9061,363	146633,403	0,000	0	123321,600	205536,000
55		6:00 am	9252	9061,363	146824,039	0,000	0	123321,600	205536,000
56		7:00 am	10026	9061,363	147788,676	0,000	0	123321,600	205536,000
57		8:00 am	10026	9061,363	148753,313	0,000	0	123321,600	205536,000
58		9:00 am	10026	9061,363	149717,950	0,000	0	123321,600	205536,000
59		10:00 am	10026	9061,363	150682,587	0,000	0	123321,600	205536,000
60	Wed	11:00 am	10026	9061,363	151647,223	0,000	0	123321,600	205536,000
61		12:00 pm	10026	9061,363	152611,860	0,000	0	123321,600	205536,000
62		1:00 pm	9252	9061,363	152802,497	0,000	0	123321,600	205536,000
63		2:00 pm	9252	9061,363	152993,134	0,000	0	123321,600	205536,000
64		3:00 pm	9252	9061,363	153183,771	0,000	0	123321,600	205536,000
65		4:00 pm	9252	9061,363	153374,407	0,000	0	123321,600	205536,000
66		5:00 pm	9252	9061,363	153565,044	0,000	0	123321,600	205536,000
67		6:00 pm	10026	9061,363	154529,681	0,000	0	123321,600	205536,000
68		7:00 pm	10026	9061,363	155494,318	0,000	0	123321,600	205536,000
69		8:00 pm	9252	9061,363	155684,955	0,000	0	123321,600	205536,000
70		9:00 pm	9252	9061,363	155875,591	0,000	0	123321,600	205536,000
71		10:00 pm	9252	9061,363	156066,228	0,000	0	123321,600	205536,000
72		11:00 pm	9252	9061,363	156256,865	0,000	0	123321,600	205536,000
73		12:00 am	9252	9061,363	156447,502	0,000	0	123321,600	205536,000
74		1:00 am	9252	9061,363	156638,139	0,000	0	123321,600	205536,000
75		2:00 am	9252	9061,363	156828,775	0,000	0	123321,600	205536,000
76		3:00 am	9252	9061,363	157019,412	0,000	0	123321,600	205536,000
77		4:00 am	9252	9061,363	157210,049	0,000	0	123321,600	205536,000

78		5:00 am	9252	9061,363	157400,686	0,000	0	123321,600	205536,000
79		6:00 am	9252	9061,363	157591,323	0,000	0	123321,600	205536,000
80		7:00 am	10026	9061,363	158555,959	0,000	0	123321,600	205536,000
81		8:00 am	10026	9061,363	159520,596	0,000	0	123321,600	205536,000
82		9:00 am	10026	9061,363	160485,233	0,000	0	123321,600	205536,000
83		10:00 am	10026	9061,363	161449,870	0,000	0	123321,600	205536,000
84	Thu	11:00 am	10026	9061,363	162414,507	0,000	0	123321,600	205536,000
85		12:00 pm	10026	9061,363	163379,143	0,000	0	123321,600	205536,000
86		1:00 pm	9252	9061,363	163569,780	0,000	0	123321,600	205536,000
87		2:00 pm	9252	9061,363	163760,417	0,000	0	123321,600	205536,000
88		3:00 pm	9252	9061,363	163951,054	0,000	0	123321,600	205536,000
89		4:00 pm	9252	9061,363	164141,690	0,000	0	123321,600	205536,000
90		5:00 pm	9252	9061,363	164332,327	0,000	0	123321,600	205536,000
91		6:00 pm	10026	9061,363	165296,964	0,000	0	123321,600	205536,000
92		7:00 pm	10026	9061,363	166261,601	0,000	0	123321,600	205536,000
93		8:00 pm	9252	9061,363	166452,238	0,000	0	123321,600	205536,000
94		9:00 pm	9252	9061,363	166642,874	0,000	0	123321,600	205536,000
95		10:00 pm	9252	9061,363	166833,511	0,000	0	123321,600	205536,000
96		11:00 pm	9252	9061,363	167024,148	0,000	0	123321,600	205536,000
97		12:00 am	9252	8797,440	167478,708	0,000	0	123321,600	205536,000
98		1:00 am	9252	8797,440	167933,268	0,000	0	123321,600	205536,000
99		2:00 am	9252	8797,440	168387,828	0,000	0	123321,600	205536,000
100		3:00 am	9252	8797,440	168842,388	0,000	0	123321,600	205536,000
101		4:00 am	9252	8797,440	169296,948	0,000	0	123321,600	205536,000
102		5:00 am	9252	8797,440	169751,508	0,000	0	123321,600	205536,000
103		6:00 am	9252	8797,440	170206,068	0,000	0	123321,600	205536,000
104		7:00 am	10026	8797,440	171434,628	0,000	0	123321,600	205536,000
105		8:00 am	10026	8797,440	172663,188	0,000	0	123321,600	205536,000
106		9:00 am	10026	8797,440	173891,748	0,000	0	123321,600	205536,000
107		10:00 am	10026	8797,440	175120,308	0,000	0	123321,600	205536,000
108	Fri	11:00 am	10026	8797,440	176348,868	0,000	0	123321,600	205536,000
109		12:00 pm	10026	8797,440	177577,428	0,000	0	123321,600	205536,000
110		1:00 pm	9252	8797,440	178031,988	0,000	0	123321,600	205536,000
111		2:00 pm	9252	8797,440	178486,548	0,000	0	123321,600	205536,000
112		3:00 pm	9252	8797,440	178941,108	0,000	0	123321,600	205536,000
113		4:00 pm	9252	8797,440	179395,668	0,000	0	123321,600	205536,000
114		5:00 pm	9252	8797,440	179850,228	0,000	0	123321,600	205536,000
115		6:00 pm	10026	8797,440	181078,788	0,000	0	123321,600	205536,000
116		7:00 pm	10026	8797,440	182307,348	0,000	0	123321,600	205536,000
117		8:00 pm	9252	8797,440	182761,908	0,000	0	123321,600	205536,000
118		9:00 pm	9252	8797,440	183216,468	0,000	0	123321,600	205536,000
119		10:00 pm	9252	8797,440	183671,028	0,000	0	123321,600	205536,000
120		11:00 pm	9252	8797,440	184125,588	0,000	0	123321,600	205536,000
121		12:00 am	9252	8366,365	185011,223	0,000	0	123321,600	205536,000
122		1:00 am	9252	8366,365	185896,857	0,000	0	123321,600	205536,000
123		2:00 am	9252	8366,365	186782,492	0,000	0	123321,600	205536,000
124		3:00 am	9252	8366,365	187668,126	0,000	0	123321,600	205536,000
125		4:00 am	9252	8366,365	188553,761	0,000	0	123321,600	205536,000

126		5:00 am	9252	8366,365	189439,395	0,000	0	123321,600	205536,000
127		6:00 am	9252	8366,365	190325,030	0,000	0	123321,600	205536,000
128		7:00 am	9252	8366,365	191210,664	0,000	0	123321,600	205536,000
129		8:00 am	9252	8366,365	192096,299	0,000	0	123321,600	205536,000
130		9:00 am	9252	8366,365	192981,934	0,000	0	123321,600	205536,000
131		10:00 am	9252	8366,365	193867,568	0,000	0	123321,600	205536,000
132	Sat	11:00 am	9252	8366,365	194753,203	0,000	0	123321,600	205536,000
133		12:00 pm	9252	8366,365	195638,837	0,000	0	123321,600	205536,000
134		1:00 pm	9252	8366,365	196524,472	0,000	0	123321,600	205536,000
135		2:00 pm	9252	8366,365	197410,106	0,000	0	123321,600	205536,000
136		3:00 pm	9252	8366,365	198295,741	0,000	0	123321,600	205536,000
137		4:00 pm	9252	8366,365	199181,375	0,000	0	123321,600	205536,000
138		5:00 pm	9252	8366,365	200067,010	0,000	0	123321,600	205536,000
139		6:00 pm	9252	8366,365	200952,645	0,000	0	123321,600	205536,000
140		7:00 pm	9252	8366,365	201838,279	0,000	0	123321,600	205536,000
141		8:00 pm	9252	8366,365	202723,914	0,000	0	123321,600	205536,000
142		9:00 pm	9252	8366,365	203609,548	0,000	0	123321,600	205536,000
143		10:00 pm	9252	8366,365	204495,183	0,000	0	123321,600	205536,000
144		11:00 pm	5940	8366,365	202068,817	0,000	0	123321,600	205536,000
145		12:00 am	5940	8251,999	199756,819	0,000	0	123321,600	205536,000
146		1:00 am	5940	8251,999	197444,820	0,000	0	123321,600	205536,000
147		2:00 am	5940	8251,999	195132,821	0,000	0	123321,600	205536,000
148		3:00 am	4086	8251,999	190966,822	0,000	0	123321,600	205536,000
149		4:00 am	4086	8251,999	186800,824	0,000	0	123321,600	205536,000
150		5:00 am	4086	8251,999	182634,825	0,000	0	123321,600	205536,000
151		6:00 am	4086	8251,999	178468,826	0,000	0	123321,600	205536,000
152		7:00 am	4086	8251,999	174302,827	0,000	0	123321,600	205536,000
153		8:00 am	4086	8251,999	170136,829	0,000	0	123321,600	205536,000
154		9:00 am	4086	8251,999	165970,830	0,000	0	123321,600	205536,000
155		10:00 am	4086	8251,999	161804,831	0,000	0	123321,600	205536,000
156	Sun	11:00 am	4086	8251,999	157638,833	0,000	0	123321,600	205536,000
157		12:00 pm	4086	8251,999	153472,834	0,000	0	123321,600	205536,000
158		1:00 pm	4086	8251,999	149306,835	0,000	0	123321,600	205536,000
159		2:00 pm	4086	8251,999	145140,836	0,000	0	123321,600	205536,000
160		3:00 pm	4086	8251,999	140974,838	0,000	0	123321,600	205536,000
161		4:00 pm	3312	8251,999	136034,839	0,000	0	123321,600	205536,000
162		5:00 pm	3312	8251,999	131094,840	0,000	0	123321,600	205536,000
163		6:00 pm	3312	8251,999	126154,842	0,000	0	123321,600	205536,000
164		7:00 pm	3312	8251,999	121214,843	0,000	1	123321,600	205536,000
165		8:00 pm	0	8251,999	112962,844	0,000	2	123321,600	205536,000
166		9:00 pm	0	8251,999	104710,845	0,000	3	123321,600	205536,000
167		10:00 pm	0	8251,999	96458,847	0,000	4	123321,600	205536,000
168		11:00 pm	0	8251,999	88206,848	0,000	5	123321,600	205536,000

Appendix E: Mass balance of Onverwacht reservoir with Approach B and C

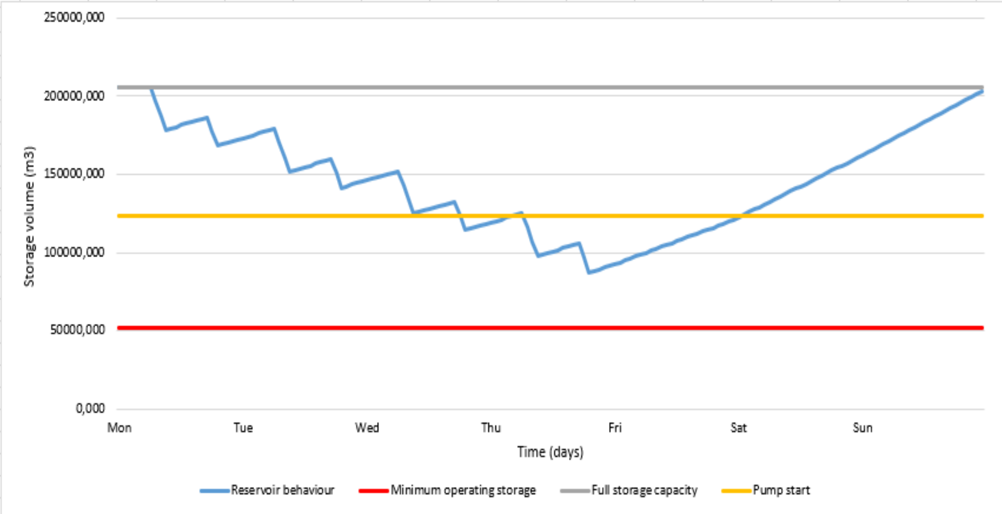
The Behaviour Analysis Method

Pumping flow (m³/s) 2,785 m3/s

Min St	de	ini	cap	env	fstate	pf (%)
51384,000	2,444	205536,000	205536,000	0,05	51384,000	0

de: demand/mean flow
ini: initial reservoir storage state
cap: reservoir capacity (Mm³)
env: required environmental flow downstream (Mm³/year)
fstate: reservoir storage state below which reservoir fails
pf: probability of failure

No.	Day	Time	Flows (m³/ hour)	Demand (m3/h)	Storage vol. (m³)	spill (Mm³)	Count of failure years	Failure line	Cap	Pump start	Day	Index
					205536,000		0				Monday	1,027
1		12:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600	Tuesday	1,03
2		1:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600	Wednesda	1,03
3		2:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600	Thursday	1,03
4		3:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600	Friday	1
5		4:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600	Saturday	0,951
6		5:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600	Sunday	0,938
7		6:00 am	10026	9034,971	205536,000	206527,029	0	51384,000	205536,000	123321,600		
8		7:00 am	0	9034,971	196501,029	0,000	0	51384,000	205536,000	123321,600		
9		8:00 am	0	9034,971	187466,058	0,000	0	51384,000	205536,000	123321,600		
10		9:00 am	0	9034,971	178431,087	0,000	0	51384,000	205536,000	123321,600		
11		10:00 am	10026	9034,971	179422,116	0,000	0	51384,000	205536,000	123321,600		
12	Mon	11:00 am	10026	9034,971	180413,146	0,000	0	51384,000	205536,000	123321,600		
13		12:00 pm	10026	9034,971	181404,175	0,000	0	51384,000	205536,000	123321,600		
14		1:00 pm	10026	9034,971	182395,204	0,000	0	51384,000	205536,000	123321,600		
15		2:00 pm	10026	9034,971	183386,233	0,000	0	51384,000	205536,000	123321,600		
16		3:00 pm	10026	9034,971	184377,262	0,000	0	51384,000	205536,000	123321,600		
17		4:00 pm	10026	9034,971	185368,291	0,000	0	51384,000	205536,000	123321,600		
18		5:00 pm	10026	9034,971	186359,320	0,000	0	51384,000	205536,000	123321,600		
19		6:00 pm	0	9034,971	177324,349	0,000	0	51384,000	205536,000	123321,600		
20		7:00 pm	0	9034,971	168289,379	0,000	0	51384,000	205536,000	123321,600		
21		8:00 pm	10026	9034,971	169280,408	0,000	0	51384,000	205536,000	123321,600		
22		9:00 pm	10026	9034,971	170271,437	0,000	0	51384,000	205536,000	123321,600		
23		10:00 pm	10026	9034,971	171262,466	0,000	0	51384,000	205536,000	123321,600		
24		11:00 pm	10026	9034,971	172253,495	0,000	0	51384,000	205536,000	123321,600		
25		12:00 am	10026	9061,363	173218,132	0,000	0	51384,000	205536,000	123321,600		
26		1:00 am	10026	9061,363	174182,769	0,000	0	51384,000	205536,000	123321,600		
27		2:00 am	10026	9061,363	175147,405	0,000	0	51384,000	205536,000	123321,600		
28		3:00 am	10026	9061,363	176112,042	0,000	0	51384,000	205536,000	123321,600		
29		4:00 am	10026	9061,363	177076,679	0,000	0	51384,000	205536,000	123321,600		
30		5:00 am	10026	9061,363	178041,316	0,000	0	51384,000	205536,000	123321,600		
31		6:00 am	10026	9061,363	179005,953	0,000	0	51384,000	205536,000	123321,600		
32		7:00 am	0	9061,363	169944,589	0,000	0	51384,000	205536,000	123321,600		
33		8:00 am	0	9061,363	160883,226	0,000	0	51384,000	205536,000	123321,600		



34		9:00 am	0	9061,363	151821,863	0,000	0	51384,000	205536,000	123321,600
35		10:00 am	10026	9061,363	152786,500	0,000	0	51384,000	205536,000	123321,600
36	Tue	11:00 am	10026	9061,363	153751,137	0,000	0	51384,000	205536,000	123321,600
37		12:00 pm	10026	9061,363	154715,773	0,000	0	51384,000	205536,000	123321,600
38		1:00 pm	10026	9061,363	155680,410	0,000	0	51384,000	205536,000	123321,600
39		2:00 pm	10026	9061,363	156645,047	0,000	0	51384,000	205536,000	123321,600
40		3:00 pm	10026	9061,363	157609,684	0,000	0	51384,000	205536,000	123321,600
41		4:00 pm	10026	9061,363	158574,320	0,000	0	51384,000	205536,000	123321,600
42		5:00 pm	10026	9061,363	159538,957	0,000	0	51384,000	205536,000	123321,600
43		6:00 pm	0	9061,363	150477,594	0,000	0	51384,000	205536,000	123321,600
44		7:00 pm	0	9061,363	141416,231	0,000	0	51384,000	205536,000	123321,600
45		8:00 pm	10026	9061,363	142380,868	0,000	0	51384,000	205536,000	123321,600
46		9:00 pm	10026	9061,363	143345,504	0,000	0	51384,000	205536,000	123321,600
47		10:00 pm	10026	9061,363	144310,141	0,000	0	51384,000	205536,000	123321,600
48		11:00 pm	10026	9061,363	145274,778	0,000	0	51384,000	205536,000	123321,600
49		12:00 am	10026	9061,363	146239,415	0,000	0	51384,000	205536,000	123321,600
50		1:00 am	10026	9061,363	147204,052	0,000	0	51384,000	205536,000	123321,600
51		2:00 am	10026	9061,363	148168,688	0,000	0	51384,000	205536,000	123321,600
52		3:00 am	10026	9061,363	149133,325	0,000	0	51384,000	205536,000	123321,600
53		4:00 am	10026	9061,363	150097,962	0,000	0	51384,000	205536,000	123321,600
54		5:00 am	10026	9061,363	151062,599	0,000	0	51384,000	205536,000	123321,600
55		6:00 am	10026	9061,363	152027,236	0,000	0	51384,000	205536,000	123321,600
56		7:00 am	0	9061,363	142965,872	0,000	0	51384,000	205536,000	123321,600
57		8:00 am	0	9061,363	133904,509	0,000	0	51384,000	205536,000	123321,600
58		9:00 am	0	9061,363	124843,146	0,000	0	51384,000	205536,000	123321,600
59		10:00 am	10026	9061,363	125807,783	0,000	0	51384,000	205536,000	123321,600
60	Wed	11:00 am	10026	9061,363	126772,420	0,000	0	51384,000	205536,000	123321,600
61		12:00 pm	10026	9061,363	127737,056	0,000	0	51384,000	205536,000	123321,600
62		1:00 pm	10026	9061,363	128701,693	0,000	0	51384,000	205536,000	123321,600
63		2:00 pm	10026	9061,363	129666,330	0,000	0	51384,000	205536,000	123321,600
64		3:00 pm	10026	9061,363	130630,967	0,000	0	51384,000	205536,000	123321,600
65		4:00 pm	10026	9061,363	131595,604	0,000	0	51384,000	205536,000	123321,600
66		5:00 pm	10026	9061,363	132560,240	0,000	0	51384,000	205536,000	123321,600
67		6:00 pm	0	9061,363	123498,877	0,000	0	51384,000	205536,000	123321,600
68		7:00 pm	0	9061,363	114437,514	0,000	0	51384,000	205536,000	123321,600
69		8:00 pm	10026	9061,363	115402,151	0,000	0	51384,000	205536,000	123321,600
70		9:00 pm	10026	9061,363	116366,788	0,000	0	51384,000	205536,000	123321,600
71		10:00 pm	10026	9061,363	117331,424	0,000	0	51384,000	205536,000	123321,600
72		11:00 pm	10026	9061,363	118296,061	0,000	0	51384,000	205536,000	123321,600
73		12:00 am	10026	9061,363	119260,698	0,000	0	51384,000	205536,000	123321,600
74		1:00 am	10026	9061,363	120225,335	0,000	0	51384,000	205536,000	123321,600
75		2:00 am	10026	9061,363	121189,972	0,000	0	51384,000	205536,000	123321,600
76		3:00 am	10026	9061,363	122154,608	0,000	0	51384,000	205536,000	123321,600
77		4:00 am	10026	9061,363	123119,245	0,000	0	51384,000	205536,000	123321,600
78		5:00 am	10026	9061,363	124083,882	0,000	0	51384,000	205536,000	123321,600
79		6:00 am	10026	9061,363	125048,519	0,000	0	51384,000	205536,000	123321,600
80		7:00 am	0	9061,363	115987,156	0,000	0	51384,000	205536,000	123321,600
81		8:00 am	0	9061,363	106925,792	0,000	0	51384,000	205536,000	123321,600

82		9:00 am	0	9061,363	97864,429	0,000	0	51384,000	205536,000	123321,600
83		10:00 am	10026	9061,363	98829,066	0,000	0	51384,000	205536,000	123321,600
84	Thu	11:00 am	10026	9061,363	99793,703	0,000	0	51384,000	205536,000	123321,600
85		12:00 pm	10026	9061,363	100758,339	0,000	0	51384,000	205536,000	123321,600
86		1:00 pm	10026	9061,363	101722,976	0,000	0	51384,000	205536,000	123321,600
87		2:00 pm	10026	9061,363	102687,613	0,000	0	51384,000	205536,000	123321,600
88		3:00 pm	10026	9061,363	103652,250	0,000	0	51384,000	205536,000	123321,600
89		4:00 pm	10026	9061,363	104616,887	0,000	0	51384,000	205536,000	123321,600
90		5:00 pm	10026	9061,363	105581,523	0,000	0	51384,000	205536,000	123321,600
91		6:00 pm	0	9061,363	96520,160	0,000	0	51384,000	205536,000	123321,600
92		7:00 pm	0	9061,363	87458,797	0,000	0	51384,000	205536,000	123321,600
93		8:00 pm	10026	9061,363	88423,434	0,000	0	51384,000	205536,000	123321,600
94		9:00 pm	10026	9061,363	89388,071	0,000	0	51384,000	205536,000	123321,600
95		10:00 pm	10026	9061,363	90352,707	0,000	0	51384,000	205536,000	123321,600
96		11:00 pm	10026	9061,363	91317,344	0,000	0	51384,000	205536,000	123321,600
97		12:00 am	10026	8797,440	92545,904	0,000	0	51384,000	205536,000	123321,600
98		1:00 am	10026	8797,440	93774,464	0,000	0	51384,000	205536,000	123321,600
99		2:00 am	10026	8797,440	95003,024	0,000	0	51384,000	205536,000	123321,600
100		3:00 am	10026	8797,440	96231,584	0,000	0	51384,000	205536,000	123321,600
101		4:00 am	10026	8797,440	97460,144	0,000	0	51384,000	205536,000	123321,600
102		5:00 am	10026	8797,440	98688,704	0,000	0	51384,000	205536,000	123321,600
103		6:00 am	10026	8797,440	99917,264	0,000	0	51384,000	205536,000	123321,600
104		7:00 am	10026	8797,440	101145,824	0,000	0	51384,000	205536,000	123321,600
105		8:00 am	10026	8797,440	102374,384	0,000	0	51384,000	205536,000	123321,600
106		9:00 am	10026	8797,440	103602,944	0,000	0	51384,000	205536,000	123321,600
107		10:00 am	10026	8797,440	104831,504	0,000	0	51384,000	205536,000	123321,600
108	Fri	11:00 am	10026	8797,440	106060,064	0,000	0	51384,000	205536,000	123321,600
109		12:00 pm	10026	8797,440	107288,624	0,000	0	51384,000	205536,000	123321,600
110		1:00 pm	10026	8797,440	108517,184	0,000	0	51384,000	205536,000	123321,600
111		2:00 pm	10026	8797,440	109745,744	0,000	0	51384,000	205536,000	123321,600
112		3:00 pm	10026	8797,440	110974,304	0,000	0	51384,000	205536,000	123321,600
113		4:00 pm	10026	8797,440	112202,864	0,000	0	51384,000	205536,000	123321,600
114		5:00 pm	10026	8797,440	113431,424	0,000	0	51384,000	205536,000	123321,600
115		6:00 pm	10026	8797,440	114659,984	0,000	0	51384,000	205536,000	123321,600
116		7:00 pm	10026	8797,440	115888,544	0,000	0	51384,000	205536,000	123321,600
117		8:00 pm	10026	8797,440	117117,104	0,000	0	51384,000	205536,000	123321,600
118		9:00 pm	10026	8797,440	118345,664	0,000	0	51384,000	205536,000	123321,600
119		10:00 pm	10026	8797,440	119574,224	0,000	0	51384,000	205536,000	123321,600
120		11:00 pm	10026	8797,440	120802,784	0,000	0	51384,000	205536,000	123321,600
121		12:00 am	10026	8366,365	122462,419	0,000	0	51384,000	205536,000	123321,600
122		1:00 am	10026	8366,365	124122,053	0,000	0	51384,000	205536,000	123321,600
123		2:00 am	10026	8366,365	125781,688	0,000	0	51384,000	205536,000	123321,600
124		3:00 am	10026	8366,365	127441,322	0,000	0	51384,000	205536,000	123321,600
125		4:00 am	10026	8366,365	129100,957	0,000	0	51384,000	205536,000	123321,600
126		5:00 am	10026	8366,365	130760,591	0,000	0	51384,000	205536,000	123321,600
127		6:00 am	10026	8366,365	132420,226	0,000	0	51384,000	205536,000	123321,600
128		7:00 am	10026	8366,365	134079,861	0,000	0	51384,000	205536,000	123321,600
129		8:00 am	10026	8366,365	135739,495	0,000	0	51384,000	205536,000	123321,600

130		9:00 am	10026	8366,365	137399,130	0,000	0	51384,000	205536,000	123321,600
131		10:00 am	10026	8366,365	139058,764	0,000	0	51384,000	205536,000	123321,600
132	Sat	11:00 am	10026	8366,365	140718,399	0,000	0	51384,000	205536,000	123321,600
133		12:00 pm	10026	8366,365	142378,033	0,000	0	51384,000	205536,000	123321,600
134		1:00 pm	10026	8366,365	144037,668	0,000	0	51384,000	205536,000	123321,600
135		2:00 pm	10026	8366,365	145697,302	0,000	0	51384,000	205536,000	123321,600
136		3:00 pm	10026	8366,365	147356,937	0,000	0	51384,000	205536,000	123321,600
137		4:00 pm	10026	8366,365	149016,572	0,000	0	51384,000	205536,000	123321,600
138		5:00 pm	10026	8366,365	150676,206	0,000	0	51384,000	205536,000	123321,600
139		6:00 pm	10026	8366,365	152335,841	0,000	0	51384,000	205536,000	123321,600
140		7:00 pm	10026	8366,365	153995,475	0,000	0	51384,000	205536,000	123321,600
141		8:00 pm	10026	8366,365	155655,110	0,000	0	51384,000	205536,000	123321,600
142		9:00 pm	10026	8366,365	157314,744	0,000	0	51384,000	205536,000	123321,600
143		10:00 pm	10026	8366,365	158974,379	0,000	0	51384,000	205536,000	123321,600
144		11:00 pm	10026	8366,365	160634,013	0,000	0	51384,000	205536,000	123321,600
145		12:00 am	10026	8251,999	162408,015	0,000	0	51384,000	205536,000	123321,600
146		1:00 am	10026	8251,999	164182,016	0,000	0	51384,000	205536,000	123321,600
147		2:00 am	10026	8251,999	165956,017	0,000	0	51384,000	205536,000	123321,600
148		3:00 am	10026	8251,999	167730,019	0,000	0	51384,000	205536,000	123321,600
149		4:00 am	10026	8251,999	169504,020	0,000	0	51384,000	205536,000	123321,600
150		5:00 am	10026	8251,999	171278,021	0,000	0	51384,000	205536,000	123321,600
151		6:00 am	10026	8251,999	173052,022	0,000	0	51384,000	205536,000	123321,600
152		7:00 am	10026	8251,999	174826,024	0,000	0	51384,000	205536,000	123321,600
153		8:00 am	10026	8251,999	176600,025	0,000	0	51384,000	205536,000	123321,600
154		9:00 am	10026	8251,999	178374,026	0,000	0	51384,000	205536,000	123321,600
155		10:00 am	10026	8251,999	180148,028	0,000	0	51384,000	205536,000	123321,600
156	Sun	11:00 am	10026	8251,999	181922,029	0,000	0	51384,000	205536,000	123321,600
157		12:00 pm	10026	8251,999	183696,030	0,000	0	51384,000	205536,000	123321,600
158		1:00 pm	10026	8251,999	185470,031	0,000	0	51384,000	205536,000	123321,600
159		2:00 pm	10026	8251,999	187244,033	0,000	0	51384,000	205536,000	123321,600
160		3:00 pm	10026	8251,999	189018,034	0,000	0	51384,000	205536,000	123321,600
161		4:00 pm	10026	8251,999	190792,035	0,000	0	51384,000	205536,000	123321,600
162		5:00 pm	10026	8251,999	192566,036	0,000	0	51384,000	205536,000	123321,600
163		6:00 pm	10026	8251,999	194340,038	0,000	0	51384,000	205536,000	123321,600
164		7:00 pm	10026	8251,999	196114,039	0,000	0	51384,000	205536,000	123321,600
165		8:00 pm	10026	8251,999	197888,040	0,000	0	51384,000	205536,000	123321,600
166		9:00 pm	10026	8251,999	199662,042	0,000	0	51384,000	205536,000	123321,600
167		10:00 pm	10026	8251,999	201436,043	0,000	0	51384,000	205536,000	123321,600
168		11:00 pm	10026	8251,999	203210,044	0,000	0	51384,000	205536,000	123321,600

Appendix F: Energy costs of Jericho pumping system with proposed changes

Pumping combination	Power consumption (kW)
H	13434,00
D	8400,00

	Rates (cents/KWh)	
	High demand season (June to August)	Low demand season (September to May)
Peak	517,83	168,9
Standard	156,87	116,27
Off - Peak	85,2	73,76

	Weekday - Pumping combination H	Pumping combination	Saturday	Sunday
Peak	0,76	4,1	0	0
Standard	11	11	7	0
Off-peak	8	8	17	24

Pumping combination	Number of weekdays	Number of Saturdays	Number of Sundays	Weekly TOU (hours)			Saturday TOU (hours)		Sunday TOU (hours)	Weekly TOU costs (cents)			Saturday TOU (cents)		Sunday TOU (cents)	Total costs (rands)
				Peak	Standard	Off-peak	Standard	Off-peak	Off-peak	Peak	Standard	Off-peak	Standard	Off-peak	Off-peak	
H (Aug)	18	3	3	13,68	198	144	21	51	72	95165306,05	417263532,8	164819059,2	44255223,18	58373416,8	82409529,6	R8 622 860,68
H (Sept - April)	167	34	34	126,92	1837	1336	238	578	816	287981810	2869341058	1323831498	371749140,8	572735483,5	808567741,4	R62 342 067,32
D (May)	27	5	5	110,7	297	216	35	85	120	157056732	290070396	133830144	34183380	52664640	74350080	R7 421 553,72
D (Jun - Jul)	33	7	7	135,3	363	264	49	119	168	588524151,6	478328004	188939520	64567692	85165920	120234240	R15 257 595,28
																R93 644 076,99

Appendix G: Energy costs of proposed Onverwacht pump station

	Rates (cents/KWh)	
	High demand season (June to August)	Low demand season (September to May)
Peak	517,83	168,9
Standard	156,87	116,27
Off - Peak	85,2	73,76

Onverwacht pump station power consumption = 237,51 kW

Pumps	Number of weekdays	Weekday TOU (hours)			Weekday TOU costs (cents)			Total operating costs (Rands)
		Peak	Standard	Off-peak	Peak	Standard	Off-peak	
H (Aug) - HD	18	2,2	4,4	3,8	4870396,211	2950848,941	1384132,277	R92 053,77
H (Sept - April)	167	2,2	4,4	3,8	14738412,29	20291713,4	11117390,88	R461 475,17
					R196 088,08	R232 425,62	R125 015,23	R553 528,94

Appendix H: Weekly pump performance report – 26 September to 03 October

USUTU - RIVER: PUMP PERFORMANCE REPORT

Area Manager: MM Sethosa

Date of Report	2022/10/03	Reporting Period	26-Sep	to	03-Oct	Days Reported	7

Pump-station	Pump-train	Duty	Available (Yes/No)	Max Delivery Capacity (m^3/s)	Actual delivery	No. Hours Operational (Hours)	Volume Transferred (Mm^3)	Reportable Incidents/Defects/Risks	Corrective Action / Status
Jericho	Pump 1	Standby	Available	0,92	0,79	95,25	0,315		
	Pump 2	Production	Available	0,92	0,66	108,15	0,358	*Pump DE Bearing problem*	
	Pump 3	Standby	Unavailable	0,92	N/A	0	0,000		Commissioning are still ongoing
	Pump 4	Standby	Unavailable	0,92	N/A	0	0,000	*Refurbish Pump*	Refurbish Pump. Mulbert: Pump at Workshop / Power Pumps for refurbishment. Delivery Jan 2022
	Pump 5	Production	Available	0,92	0,77	99,15	0,328		
	Pump 6	Production	Available	0,92	N/A	145,20	0,481		
Primary Source (Dam & Level)	Jericho Dam	92,31%	Totals:	5,52		447,75	1,483	Pumping Performance Index (Volume): 114%	*For Noting:*
Secondary Source (Dam & Level)	Westoe Dam	75,03%	Operational Targets:	4,20			1,300	Pump Availability Index: 50%	
Receiving Dam Dam & Level	None		Transferred Volume Measured/Metered:				1,055	Measurement Discrepency: 71%	Standby Availability (Redundency): 100%

Pump-station	Pump-train	Duty	Available (Yes/No)	Max Delivery Capacity (m^3/s)	Actual delivery	No. Hours Operational (Hours)	Volume Transferred (Mm^3)	Reportable Incidents/Defects/Risks	Corrective Action / Status
Kliphoek	Pump 1	Standby	Available	1,66	1,63	8,3	0,050		
	Pump 2	Production	Unavailable	1,66	1,63	0	0,000		Electrical/Mechanical to test line #2 and handover to Operatiiions/Control
	Pump 3	Production	Available	1,66	1,63	95,00	0,568		
	Pump 4	Standby	Unavailable	1,66	1,63	0	0,000		Commissioning are still ongoing

Appendix I – Proposed Onverwacht pumping system.