Integration of electricity cost saving interventions on a water distribution utility

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Abstract

Title: Integration of electricity cost saving interventions on a water distribution utility

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Keywords: DSM, Eskom, electricity cost saving intervention, water distribution utility, load shifting, pumping station

Electrical energy has become a very important and integrated part of the current era. Electricity cost saving interventions, such as load shifting, form part of demand side management (DSM) interventions. DSM interventions have been successfully implemented in the past to ensure reliable supply of electricity during the Eskom peak periods. It has been established that there is a need to implement an electricity cost saving intervention on a large water distribution utility.

This dissertation focuses on the integration of electricity cost saving interventions on a water distribution utility. An investigation methodology, as well as an integration strategy for implementing an electricity cost saving intervention were developed. This study expands on the importance of an integrated approach. It further discusses the shortcomings of the current control philosophies of a large water distribution utility in South Africa.

A load shifting project was implemented as an electricity cost saving intervention on a large water distribution utility in South Africa. The proposed integrated strategy was simulated and an optimised approach developed. It was found that the implementation of the strategy was limited due to process constraints and increasing water demand.

Utilising the large combined installed capacity of the pumps in the water distribution utility and the storage capacity, the strategy was implemented and cost savings obtained. It was concluded that load shifting was possible on individual pumping stations in the water distribution utility subsystems, and could, therefore, be quantified to an integrated approach.

Preface and Acknowledgements

It is my hope that this dissertation provides a starting point and a stepping stone towards energy efficient and cost efficient operations in the water industry. If you wish to continue research in this field, or to take the implementation of the strategies further, I wish you the best of luck.

I would, firstly, like to thank my parents, Marietjie and Hannes Breytenbach, and the rest of my family. You have encouraged me and stood by me while I completed this dissertation, and throughout my whole life in general.

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Nomenclature

Abbreviations

ANN	Artificial neural network
BPS	Booster pumping station
DSM	Demand side management
DSS	Decision support system
EEDSM	Energy Efficient Demand Side Management
ESCo	Energy service company
GA	Genetic algorithm
HMI	Human machine interface
MOL	Metering On-line
NMD	Notified maximum demand
NORAT	Network Optimization and Reliability Assessment Tool
PLC	Programmable logic controller
PTB	Process Toolbox
REMS	Real-time Energy Management System
SCADA	Supervisory control and data acquisition
TOU	Time-of-use
VSD	Variable speed drive
WDU	Water distribution utility
WRC	South African Water Research Commission
WTW	Water treatment works

Symbols

A	Ampere
GW	Gigawatt
kVA	Kilovolt-ampere
KVarh	Kilovolt amps reactive power
kW	Kilowatt
kWh	Kilowatt-hour
m^3	Cubic metre
Ml	Megalitre
MVA	Megavolt-ampere
TWh	Terawatt-hour
V	Volt

Naming Convention

Bal-Res1, …, …, *n*	Specific balancing reservoirs at WDU-A
BPS-A, …, …, BPS-D	Specific pumping stations at WDU-A
IPH-A, …, …, IPH-B	Specific intake pump houses at WDU-A
Res-A, …, …, Res-*n*	Specific reservoirs at WDU-A
ResA1, …, …, ResD*n*	Specific distribution reservoirs at WDU-A
WDU-A	Case study conducted at a water distribution utility
WTW-A and WTW-B	Specific pumping stations at WDU-A water treatment works

1 Introduction and background

Figure 1: Eskom sub-station

Eskom supply electricity to the pumping stations in the WDU. This sub-station is located at BPS-B.

1.1 Background

1.1.1 Electricity situation

Electrical energy has become a very important and integrated part of the current era. It supports industries and economic systems [1]. Energy can be seen as a quality-of-life indicator. Energy provides electricity, transportation fuel and heat. For these important reasons, power authorities need to operate their power systems in a way that allows for contingencies. This will mean that there needs to be spare capacity available at all times [2].

In terms of generation capacity, Eskom is the largest supplier of electricity in South Africa. It has a generation capacity of 41.9 GW. This amounts to 95% of the electricity used in South Africa. Of the electricity generated by Eskom, 85% is generated by coal-fired power stations as indicated in Figure 2. This implies that Eskom has a major carbon footprint on the environment. It also has an effect on water availability which is a critical issue in South Africa [3]. The water aspect is discussed further in in this chapter.

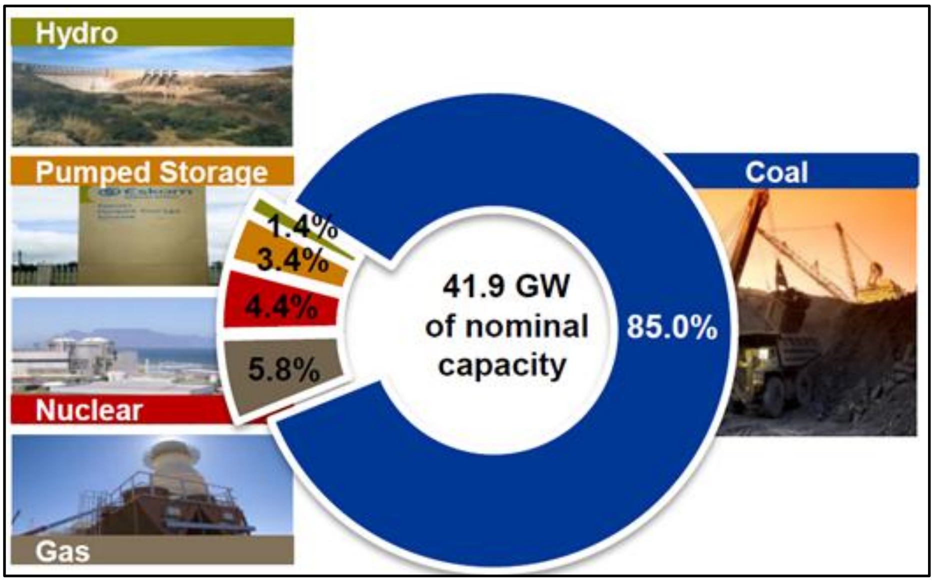


Figure 2: Generation capacity – Eskom [4]

Progress has been made in the past years to electrify all households, but 11% of the households in South Africa remains deprived of electricity. There are even more households that cannot afford the electricity required for domestic tasks [5]. The actual consumption of electricity increased by 1,2% year-on-year in January 2013/2014, according to Statistics South Africa [6].

It is, therefore, a reality that there is an electricity shortage. Failing to address the electricity needs of the country will have a negative impact on economic output. It would limit investments, which in turn would result in fewer jobs being created [7].

Figure 3 shows Eskom's electricity sales by customer for the year ending 31 March 2013. Figure 3 indicates that the industrial sector is using a large amount of the available electricity with 23,8% of the total usage [4].

After municipalities, the industrial sector is the second biggest electricity user in South Africa. In South Africa, the water industry is dependent on electricity from the municipalities for many applications. There are, however, cases where electricity is directly received from Eskom [4].

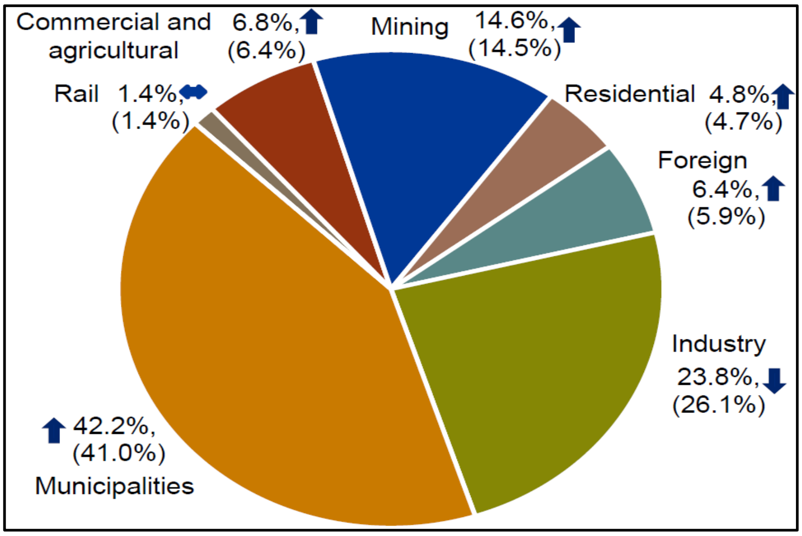


Figure 3: Electricity sales by customer

Eskom has a current expansion plan in place to solve the electricity shortage problem. The plan is ongoing to 2019, with a total planned expansion of 11 126 MW [4]. The plan, as stated by Eskom, is summarised below. The planned expansion is a work in progress and was not necessarily finalised at the time of writing [4]:

- Grootvlei power station (return to service) – Scheduled completion 31 March 2014;
- Komati power station (return to service) – Scheduled completion 31 March 2014;
- Medupi power station (coal-fired) – Scheduled completion 31 March 2017;
- Kusile power station (coal-fired) – Scheduled completion 31 March 2019;
- Ingula (pumped storage scheme) – Scheduled completion 31 March 2015; and
- Sere wind farm (renewable energy) – Scheduled completion 31 March 2015.

1.1.2 Electricity cost increase

A sustainable electricity industry needs resources to maintain current operations. It also needs resources for continuous increasing generation capacity to ensure future security of supply [7]. Eskom proposed a five-year electricity price increase from 1 April 2013 to 31 March 2018. This entailed a price increase of 16% per year, however, only 8% was approved by the National Energy Regulator of South Africa (NERSA) [8].

On 28 February 2013, NERSA approved an 8% average price increase per annum for the next five years. The average electricity price would increase from 65.51c/Kwh in 2013/14 to 89.13c/kWh in 2018. The total revenue approved for the five years amounts to R906 553 million [9].

1.1.3 Electricity cost saving intervention

With the electricity price increase and the shortage thereof, electricity savings and electricity cost savings have become important and integrated. Saving on electricity costs can primarily be done in two ways. The first is to implement an energy efficiency intervention; the second it to implement a load management intervention. Both are beneficial to an electricity consumer in the sense that electricity costs are reduced which in turn results in money being saved. Electricity cost savings can be done by implementing one or both of these interventions [10].

Due to the electricity shortage discussed in Section 1.1.1, electricity savings is of great importance and needed in South Africa. Figure 4 shows the supply and demand power profile for a 24-hour period in 2008. An important aspect to notice is the large peaks and dips, which is a demand side management (DSM) concern. To reduce electricity demand, Eskom introduced the DSM programme. It can be characterised in two categories: energy efficiency and load management [10].

The evening peak is indicated in Figure 4 using a red block. In the peak demand hours between 18:00 and 20:00, Eskom needed to generate enough electricity to match the consumer demand that was elevated [10].

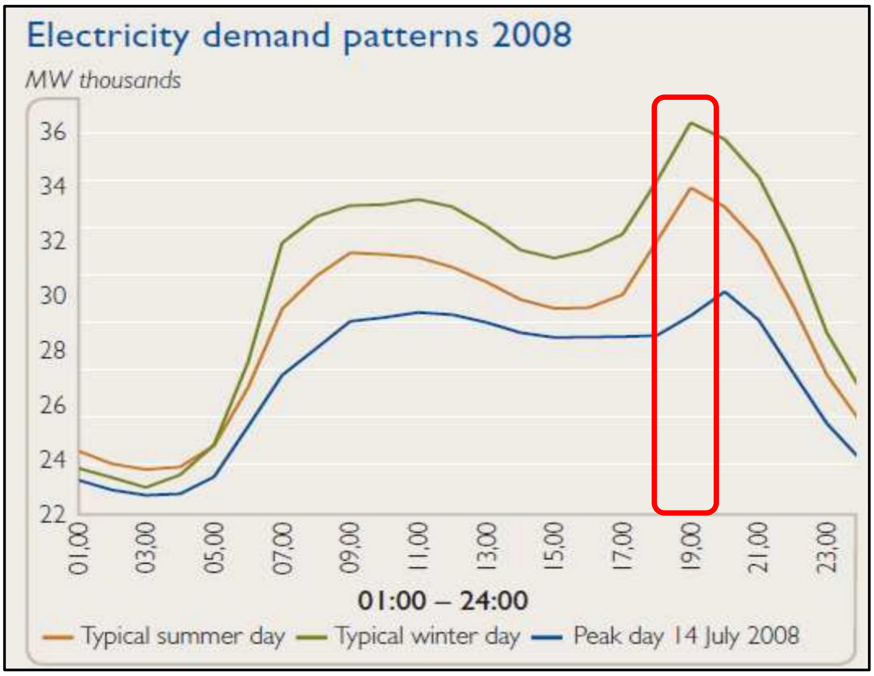


Figure 4: Electricity demand patterns [9]

1.1.3.1 Energy efficiency

Energy Efficient Demand Side Management (EEDSM) encourages the use of energy efficient technologies to lower electricity demand [10]. This means that electricity is utilised in a more efficient way. Efficient technologies refer both to more efficient equipment and more efficient processes. In short, it means to achieve the same results using less electricity.

1.1.3.2 Load management

Load management is an electricity cost saving intervention where electrical load is reduced. It takes place during peak demand periods. Load management can be subdivided into two categories: load shifting and peak clipping.

Load shifting

Load shifting transfers customer load during high demand peak periods to low demand off-peak periods [11]. It is merely the shifting of load and energy consumption. There is no reduction in the average power consumption. A simple graph in Figure 5 shows the basic principle of load shifting.

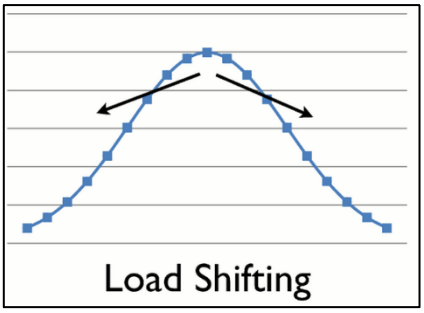


Figure 5: Load shifting [12]

Peak clipping

During peak clipping, peak electricity consumption is reduced. It can be achieved by switching off, or stopping a process. This will result in an electricity cost saving, but can eventually result in the loss of production for a specific process, unless energy was being wasted. Figure 6 shows a simple representation of an energy profile linked to peak clipping.

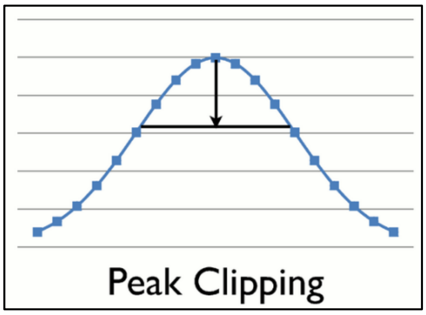


Figure 6: Peak clipping [12]

National government has committed R978 million to Eskom and local municipalities for electricity DSM. This commitment was for a period stretching over three years from 2009/10 to 2011/12. Eskom achieved the savings through a range of DSM programmes. These programmes included energy efficient lighting, heat pumps, solar water heating, efficient shower heads and process optimisation [13].

In 2010, DSM projects were expected to save 252 MW; this target was exceeded with a saving of 304 MW. In 2013, a saving of 1 310 MW was expected. The savings achieved against the target set are indicated in Figure 7 [13].

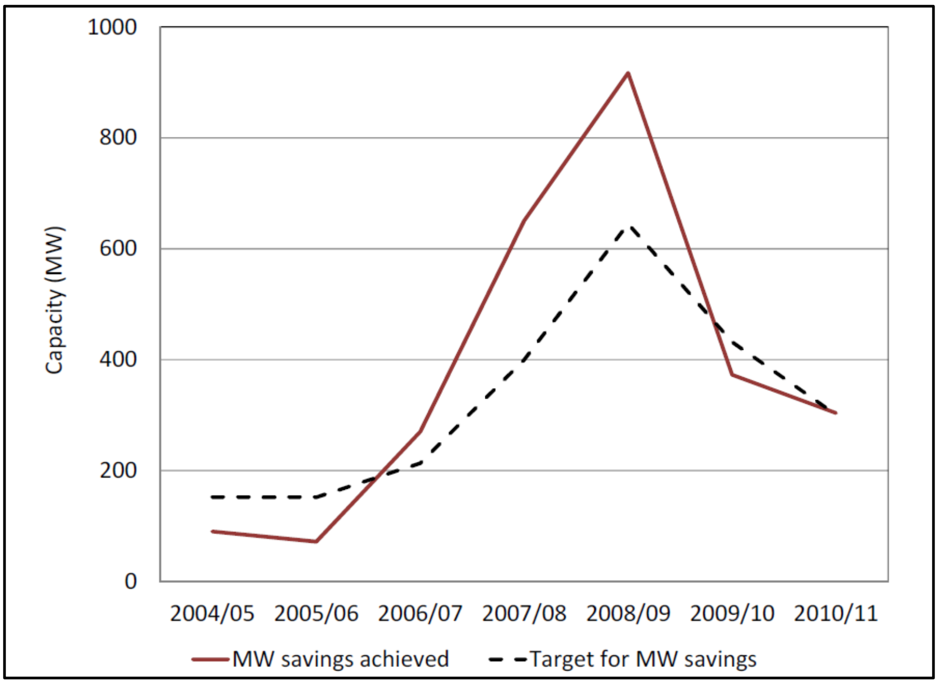


Figure 7: Targeted and achieved results from implemented DSM projects [13]

1.1.4 Water distribution and electricity consumption

Electrical energy is a critical resource for water utilities due to two main reasons [14]:

- Electrical energy plays a fundamental role in water treatment and delivery; and
- Electrical energy is a significant expense for water utilities.

There are a number of water utilities that do not possess the necessary knowledge about facility and equipment energy usage characteristics. Without this important knowledge, optimisation of energy usage is not effective. It is of great importance within the current utility pricing practices to understand these interdependencies [14].

A greater gain in efficiency and cost savings may be achieved through automated control systems that allow for time-of-use scheduling or more efficient equipment. These actions mentioned constitute the traditional approaches to utility energy management [14]. In this dissertation, the focus will be on electricity cost savings on an integrated water distribution utility (WDU).

In the past, the efficient usage of electricity in the South African water industry has not been a priority due to the relatively low cost of electricity. The situation has changed over the past few years with the rapid increase in electricity costs. In the foreseen future, energy will remain a high-cost item for municipalities and utilities in the maintenance of water processes [15].

As more people are provided with water and sanitation, energy consumption continues to increase. Contrary to published energy information available for the United Kingdom and the United States of America, South Africa has little published energy information readily available for the water industry [15].

This lack of information is because no energy savings projects have been implemented on a large scale in the water industry. In instances where energy savings projects were implemented, the data was not properly recorded. The results and data acquired from energy savings projects in the water industry have not been verified properly [15].

According to the South African Water Research Commission (WRC), South Africa has one of the most advanced water and wastewater sectors on the African continent. It is important to understand the complexity of the supply chain to study the impact of electricity saving interventions on the water sector. Factors that influence the amount of energy used in a typical water supply chain are [15]:

- Stage in the water supply chain;
- Technology used;
- Use of pumps or gravity-fed; and
- Quality of the water being treated.

When considering the technologies used, it is important to know that some of the treatment technologies consume more energy than others [15].

According to the WRC, issues such as electrical load management during peak demand periods must be clear and understood by the operational staff at the WDU site. The WRC recommends that large treatment plants investigate such electricity cost saving interventions. This is where an energy service company (ESCo) becomes important as it can do the investigation and provide the necessary knowledge to implement such an intervention [15].

1.2 Water distribution utility

1.2.1 Introduction

The main purpose of a WDU is to supply clients with required amounts of water under adequate pressure and various loading conditions. A loading condition can be defined as a time pattern of demands [16].

A large WDU typically consists of a raw-water feed, water treatment works, booster pumping stations (BPSs), pipelines and reservoirs. This dissertation will use one utility as a case study of a typical WDU.

Figure 8 shows the water distribution life cycle. A red block is used to indicate the dissertation focus. For the purposes of this dissertation, the focus will only be on the process from the extraction of raw water up to the distribution of potable water at the distribution reservoirs. This section will be discussed in two major parts: supply and demand.

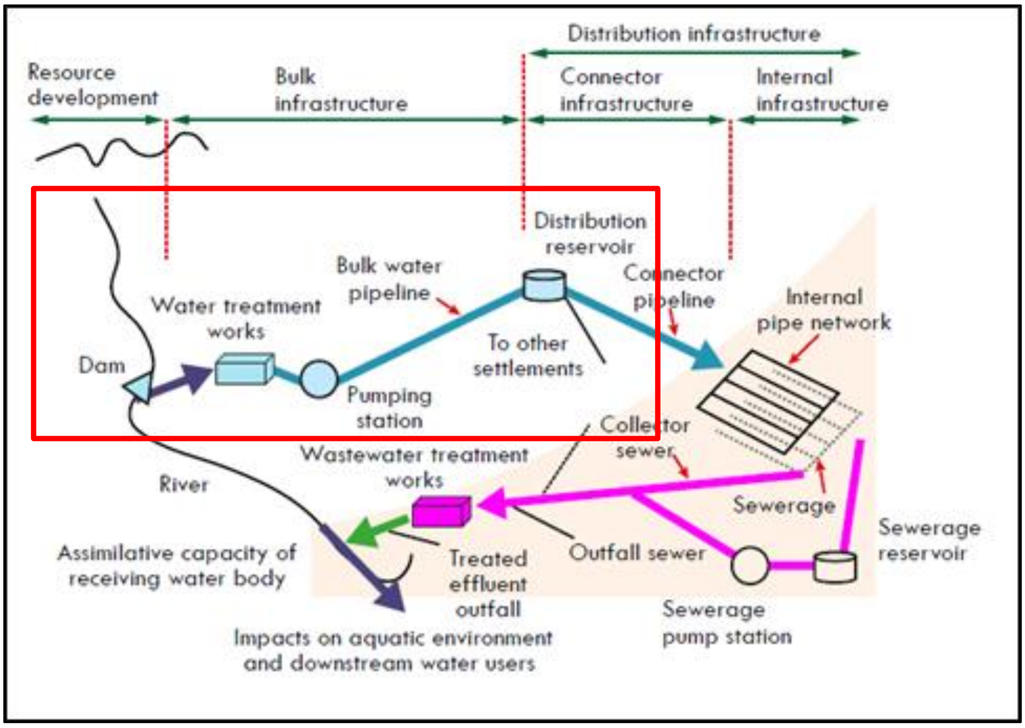


Figure 8: Water distribution life cycle [14]

1.2.2 Supply

1.2.2.1 Raw-water feed

The raw-water feed is the supply of raw water to the water treatment works. The supply of raw water can take place in different ways. Raw water can be extracted from a river, man-made reservoir or natural lake [17]. The water treatment works are typically situated as close as possible to the raw-water supply resource. It reduces the amount of energy needed to pump the water to the water treatment works or the length of the canal, if used, for supply. The raw water is normally not suitable for drinking purposes and must, therefore, be purified [17].

1.2.2.2 Water treatment works

The heart of the WDU is the water treatment works. This is where the water is purified to a potable water standard. The purification process involves several stages. Each stage of the purification process involves changes in both the chemical and physical composition of the water. There are prescribed limits and monitoring is important to prevent water quality from deviating from these limits. The seven stages of a typical purification process are [18]:

1. Coagulation;
2. Flocculation;
3. Sedimentation;
4. Stabilisation;
5. Filtration;
6. Disinfection; and
7. Chlorination.

Figure 9 is a schematic representation of the purification process including some of the stages as listed above.

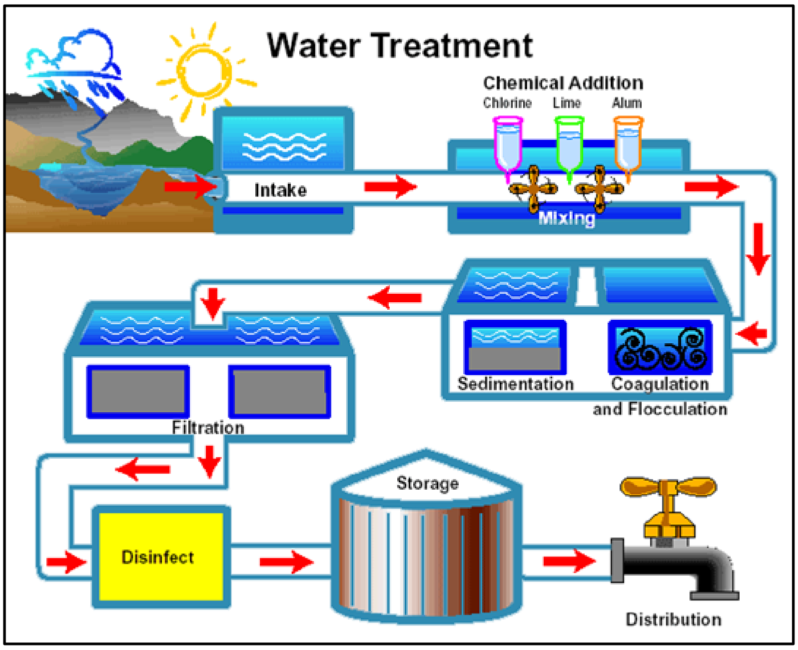


Figure 9: Water treatment works [19]

This dissertation will not focus on the specific stages of the water treatment process. The focus will be on the WDU network as a whole up to the bulk distribution of water.

1.2.2.3 Booster pumping stations

The main purpose of BPSs is to elevate water to the distribution reservoirs [18]. BPSs are not always necessary, except when water needs to be shifted over large areas with elevation.

BPSs consist of numerous pumps depending on the amount of water that needs to be handled. The sizes of the pumps and pump motors differ depending on the elevation that the water needs to be pumped. For the larger BPSs, it is also common to have balancing reservoirs on-site.

Balancing reservoirs can act as buffer capacity when there is a drop in the amount of water received from the water treatment works. In the same way, it can also absorb excess water when more water is received from the water treatment works than has been pumped to the distribution reservoir.

The water pumped from the BPS is received from the water treatment works. The composition of the water is in a purified state as obtained from the purification process. At the BPSs, water tests are conducted to check the water quality. If needed, the water state is changed by adding chlorine or ammonia.

1.2.3 Demand

1.2.3.1 Distribution reservoir

Distribution reservoirs are elements in the WDU that are on the potable water demand side. They are the final elements in the integrated WDU before it reaches the specific client. In a WDU, there is a number of distribution reservoirs located in strategic places; mostly on top of hills or at elevated locations in order to use gravity to feed water to users [18].

Distribution reservoirs store the purified water pumped from the BPSs. The water is readily available for commercial, industrial or residential use. From the distribution reservoir, the water flows under gravity and is repumped at distribution stations. From the distribution stations the water moves to the extreme boundaries of the WDU's supply area [18].

1.2.3.2 Pipeline network

The pipeline network forms part of the whole WDU. It is important because it eliminates evaporation and retains water quality. The pipeline infrastructure can stretch over a large area. It can be installed underground or above ground [20].

One of the largest bulk water suppliers in South Africa has a total pipeline length of 3 056 km. The pipeline supplies an area of 18 000 km^2 with potable water. There are

12 million consumers in the WDU's distribution area. This large bulk water supplier will also be used as the case study for the implementation of the electricity cost saving intervention in Chapter 3, Chapter 4 and Chapter 5 [20].

1.2.4 Water withdrawals and uses

Water withdrawal can be understood as a way of taking water from a source for storage or use. From a hydrologic perspective, water use is defined as all water flow due to human interference. Sustainable water is important for human society [21].

Sustainable water is defined as "the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depends on it." It is, therefore, important to intertwine DSM initiatives with a sustainable approach to the water supply industry. The demand for fresh water increases due to extensive development and population growth [21].

1.3 Cost saving through time-of-use structures

1.3.1 Tariff structure

Every electricity customer has a different load profile. Eskom applies tariffs with multiple energy rates. This results in customers having to respond by using less power during more expensive times. Most of the large energy consumers buy electricity from Eskom within a time-of-use (TOU) tariff structure. Municipalities only have a small percentage of sales at TOU tariffs [22].

Eskom Miniflex, Ruraflex and Megaflex tariffs are based on TOU tariff structures [23]. Municipalities apply only one set of tariffs. The tariffs are within the relevant area of jurisdiction of the municipalities [22].

TOU Megaflex tariff

For this dissertation, the most important tariff structure is the Eskom TOU Megaflex and will be discussed. Customers with a notified maximum demand (NMD) of greater than 1 MVA qualify for the Eskom Megaflex tariff structure. It is very common to use this tariff structure for industries and it will be discussed briefly.

Figure 10 shows the Megaflex TOU period as given by Eskom. The following charges are applicable as stipulated by Eskom [24]:

- Seasonally and TOU differentiated c/kWh active energy charges including losses, based on the supply voltage and the transmission zone;
- Three TOU periods, namely, peak, standard and off-peak;
- Basic charge per month (R);
- Demand charge (R/kVA or R/kW) differentiated seasonally;
- Reactive energy charge (c/kvarh); and
- Percentage surcharge for transmission or discount for high voltage.

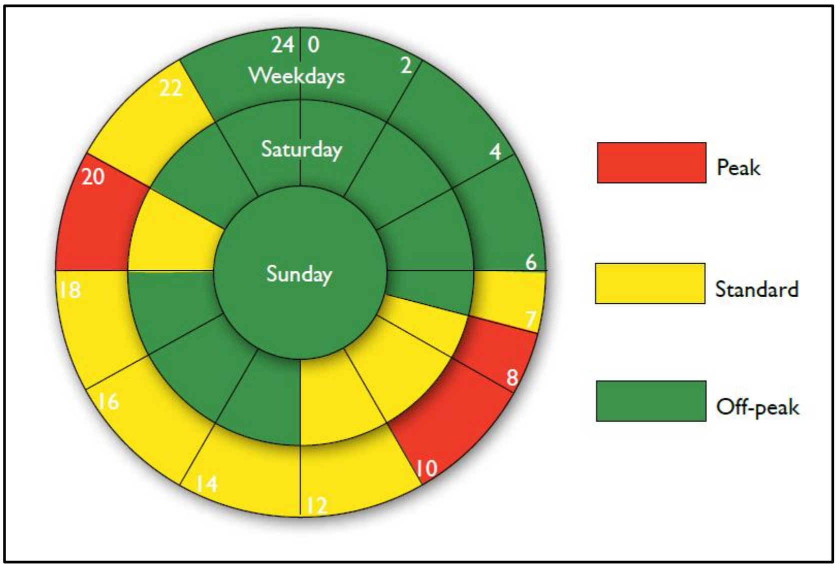


Figure 10: Eskom Megaflex TOU periods [24]

1.3.2 Different billing structures

There are different billing structures, although they are not necessarily Eskom tariffs. The tariffs also differ in the municipalities itself. The different billing structures mentioned in this dissertation include:

- Eskom's large power users at medium voltage – TOU [25];
- Emfuleni Local Municipality's special tariff for bulk consumers [26]; and
- Ekurhuleni Metropolitan Municipality's Tariff D structure [27].

1.3.3 Advantages and disadvantages of different structures

Different billing structures can influence the actual cost savings. As discussed in Section 1.3.1, it is a great advantage to do a cost saving intervention in instances where the Megaflex tariff structure applies. Any TOU tariff structure is beneficial to the client when implementing a cost saving intervention. The costs for each different tariff structure differ. It influences the amount of money saved per megawatt electricity power saving achieved.

1.4 Scope and objectives

The scope and objectives for this dissertation are summarised below:

- Investigate current DSM initiatives on WDUs;
- Develop a strategy to implement an electricity cost saving intervention on an integrated WDU;
- Develop a model for the strategy and optimise this model;
- Implement the electricity cost saving intervention on a large WDU; and
- Validate the results obtained from the implemented strategy.

1.5 Overview of dissertation

DSM initiatives have significantly reduced the demand on the national grid [14]. There is a definite need for more DSM projects. Energy efficiency and the knowledge of efficient energy usage in the water industry are lacking. The need for the integration of electricity cost saving interventions on a WDU has been identified as a research topic. The integration of these interventions will be the main focus of this dissertation.

In Chapter 2, the electricity usage and the cost savings on a WDU is investigated and discussed. Furthermore, the opportunity for electricity cost saving interventions on a WDU is investigated. The feasibility of such interventions is evaluated and discussed.

Chapter 3 focuses on the strategy for the integration of an electricity cost saving intervention. The reader is introduced to WDU-A, a large South African WDU, the company that will be used as the case study for this dissertation. The current operating strategy of WDU-A is discussed and the shortcomings of the implementation and integration of an electricity cost saving intervention is evaluated.

Chapter 4 focuses on the development of an optimisation model for an integrated WDU. The model is built for the four subsystems in WDU-A. The results and shortcomings of the model are expounded. The optimisation model is verified against real data obtained from implementing the intervention on the WDU-A's four subsystems.

Chapter 5 discusses the case study implementation and results. The intervention is applied to all four subsystems in WDU-A. The results are compared to the optimisation model results and the study is ultimately validated.

Chapter 6 includes the conclusion of the dissertation. Benefits resulting from a project of this nature will be provided, as well as recommendations for future investigations and future research.

2 Electricity usage and cost savings on a water distribution utility

Figure 11: On-site demand-balancing reservoir

Demand-balancing reservoirs serve as buffer capacity at the BPSs to absorb excess water and to compensate for loss of water.

2.1 Introduction

To implement an electricity cost saving intervention on a WDU, the WDU needs to be understood. This chapter provides an overview of a WDU, including a description of relevant equipment and elaborating on the background given in Chapter 1.

Case studies of energy efficiency and load shifting projects involving WDUs, both internationally and nationally, are included. It will be determined whether similar projects and methods can be applied to the WDU that will be investigated.

2.2 Overview of the supply side of the water distribution utility

2.2.1 Water pumping station categories

Water pumping stations can be grouped into five categories [21]:

- Raw-water pumping from a river or lake;
- In-line booster pumping into elevated tanks;
- High service pumping of potable water at high pressure (distribution of water in utility to high level places);
- Distribution system booster without storage capacity in the pipeline; and
- Source pump discharge (well pumping).

The differences between these pumping stations may be small in terms of their functionality. They may, however, differ in design. It is important to note that clear-water pumping stations differ fundamentally from wastewater pumping stations. The difference is that the clear-water pumping stations' installed capacity may be less than the peak water demand. This is not the case with wastewater pumping stations [21]. This dissertation will focus on in-line BPSs and distribution system BPSs.

2.2.2 Pumping station operations

Pumping station flow

Water demand is important for WDUs when flow requirements are addressed. It must be known or well predicted for the pumping station to be able to match the demand. The supply area may hold several users such as residential, commercial and industrial users. Demand is influenced by the average annual per capita water consumption, peak hour and daily maximum demands. Demand may also be influenced by income levels, climate and population [21].

In recent times, the distance between populations that consume water and the source of the water has increased, mainly due to population growth. Water consumption growth quadrupled in a period of fifty years [28]. It ultimately leads to fast expanding WDUs.

Supplying the immediate consumer has led to inefficiently planned strategies in many WDUs. Inefficient planning led to systems being operated inefficiently, which in turn increases energy cost for water supply and distribution [28]. It is clear that with increasing demand and inefficient shifting of water, energy costs are a major concern.

Water storage reservoirs

Water storage reservoirs include both demand-balancing reservoirs and distribution reservoirs. It is common practice to design water storage reservoirs in the WDU network. Under normal circumstances, a water storage reservoir size is designed considering the maximum demand in the system. The reservoir can then supply the pumping station with extra water if needed during peak water demand. It is also important in case of power loss and the temporarily loss of water supply [21].

Part of the water storage reservoir is the fire flow demand that needs to be satisfied. This is, however, not always part of the design specifications, as it is not a legislative requirement in all countries [21]. Fire flow demand is the amount of water that should be available for providing fire protection at selected locations [21]. Some of the general criteria for sizing water storage reservoirs are [21]:

- Peak storage needs to equal 25–50% of the average daily demand;
- Emergency storage is required in the event of loss of power where there is no backup power supply available, equal to two–three days of the maximum daily demand; and
- Fire flow equal to flow for a three-hour to eight-hour duration.

The total required storage can be calculated using the volume required by one of the criteria, up to the sum of the volume of all three the criteria. This method is only for general sizing. For more detailed sizing, the pumping station capacity is also important [21].

Pump selection

It is policy to operate pumps while having spare capacity readily available. For example, if there are four pumps in the pumping station [21]:

- Ideally, one pump would operate to provide for the average daily flow;
- The second and the third pumps would be used for an increase in demand and the subsequent pressure decreases up to the maximum daily flow; and
- The fourth pump would serve as a standby pump for when one of the other pumps trips or must be taken out for service.

This scenario is only for four pumps. When a pumping station consists of more than four pumps, this scenario can be adjusted to select the required number of pumps.

2.2.3 Overview of different types of pumping station

Raw-water pumping from rivers and lakes

The raw-water supply may be pumped to the water treatment works either directly or after passing through desalting basins. Raw-water pumping facilities are generally a combination of three basic components. It depends, however, on the source and end use of the raw water. The three basic components are [21]:

- The raw-water intake structure;
- The pumping facility; and
- The screening facility (not always required).

Most raw-water pumping facilities have shore installations with intakes below water level. There are, however, many ways to configure the raw-water pumping facility. The choice is based on the land topography and the water environment [21].

BPSs

A BPS can generally be classified as either an in-line BPS or a distribution BPS [21]:

- In-line BPSs take suction from an incoming pipeline and pressurise the water before it is discharges into another pipeline [21].

- Distribution BPSs typically use the suction from storage reservoirs and maintain the given pressure within the required limits in order to supply a distribution system with wide ranges of demand [21].

Distribution BPSs are used to distribute water to municipalities and service zones [21]. The common system characteristics of distribution BPSs are [21]:

- Water level in the elevated reservoir controls the system hydraulics.
- Pumps are started using pressure switches at the BPSs, as the pressure drops due to customer demand.
- If water is pumped in excess to the demand, the reservoir level rises. The altitude valve on the reservoir will close and the pressure will rise. A pressure switch will switch the booster pumps at the station on/off.
- The discharge of the booster pump is generally equipped with a pump-control valve or device that will limit the transient pressures during start-up and shutdown.
- If the system provides a small service area with water, an elevated reservoir is not necessary.

2.2.4 Analysis of surface water supply – Storage

The main function of a reservoir in a WDU is to even out inconsistent water demand. The use of reservoirs for storage may result in unwanted water losses through seepage and evaporation. The advantage of regulating the water flow benefits the WDU by adding capacitance to the system [21].

2.3 Energy requirements and water pricing

It is important to understand a WDU's energy requirements to know all the opportunities for electricity cost savings on a WDU. There is a direct link between water consumption and energy consumption. Energy conservation and water conservation are, therefore, linked [29].

Water becomes scarcer as communities grow, and it is not an abundant resource anymore. Thus, it has become a necessity to ration water in some way. One of the ways to ration water is to increase the price of water and to make use of tariff structures to price potable water. These tariff structures need to meet economic, social and political goals in specific situations to best utilise water resources [30].

To meet electricity tariff structure goals, there are certain elements that can be used in the construction of tariff structures. The combination of elements differs for specific situations, behaviour of customers and the utility [30].

The following elements can be used in combination [30]:

- Minimum charge;
- Fixed charge;
- Connection charge;
- Block charge; and
- Volumetric charge.

Figure 12 shows a typical municipal water life cycle. In this dissertation, only the water treatment, water distribution and the end users will be investigated. The end users will be reviewed while focusing on demand. The water treatment and distribution parts consist mainly of pumps and form the largest electricity consumers.

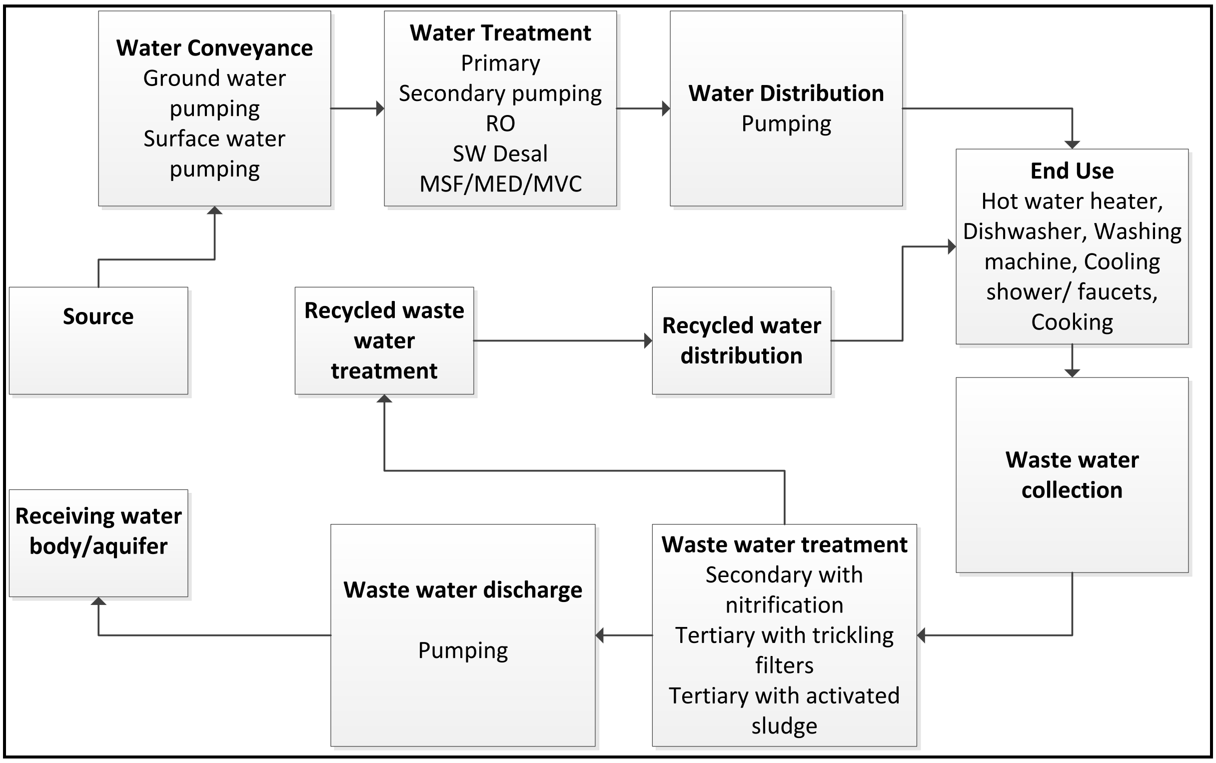


Figure 12: Stages of the water life cycle – Municipal sector [29]

Energy consumption differs between WDUs depending on various elements [29]. The elements of the water life cycle to be investigated are water treatment and delivery of water to the consumer. Figure 13 shows which process units in the water treatment works have the highest energy consumption. Knowing which process units use the most energy can reduce the investigation period on a water treatment works, because an electricity cost saving intervention can be considered for those specific process units.

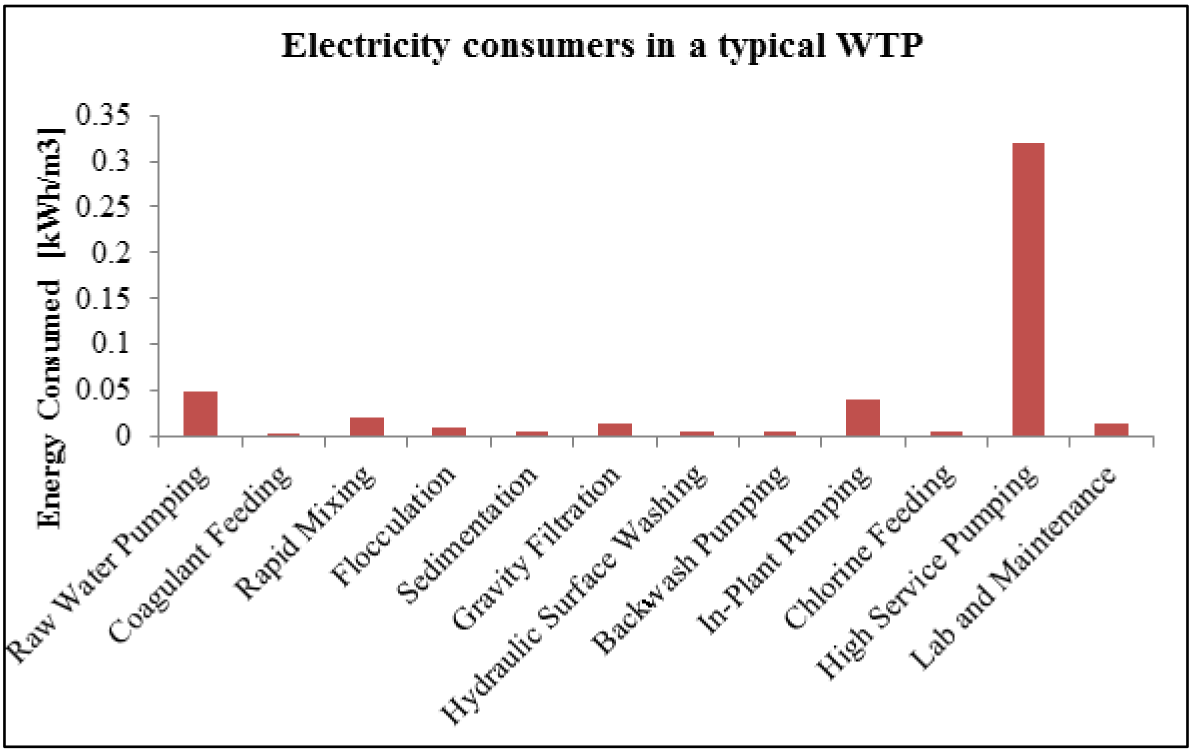


Figure 13: Process units energy consumption in US surface water treatment works [1]

It is clear from Figure 13 that the largest energy consumers are raw-water pumping and high-service pumping. High-service pumping includes the pumps at the water treatment works that pumps water to the BPSs, and the pumps at the BPSs that pumps water to the distribution reservoirs. The overall unit electricity consumption for water treatment and the supply thereof is 0.079 kWh/m^3 in the USA [29].

It is also evident that booster pumping, which forms part of high-service pumping, is the most energy intensive step in the treatment and delivery of the water. The energy needed to pump water into pressurised distribution systems amounts to around 85% of the total energy used by water distribution systems in the United States. As a general rule, the larger the volume of water pumped, the lower the energy per unit pumped gets [29].

At this point, it is known that pumps are the biggest consumer of electricity. In the European Union, pumps are the number one user of electricity. Pumps consume 160 TWh per annum of

[1] Adapted from [29]

electricity and produce up to 79 million tonnes of carbon dioxide. With centrifugal pumps, 90% of the life cycle cost of a pumping system can be attributed to energy [31].

Generally, the following methods can be used on centrifugal pumps to save energy [31]:

- Design system with lower capacity;
- Avoid excessive overdesigning;
- Select most efficient pump type for the system;
- Use variable speed drives (VSDs);
- Use two or more smaller pumps instead of one larger pump;
- Use pumps that can operate as turbines for energy recovery; and
- Do maintenance on pumps.

In this dissertation it will be argued that an electricity cost saving intervention, such as load shifting the pumping of water away from the Eskom evening peak periods, will result in instant cost savings. On the case study WDU applicable to this dissertation, there will be no energy efficiency improvements and all the pumps are assumed to be operational and maintained. This will be a holistic approach focusing on the WDU in its entirety.

2.4 Energy efficiency in water distribution utilities

Water loss in a water supply system such as a WDU is a major concern. Worldwide, water loss in WDUs is calculated to be approximately 30%. Water loss means that there is an immediate loss in electrical energy. There may also be other factors causing electrical energy losses [28]:

- Inefficient pumping stations;
- Installations and maintenance;
- Poor network design;
- Head loss due to old piping infrastructure;
- Bottlenecks in the WDU; and
- Inefficient operating strategies.

Energy efficiency problems in water supply systems can be improved by [28], [32]:

- Improving pumping station design;
- Improving system design;
- Operating pumps efficiently;
- Reducing leakages through pressure modulation; and
- Installing VSDs.

Generally, inefficient pumping stations are caused by oversizing systems and by controlling pumps inefficiently. Oversized pump systems represent opportunities for improved energy efficiency in the WDU. Because oversizing causes spare capacity, flow in a pumping station can be controlled with a VSD, bypass line or throttling valve. Pump speed control by terms of a VSD is the most common and most efficient technique to use for flow control in a pumping station [33].

VSDs for centrifugal pumps allow for operation with fixed flow and variable pressure or variable flow and fixed pressure [28]. The number of on/off switches and pipe breaks are reduced [32]. It has been found that VSDs have the potential to save between 10–20% of the total pumping energy [28].

Using VSDs is not the only solution to solving inefficient pumping systems. Efficiency can also be enhanced by [28]:

- Managing leakages;
- Replacing inefficient equipment;
- Selecting suitable energy tariff structures; and
- Incorporating renewable energy sources.

2.5 Optimisation in water distribution utilities

Growing demand, high electricity prices and the need for efficient WDUs led to optimal structures in the water industry being a necessity. Less than optimal WDUs translate into non-efficient pumping structures regarding design and operation [28].

Conventional trial-and-error methods can be used to solve optimisation problems but there might be difficulties when using these methods. This is due to the complexity of the systems in the WDU; a large number of multiple pumps, head losses; large variations in pressure values; valves and reservoirs and demand variations being present. These are only a few of the aspects that form part of a complex WDU [28].

For the reason discussed in the previous paragraph, non-linear optimisation algorithms are becoming more widely used in the water supply industry to solve optimisation problems [28]. An optimisation problem can be defined as the maximisation/minimisation of a function f, subject to equality and/or inequality constraints [34]. The optimisation problem generally can be defined with Equation 1 [34].

$$\begin{aligned} &\text{Min (or max)} && f(X) && \\ &\text{Subject to} && g_m(X) \leq 0, && m = 1, \dots\dots, M, \\ & && h_l(X) = 0, && l = 1, \dots\dots.., L \qquad \text{(Eq. 1)} \end{aligned}$$

Where $X = (x_1, \dots.., x_n)$ is a vector of the decision variable (discrete or continuous). Dimensions n, M and L are, respectively, the number of inequality and equality constraints that need to be satisfied for the optimisation of the objective function f [28], [34].

Constraints are usually linked to a system's hydraulic requirements, including equations of mass and energy conservation, nodal pressure and design and/or operational parameters bounds [28]. There is not a single 'perfect' algorithm to solve all the optimisation problems.

2.6 Pumping stations scheduling

Usually, pumping stations in a WDU or other facilities are operated with one, or a combination of the following controls [28]:

- Pressure control: Pumps are started and stopped according to suction pressure variation. Increasing demand reduces the network pressure and triggers a pump to start. The opposite applies when the demand is reduced.
- Level control: Pumps are stopped and started according to reservoir water level variations.
- Time control: Pumps are started and stopped on specific fixed hours of the day.

Power tariffs impacts

Time-of-day energy tariffs apply to many countries. Rates policies, such as TOU structures, change the pumping operations concept. Large savings can be achieved by shifting pumps operations from peak periods to off-peak periods and standard periods. The goal will be to utilise the pumps maximally in the off-peak period. This strategy, as opposed to pressure and level control, plans operations in advance and leads to more energy and cost efficient operations of the WDU [32].

Energy management system

For a WDU energy management system, two main components exist [32]:

- Demand forecaster: Prediction of a water-demand profile for a planning period (typically 24 hours).
- Scheduler: The goal of the scheduler is to generate a daily schedule for operating the water system pumps in the WDU. The schedule must be calculated while considering current source capacity as well as system characteristics. It also needs to satisfy various operational constraints and supply consumer demand. An optimal schedule can be achieved by minimising pumping during peak periods and avoiding pump cycling.

The schedule is computed using a supervisory control and data acquisition (SCADA) system. Figure 14 shows a typical energy management system that can be applied to a WDU.

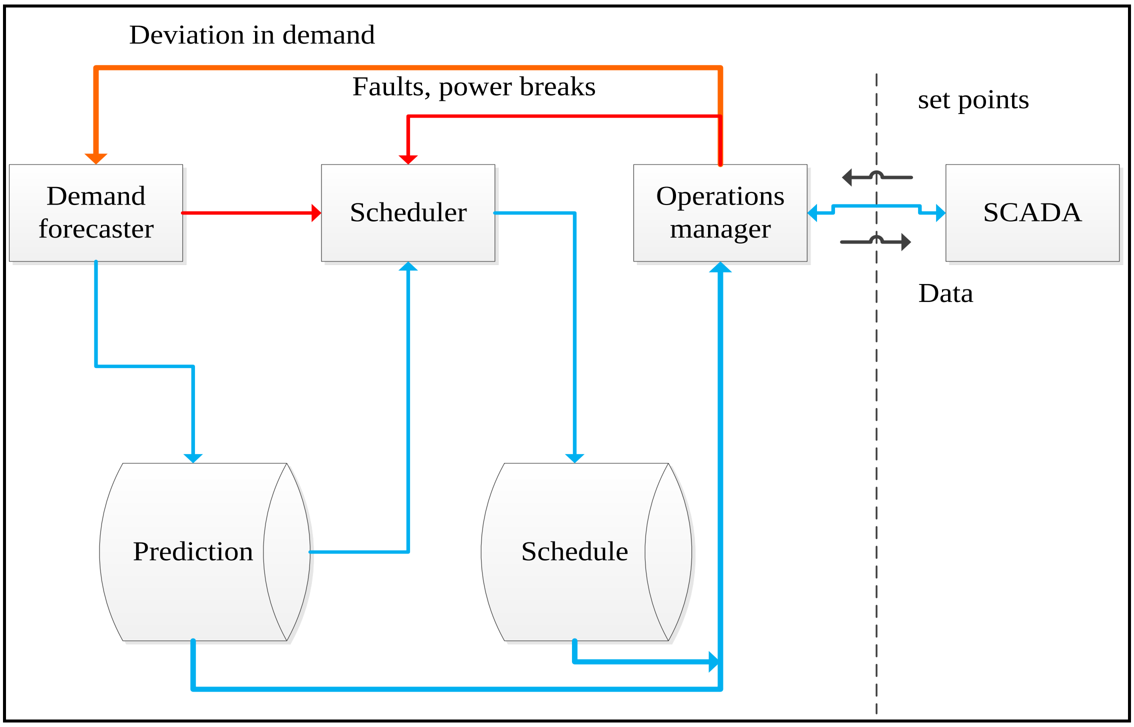


Figure 14: Typical energy managements system for a WDU [2]

The optimised schedule only shifts water load. WDUs optimise their energy cost rather than their energy consumption [32].

[2] Adapted from [32]

2.7 Previous DSM initiatives

This section focuses on many aspects that form part of DSM, including:

- Energy management;
- Energy usage versus cost optimisation;
- Pump scheduling and storage levels;
- Incorporating demand-balancing reservoirs; and
- Water demand.

The above-mentioned topics form part of a WDU and are chosen as important aspects for the implementation of a DSM initiative.

2.7.1 Energy management

ICeWater is a project funded by the European Commission that addresses energy management. The focus of this initiative is on improving energy efficiency of water networks which are highly dependent on energy. The goal is to minimise energy consumption through smart-grid integration. ICeWater uses a network of wireless sensors for water flow monitoring. With this technique, a decision support system (DSS) matches supply and demand patterns in real time. The DSS optimises the water grid network, resulting in the scheduling of pumps. This is known to be a cost saving intervention that benefits operations as well [35]. Figure 15 gives a summary of the DSS architecture.

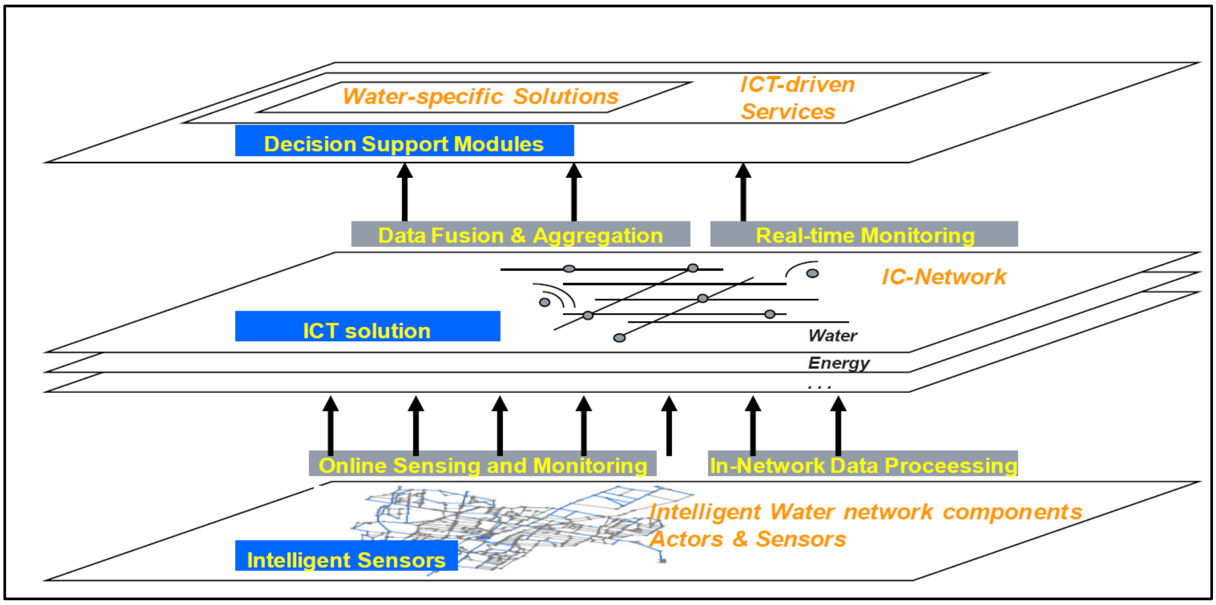


Figure 15: ICeWater system's layered architecture [35]

The first layer includes sensors, data loggers and other electrical devices used to retrieve information and physical parameters. Furthermore, the first layer includes the parameters that were retrieved from the SCADA system and were passed on to the upper layers [35]. The SCADA system integrates information coming from different technologies and presents it for specific applications on the WDU [36].

The second layer is where data is gathered, cleaned, normalised and sorted ensuring that the data is ready for the DSS layer. The third layer comprises different modules that provide functionality to the user [35].

There are five different modules in the DSS solution as can be seen in Figure 16. It is important to see where energy management fits into the setup. The functions used for implementing energy management are monitoring, operational support, data evaluation and planning [35].

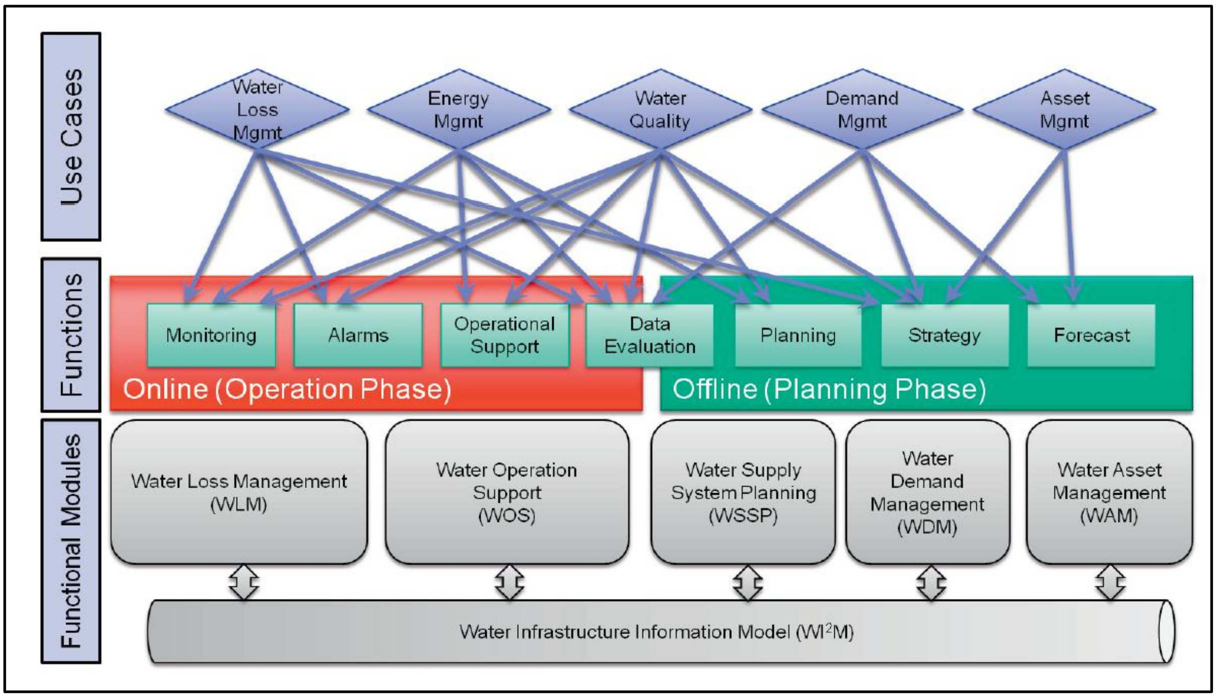


Figure 16: ICeWater DSS modules [35]

The ICeWater solution for energy management was implemented and tested on Milan's water distribution network. It was found that energy consumption represented a key component of a WDU's budget and that 90% of the energy was consumed by pumping systems. It is, therefore, important to implement solutions that reduce the cost of energy used in WDUs [35].

As found from implementing the DSS solution, the following energy optimisation activities are important for implementation [35]:

- Checking efficiencies of the pumps in the distribution system;
- Analysing pumping needs according to consumption patterns as well as periodical variations (weather and seasonality);
- Identifying pumps with low efficiency and replacing them if needed;
- Meeting the utility's objective for cost efficiency through the optimal pump configuration; and
- Identifying operational opportunities to optimise the storage reservoirs during periods of low tariffs and high tariffs by filling and draining.

Using this research and approach, much can be seen regarding energy management. The research brings to light where energy management fits into the WDU as a whole and how it must be integrated. It also shows the practical side of using this approach as a DSM initiative and cost saving intervention. Valid literature is obtained to investigate a WDU to search for electricity cost saving intervention opportunities.

2.7.2 Energy versus cost optimisation

Recently, the need for optimal asset design versus the energy cost of pumping has increased. In the WDU industry, the norm has shifted from classical sizing of equipment, such as pumps and pipes, to combining energy consumption and minimising pump cost. This accounts for the typical electricity tariff pattern over an operation cycle [37].

This section involves a study done by Giustolisi et al. [37]. The study focused on finding the balance between energy optimisation and cost optimisation. The upgrade of assets, such as pumps, reservoirs and pipes of existing WDUs, can be seen as a DSM initiative in terms of the energy optimisation of a network that results in cost savings. This study aimed at showing the different cost aspects and finding the optimal solution accounting for hydraulic capacity upgrading against the energy costs. This is regarding decreasing and increasing of demands and pumping strategies [37].

A set of optimal solutions, also called the Pareto set of optimal solutions, in a multi-objective framework were developed to help with the decision-making process for water managers. It is a method that provides optimal trade-off solutions. The key idea tested with the implementation of the developed method, was to test the solution with assumed demand patterns during optimisation. The demand values were increased and decreased. The implementation was done on a real-life application called Town-D [37].

Optimisation problem

Optimising a pumping network over a certain time period, called operating cycle *T,* requires a system behaviour forecast. An extended period simulation is required for the WDU. An extended period simulation is a sequence of steady-state simulation runs that are necessary to obtain the hydraulic status of the WDU [37].

The decision variables to be optimised over *T* are the pump states. This is in consideration of minimising pumping cost against the energy usage and electricity tariffs [37]. It is important to know that there are operational system constraints – such as supply reliability, global mass balances and water overflows – that limit the optimisation problem [37].

The energy versus cost optimisation problem discussed in this section was addressed using a multi-objective strategy. General algorithms were used to solve the multi-objective strategy. The constraints were simulated by rearranging them as an extra objective function. As said previously, the optimisation model was implemented on Town-D. The physical optimisation was performed using a Microsoft Excel®-based program called WDNetXL [37].

Discussing the implementation in detail will not add much value since the study focused more on the optimisation of new assets added to the existing infrastructure at that time. The results and the problems encountered with the optimisation model will be discussed in short.

Results

The aim of the multi-objective strategy for the optimisation of the implementation problem was minimising annual pipe and pump cost versus annualised reservoir cost versus energy cost and extra function of constraints.

The optimisation of the pump scheduling was performed using reservoir levels. The reason for optimising with reservoir levels as objective was that the optimisation problem simplified with respect to the temporal scheduling of pumps. The second reason was that scheduling with reservoirs could be transformed in the temporal scheduling for delta $T = 1$ h [37].

The results of the study showed that scheduling of pumps using reservoir levels is feasible as it is more adaptable to demand variations [37]. It is also less energy consuming than temporal scheduling of pumps. This study showed that the best way for scheduling pumps is using reservoir levels as the objective with the varied demand out of the reservoir [37].

2.7.3 Pump scheduling and storage level

Operational optimisation problems are most commonly addressed by pump scheduling. This means predicting a set of either implicit control rules or explicit time-based specifications for when to turn pumps on and off. This prediction should be within the supply service requirements with the goal of minimising energy costs [38].

Pump scheduling on its own has been researched extensively over the past years. A variety of techniques were developed for optimising pumping schedules. The most popular technique used has been genetic algorithms (GA). Most of the earlier studies were based on single objective function such as operation energy or operation cost [38].

Multi-objective optimisation algorithms have also been developed. In both single and multi-objective pump scheduling, the application of hydraulic solvers is computationally intensive when applied to large utility models [38]. This is important for this dissertation since a large WDU is investigated.

There are additional hydraulic parameters related to energy consumption other than the pump schedule. One of these parameters is the operational ranges of storage tank levels (reservoir levels). This introduces an independent set of additional decision variables alongside the normal pump-control settings [38].

As discussed in the previous section, a reservoir is not necessarily designed for optimum energy consumption when its entire capacity is used. As a result, some balancing reservoirs may impact energy savings more than others, especially when they are filled when electricity is expensive and drained when electricity is less expensive [38]. The reservoirs fill up when fewer pumps run in the peak time.

The pump scheduling problem can be defined using three elements:

- Pump (p_i) combinations,
- Reservoir volume V_{volume} (m^3), and
- Energy e_i (kW) in the WDU.

The reservoir needs to hold the water volume V_{min} (m^3) at any given time. A certain pump (p_i), pumps water of magnitude v_i (m^3/h) and uses e_i (kW) of energy. The water is pumped from a pumping station via one or more mutual pipelines to the reservoir. More than one pump work together to transfer the water to the reservoir [39].

Cooperative pumps consume more energy than when pumps work individually. The higher power consumption is due to friction that is caused by using pumps concurrent in the system. Extra cost is, therefore, paid reflecting the reality of multiple cooperative pumps that consume extra energy [39]. Figure 17 indicates the concept of multiple cooperative pumps pumping to the reservoir. It captures the core of a WDU.

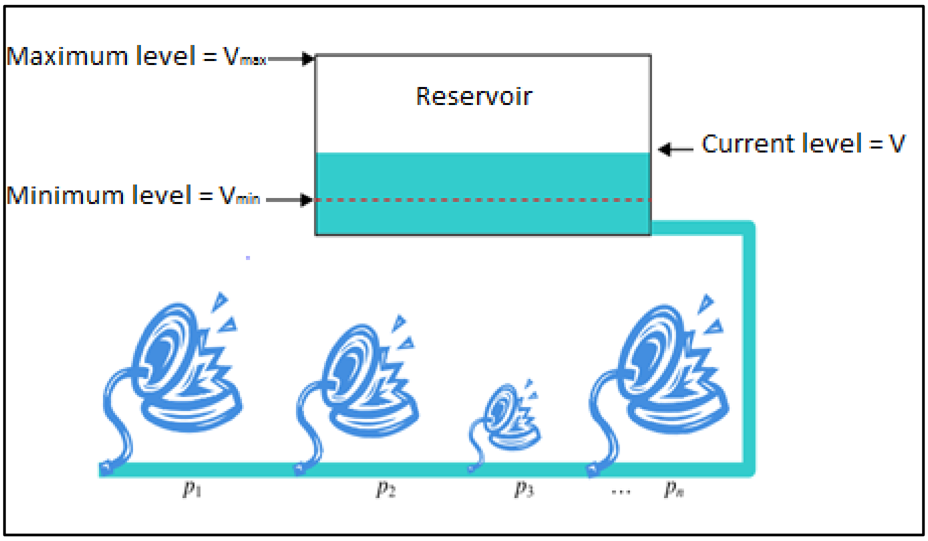


Figure 17: Simplified water distribution system [39]

An optimisation metamodel was developed by Behandish et al. [38]. An artificial neural network (ANN) was employed with a GA in the developed model. The model is used for simultaneously optimising the pump operation and the reservoir level [38]. The technique developed was applied to a water utility in the United Kingdom. The system consisted of the elements as shown in Table 1.

Table 1: Elements of optimisation metamodel

Junctions	Pipes	Reservoirs	Balancing reservoirs	Pumps	Valves
3 537	3 273	5	12	19	420

The optimisation was carried out for 24 hours with one-hour time steps. The results from the study were compared with existing operations and pump scheduling on the same system. It was compared with an existing rule-based control. The rule-based control used thresholds on the maximum and minimum reservoir levels.

For example, the threshold would be large during less expensive energy rate periods and small during more expensive energy time periods. The result of the study showed a total of

10–15% cost saving per day with a maximum of four pump switches during the same period using the GA+ANN solution [38].

The study, therefore, showed that adding the decisions on reservoir operation range to the pump scheduling policy could play a substantial part in reducing water distribution operation cost. It also influenced the storage utilisation positively [38].

This is an important existing DSM initiative. In this dissertation, the optimisation model for the integration of an electricity cost saving intervention on a WDU will be dealt with. Reservoir level optimisation will also form part of the development of such a model.

2.7.4 Incorporating demand-balancing reservoirs

A vital part of any urban infrastructure is the WDU. It requires substantial investment, operational costs and maintenance costs. The design can be complex due to the interconnections between the network components and the hydraulic parameters. Nodal pressures and demands are two of the most important hydraulic parameters. The larger the network, and the more components it consists off, the more complex the design [40].

For this study and for the implementation of an electricity cost saving intervention, certain aspects of the WDU are essential. One of the DSM initiatives to be reviewed is the incorporation of demand-balancing reservoirs into the network. Demand-balancing reservoirs are important to the WDU because, they serve multiple purposes in the network [40].

Demand-balancing reservoirs only represent a small part of the whole WDU. They, therefore, contribute only a small part to the entire network cost. If the reservoirs are designed properly and placed strategically, they may reduce total WDU costs and enhance network performance [40].

Traditional designing of demand-balancing reservoirs focused mostly on reservoir volume while neglecting other important variables such as elevation and location [40]. However, the complexity of optimisation increases with the number of decision variables. The number of possible solutions can increase exponentially. It is also possible that if too many decision variables are ignored, the optimisation model can produce solutions that may be technically incorrect [40].

NORAT

Network Optimization and Reliability Assessment Tool (NORAT) is an optimisation tool used to calculate cost and assess the reliability of a WDU. It uses C++ programming language and is integrated with the EPANET Programmer's Toolkit function for hydraulic analysis. NORAT uses the NetOpt model to optimise the reservoir volume, pipe diameters and reservoir elevation. The NetRel model is then used to assess the hydraulic reliability of the WDU [40].

With the NORAT tool, the demand-balancing pattern is analysed four times. The least expensive design that satisfies network constraints will be selected. From a study by Abunada et al. [40], it was found that incorporating the demand-balancing reservoirs into the network can decrease the total costs and increase the system reliability. However, no general trend could be proposed to determine optimal reservoir location [40].

For the purposes of the DSM strategy proposed in this dissertation, it is not important to know where to design these reservoirs in the network, referring to a specific location. It is important though, that demand-balancing reservoirs as an element in the WDU can decrease costs. Therefore, it can be seen as a DSM initiative [40].

NORAT can serve as part of the cost saving intervention on a larger WDU. It must also be taken into account when a WDU is simulated and optimised. NORAT, however, only focuses on the demand-balancing reservoirs in the optimisation and reliability assessment of the water distribution network [40]. It is a valuable tool to use in the decision-making process for the use of demand-balancing reservoirs. It leaves no room for adding multiple reservoirs or with multiple purposes in the water distribution network [40]. A further disadvantage is that it cannot be used to simulate or optimise the water distribution network as an integrated utility.

2.7.5 Water demand

In water supply systems, there is a continuous strive to automate the centralised operation of the water supply system fully. The aim of automatic control is reducing costs and at the same time improving operational quality. Water-demand forecasting forms an important part of such a control philosophy. Short-term demand forecasting can be used for optimal pump scheduling [41]. Pump scheduling according to TOU tariff structure forms the basis for the cost saving intervention introduced in this dissertation. It is, therefore, important to understand the water demand in a WDU.

Forecasting models are used in a number of utilities around the world. In the Netherlands in 2012, 57% of all supplied water was controlled on the basis of short-term water-demand forecasting. This strategy was also implemented on four large water utilities [41]. The accuracy of water-demand forecasting models is very important to avoid suboptimal control of the system. Inaccurate data can lead to reservoirs running empty or overflowing [41].

Different historical inputs can be used to generate water-demand forecasts. Most models use the following weather information as input [41]:

- Temperature;
- Precipitation; and
- Wind speed/humidity.

It was concluded by Bakker et al. [41] that forecasting performance does not necessarily improve when using weather inputs. Some models prefer to only use measured water demand as a single input. Connecting weather data input to a model results in extra costs and even risks. When using data to simulate and optimise a model, all normal variations in the water demand must be taken into consideration. Water demand varies over a period of a year and, therefore, the forecast will differ over the same period [41].

Thus, it is important to review demand patterns and forecasts. Taking weather inputs into consideration depends not only on the related costs, but also on the type of model developed and on the system simulated. If historical water-demand data is available, it will be assumed that it does not incorporate weather-forecasting inputs. The focus will rather be on getting the right demand forecasts to incorporate it in the simulation of the WDU. The normal variations must be taken into account, such as rain months and seasonal variances [41].

Results from the study of Bakker et al. [41] showed that forecasting models could be improved with 7% in respect of the average error on such a model [41]. It had to, therefore, be evaluated whether during the implementation of a forecasting model, the higher cost and complexity of using the weather inputs would weigh up to higher forecasting accuracy [41].

2.7.6 DSM strategy for national pumping systems

A study on DSM strategies for water pumping systems in South Africa was done by Nortje [42]. The pumping system and storage facilities were simulated to determine whether electricity cost savings could be achieved. The feasibility and sustainability of such a DSM strategy were also investigated. After the methodology discussion, a short description of the conclusion will follow with remarks regarding its relevance to the current dissertation.

Methodology

The methodology for the investigation phase of the project is summarised below:

- Determine the number of pumps and pumping stations;
- Determine the installed capacities of the pumps;
- Determine the water storage facilities and their respective sizes;
- Create a detailed layout of the system;
- Determine the water flow in and out of the system;
- Calculate the average hourly power consumption of the system on a typical day; and
- Determine the client tariff structure.

The Usutu-Vaal water distribution scheme was used as a real-life application for implementing the methodology. The methodology started with the investigation of possible opportunities for DSM. To understand the size of the water scheme, a description follows [42].

There are four Usutu-Vaal pumping stations. There are 32 pumps in the system. The system does not have any distribution BPSs, but do have in-line booster pumps. It is important to understand that the energy demand of the largest installed capacity pump in this system is 1 650 kW [42].

The system is divided into four sections or pumping stations and Table 2 gives a summary of the installed capacity and the average weekday power profile of the pumping stations [42]:

Table 2: Size and average weekday power profile of Usutu-Vaal scheme

Pumping station	Installed capacity (MW)	Average weekday power profile (MW)
Grootdraai and Tutuka	13.0	5.0
Grootfontein	10.8	3.5
Rietfontein	12.2	5.0
Naauwpoort	N/A	1.0

Nortje concluded in the investigation part of the methodology [42] that a peak-period load shift of 14 MW existed for the Usutu-Vaal system as a whole. It was calculated using historical data and by reviewing current operations of the system [42].

After the investigation phase, the simulation part of the methodology was done to see if the study was feasible. The simulation on each pumping station was done individually using Microsoft Excel®. To simulate the system as a whole, Real-time Energy Management System (REMS) was used [42].

After the simulation, the existing control systems and new requirements were investigated. The Usutu-Vaal system was operated using relay logic control, which is a manual method. An optimised REMS control system for the Usutu-Vaal water system was developed [42].

To implement the REMS model, instrumentation were needed to link the REMS model to the SCADA. The following was done [42]:

- All pumps were automated.
- All pumps were connected to hardware such as programmable logic controllers (PLCs) for communicating with the SCADA.
- Three individual SCADAs were set up.
- Fibre optic cables were installed.

The REMS model was implemented using RSLinx, which is computer-based software developed by Rockwell Software. RSLinx enables REMS to control the system by interfacing with the installed hardware. REMS can only communicate with the hardware and control the hardware when the local SCADA allows it [42].

Results of DSM initiatives

An average electrical load shift of 12.6 MW was obtained during the weekday evening peak periods between 18:00 and 20:00. This helped to ease the load demand on the national electricity grid. The electricity usage was shifted from the weekday evening peak periods to the cheaper TOU periods in the day. It was found that with REMS implemented successfully, the project could be evaluated. A financial saving of R562 000 was achieved with the project. A successful annual saving of R4 765 000 was predicted [42].

It was then concluded in the study that DSM interventions could be beneficial and a successful implementation on a water distribution scheme would be possible. It would be beneficial both from an energy perspective and also from a cost saving perspective for the pumping system where a DSM initiative was implemented. In this study, it was recommended that when a DSM initiative is carried out on other water pumping systems, it had to be investigated thoroughly. The reason was that each of the WDUs systems had its own limitations and needed its own interventions for the implementation to be successful [42].

Relevance to dissertation

The relevance of the research is of great importance to this dissertation. It shows the success of a previous DSM initiative on a WDU and, furthermore, shows the electricity cost saving interventions. The Usutu-Vaal water system is one of the larger water pumping systems in South Africa. It serves as an example of how DSM initiatives can be implemented on a water system.

The Usutu-Vaal water pumping system does not serve as a complete utility. The research did not address any water treatment works and there were no individual BPSs. It had a rather simple system layout, and from the research done it became clear that there were not many obstacles to overcome with the implementation of the project.

In this dissertation an integrated and complex WDU will be discussed incorporating demand-balancing reservoirs. The water treatment works with different variables to the BPSs will also be discussed in detail.

2.8 Conclusion

Chapter 2 provided a literature review on the following important aspects:

- Overview of a WDU;
- Energy requirements for pumping water;
- Energy efficiency in WDUs;
- Optimisation in WDUs;
- Pumping station scheduling; and
- Previous DSM initiatives.

The previous DSM initiatives focused on important aspects of an efficient, cost-saving WDU. These aspects included energy management, cost optimisation, pump scheduling, demand-balancing reservoirs and water demand.

Chapter 2 concluded with a study implementing a DSM initiative on a national water scheme, which was an integrated pumping scheme. This study, together with all the literature researched, forms the basis for the development of an approach for the integration of an electricity cost saving intervention on a WDU.

3 Integration of cost saving intervention strategy

Figure 18: WTW-A Engine Room 4

Water is pumped from WTW-A Engine Room 4, which is part of the water treatment works, to all four the BPSs in the WDU.

3.1 Introduction

In Chapter 2, the current methods for cost saving interventions on a WDU were discussed. The relevant background was given in Chapter 1. In Chapter 3, the focus is on the implementation methodology of a cost saving intervention on an integrated WDU. Integrated WDU means that the WDU uses more than one pumping station.

Electricity cost saving intervention is a DSM initiative that takes the form of a load shift in the evening during Eskom's peak period. Before the implementation of an electricity cost saving intervention, the feasibility of the intervention needs to be investigated. There are several methods and tools available to assist with the investigation. In this chapter, the chronologic development of the integration for an electricity cost saving intervention on a WDU will be discussed. The main focus areas include:

- Investigation and system integrated layout;
- Data acquisition and baseline calculations;
- Analysis of current operations; and
- Proposed integrated strategy.

Chapter 3 will inform the reader about the strategy to implement the methodology developed on a real-life application. A detailed analysis of the current control strategy on the application follows with a new proposed integrated strategy. The focus will be on the integration of the WDU and how to simplify such a complex system.

3.2 Investigation methodology for integration of cost saving interventions

In Chapter 2, the literature was discussed in detail. Referring back to Section 2.7.6, the methodology proposed during Nortje's investigation will be used as a guideline to develop an investigation methodology in this dissertation [42]. Figure 19 shows the proposed seven-step investigation methodology.

When investigating opportunities for an electricity cost saving intervention on a WDU, this seven-step methodology can be used. The methodology was adapted in such a way that it is generic to any WDU.

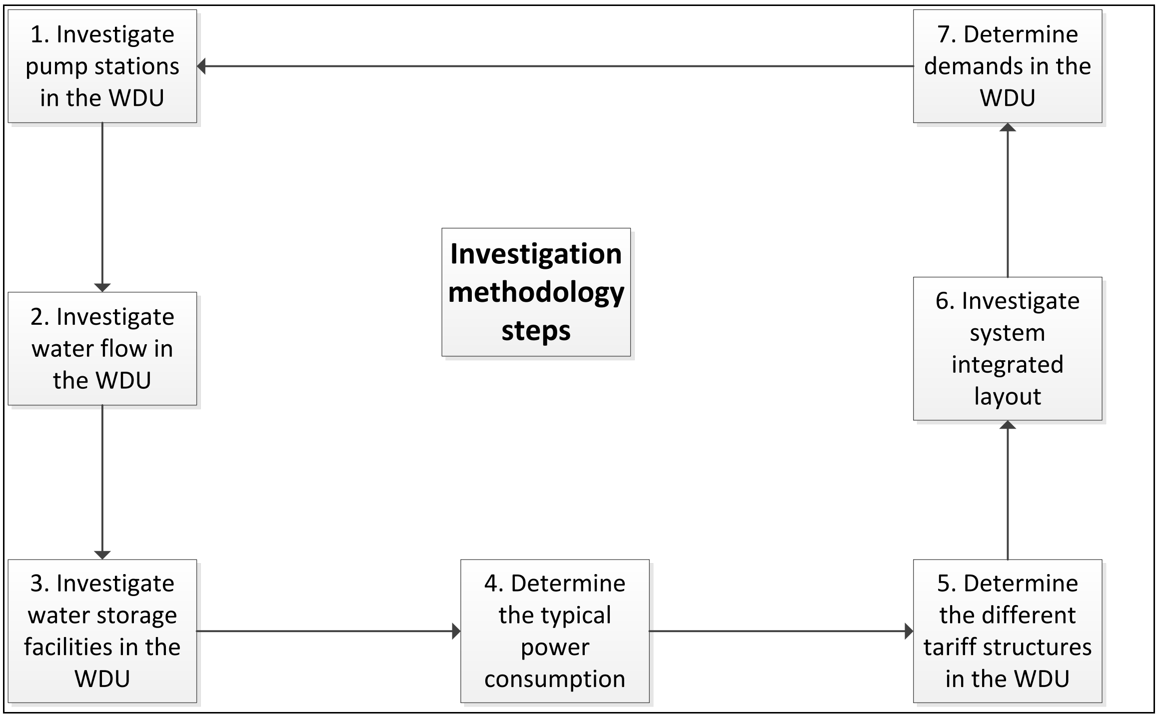


Figure 19: Investigation methodology steps for a WDU

1. Investigate pumping stations in the WDU

For a typical WDU with numerous pumping stations, it is important to understand the different pumping stations as discussed in Section 2.2.1. Each pumping station has a different function. Figure 20 shows a typical two-stage pump set in a WDU. Each pump in the pump set is indicated with a white arrow. The pump set is situated in an engine room and provides the pressure to shift water from one place to another. The first step is to identify the pumping stations. The following aspects will be investigated:

- Type of pumping station (function of the pumping station);
- Number of pumping stations in the WDU;
- Size of the pumping station (number of pumps);
- Installed capacities of the pumps and general pump information; and
- Number of stages per pump set.

Figure 20: Typical two-stage pump set in an engine room of a WDU

2. Investigate water flow in the WDU

The water flow in the WDU can now be investigated. This step allows for understanding of the WDU size. It also gives an understanding of the water path and where the consumer demand fits into the process. Figure 21 shows a typical incoming pipeline to the pump set at the pumping station. The important aspects to investigate are:

- The water path, for example, the water's origin and its end destination;
- The daily amount of water pumped in the WDU; and
- The distribution of the water, for example, how much water is pumped to each destination.

Figure 21: Typical incoming pipeline at an engine room at a WDU

3. Investigate water storage facilities in the WDU

As discussed in Section 2.7.4, demand-balancing reservoirs which serve as water storage, plays an important role in the WDU. Not only do they store water, but they also play an important role in an electricity cost saving intervention strategy. It can provide capacitance in the process that can assist with load shifting. Figure 22 shows a typical on-site balancing reservoir. The following points need to be investigated during this step of the methodology:

- Type of storage facility focusing on its function, for example, pressure tower, demand-balancing reservoir or distribution reservoir;
- Location of the storage facility, for example, the distance from the pumping station;
- Size of the storage facility; and
- Water feed and destination out of the water storage facility to the client.

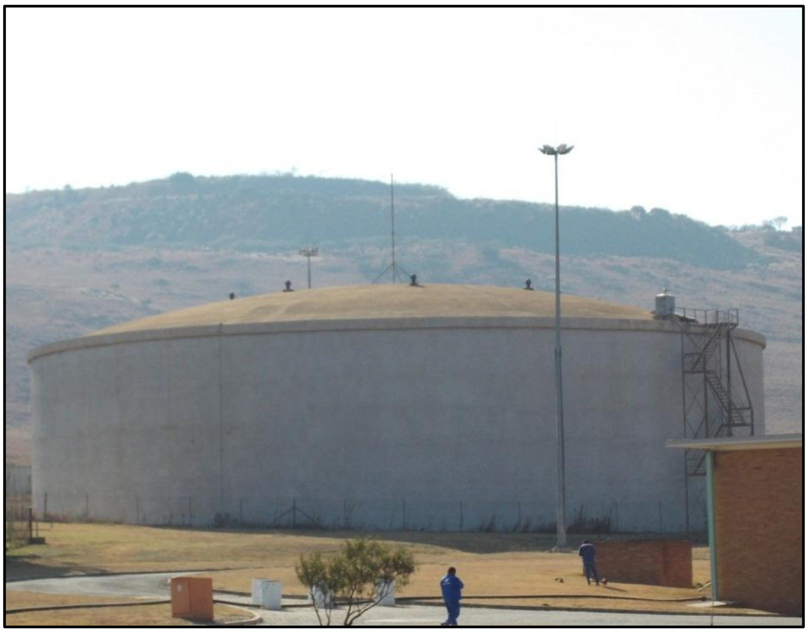


Figure 22: On-site demand-balancing reservoir part of the integrated WDU

4. Determine the typical power consumption

In order for an electricity cost saving intervention to be implemented, the power consumption of the WDU needs to be investigated. All the different aspects of the WDU need to be reviewed to find the largest electricity consumers. Figure 23 shows a typical pump motor, which is a large electricity consumer of the WDU.

If power data is accessible, an average power baseline can be calculated. The baseline, together with all the information obtained from the investigation, and the optimisation model later on will show the feasibility of a cost saving intervention on a specific WDU. Therefore, the following two aspects need to be addressed:

- Investigate all the electricity consuming aspects of the WDU to find large consuming elements; and
- Obtain the power data and calculate a typical power consumption baseline as reference.

Figure 23: Pump motor connected to a pump in an engine room

5. Determine the different tariff structures in the WDU

The emphasis in this dissertation is on reducing electricity costs by implementing a DSM project at a WDU. The tariff structure plays an important role in the amount of costs saved and on the feasibility of the DSM initiative. Therefore, investigating the tariff structure is a very crucial step in the methodology.

In a large integrated WDU, the pumping stations are far apart and different tariff structures may apply to the various pumping stations. This will influence the amount of cost savings obtained. Different tariff structures were discussed in Section 1.3.2. The following needs to be investigated regarding the tariff structure:

- Type of tariff structure;
- Fixed charge (Rand/month);
- Demand charge (Rand/kVA);

- Network access charge (Rand/kVA);
- Energy charge (c/kWh); and
- Notified maximum demand.

6. Investigate system integrated layout

The investigation into the pumping stations and the water storage facilities provides a good starting point to obtain the integrated layout of the WDU. It is also valuable to draw a layout of each individual pumping station. This part of the investigation is important in order to understand the WDU, the integrated process and how the system is interlinked.

In his study, Nortje discussed a relative small water network compared to WDU-A, that will be introduces in Section 3.4 [42]. The difference for a much larger WDU is that there may be subsystems within the WDU. The large integrated WDU must be divided into the smaller subsystems to identify all the nodes and important elements of the process. After the breakdown, the link between the subsystems must be identified and understood. The following are important investigation points for the system layout:

- Identify the size of the WDU;
- Identify subsystems if applicable;
- Obtain pipeline information, for example, length and geographical information;
- Find the link between subsystems (if applicable) and obtain the integrated system layout; and
- Understand the process.

This step is important to simplify and understand the WDU.

7. Determine demands in the WDU

As discussed in Section 2.7.5, determining demand is the final step in the WDU investigation methodology. If demand data is available, daily profiles can be calculated. Figure 24 shows an example of a typical water-demand pattern. The amount of water used is plotted against the time of day.

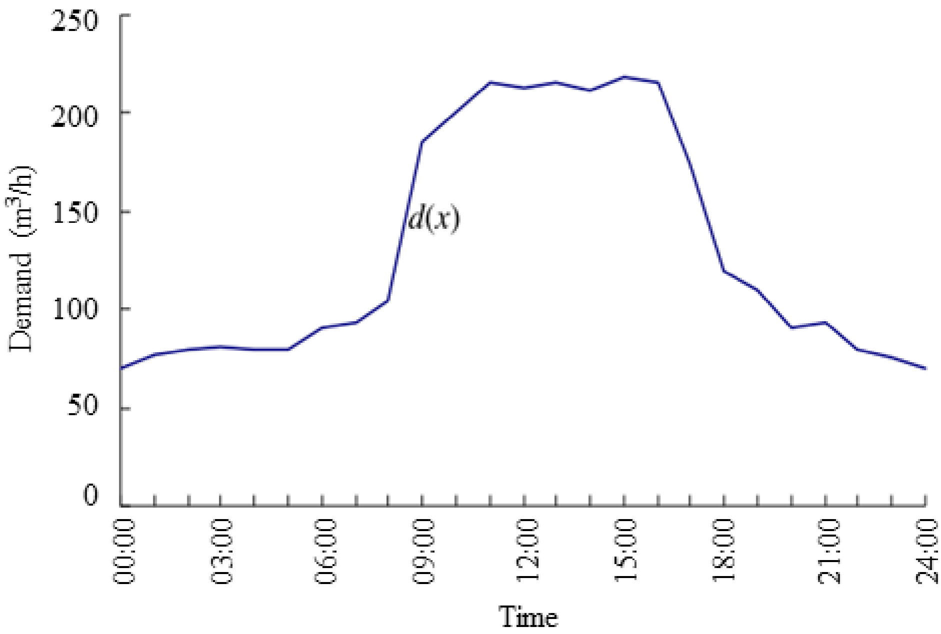


Figure 24: Example of a daily water-demand pattern [39]

As discussed in the literature review, there are factors that can influence the demand. The following factors are important to determine water demand:

- Type of client;
- Amount of water in the outgoing pipelines of the reservoirs;
- Draw-offs, for example, users drawing water along the WDU pipelines, and not specifically in municipal scheme; and
- Seasonal effects on the demand, for example, the influence of temperature and rainfall.

The investigation methodology can be applied to any WDU under investigation.

3.3 Data acquisition and baseline calculation

The ultimate goal is to build a model and optimise the network in order to identify the load shift potential. For the simulation to be verified, a baseline is needed for comparison. The baseline for two of the pumping stations in WDU-A is discussed in Section 3.4. It shows the typical power consumption of the chosen electricity users. The baseline can be calculated with data obtained from site investigations.

The baseline period is three months in order to get a good power profile. The baselines for the WDU-A pumping stations were calculated for average weekdays during the winter months of

May, June and July. These months were chosen as performance assessment because the water demand drops and temperatures decrease.

In most cases, the necessary data can be obtained from the local SCADA on-site. If it is not readily available on the SCADA, the data can be calculated using available equations. The required data was available for WDU-A, and as a result the equations will not be discussed.

The data for WDU-A was obtained from Metering On-line (MOL), an independent company that measures the energy usage of companies. The data could be accessed on the Internet. The electricity usage was measured in half-hour intervals for every day of the year.

3.4 Water distribution utility case study A (WDU-A) DSM investigation

WDU-A consists of four subsystems with a BPS for each of the systems. It also has two water treatment works (WTW) from where the BPSs received potable water. These water treatment works have their own pumping stations to pump water to the BPSs. The WDU-A pumping stations that will be discussed are:

- WTW-A
- WTW-B
- BPS-A
- BPS-B
- BPS-C
- BPS-D

The two sections that follow will show how the investigation methodology was implemented on a real-life WDU application. Two of the pumping stations are discussed in Section 3.4.1 and 3.4.2, and the other four stations are discussed in Appendix A. The reason for choosing the two specific pumping stations that will be discussed in the sections that follow, is that one pumping station is a water treatment works and the other pumping station is a BPS.

3.4.1 WTW-A

Pumping station

WTW-A is a water treatment works that purifies raw water to a potable water standard. It consists of a water purification system and four associated engine rooms. The pumping station is situated on the banks of the Vaal River, from where it extracts raw water from the river. After completing the purification process, the water is pumped to the booster stations at BPS-A, BPS-B, BPS-C and BPS-D.

The water treatment works also has a number of smaller pumps that form part of the purification process. There are also wash water pumps and air blowers that are required to wash the filters. These pumps are situated at the central sludge. The purification process requires one filter at a time to be offline for cleaning.

To clean the filter, clean water is pumped through the filter, followed by air blown through it. This process is automated and programmed into the local PLC. The installed capacities of these infrastructures are listed in Table 3. The total installed capacity of the filtration infrastructure is 1 482 kW.

Table 3: Filtration system characteristics

Pumps	Installed kW capacities
Wash water pumps	3×220 kW, 3×110 kW
Air blowers	3×164 kW

Table 4 shows the pump characteristics of the pumps installed at WTW-A. The first column shows the pump set number. The second column shows the engine room in which the pump sets are located. The third column shows the pumping capacity of the pumps, which is the amount of water that can be pumped. Columns four and five show the power of the pump sets. The last column shows the destination the water is being pumped to. The pump characteristic tables will have the same structure throughout Section 3.4 and in Appendix A.

Table 4: WTW-A pump characteristics

Pump set number	Engine room number	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Pumping destination
1	1	90	708	708	BPS-A
2	1	90	708	708	BPS-A
3	1	90	708	708	BPS-A
4	1	90	734	734	BPS-A
5	1	90	734	734	BPS-A
6	1	90	734	734	BPS-A
7	2	100	1 460	1 460	BPS-C

Pump set number	**Engine room number**	**Pump capacity (Ml/day)**	**Power – 1st stage (kW)**	**Power – 2nd stage (kW)**	**Pumping destination**
8	2	100	1 460	1 460	BPS-C
9	2	100	1 460	1 460	BPS-C
10	2	100	1 460	1 460	BPS-C
11	2	100	1 460	1 460	BPS-C
12	2	100	2 919	–	BPS-C
13	2	100	2 919	–	BPS-C
14	3	300	4 252	4 252	BPS-B
15	3	300	4 252	4 252	BPS-B
16	3	100	1 443	1 443	BPS-B
17	3	100	1 443	1 443	BPS-B
18	3	200	2 689	2 689	BPS-D
19	3	200	2 689	2 689	BPS-D
20	3	200	2 850	2 850	BPS-D
21	3	200	2 850	2 850	BPS-D
22	4	200	3 850	1 600	BPS-B
23	4	200	3 850	1 705	BPS-B
24	4	200	3 850	1 705	BPS-B
25	4	200	3 850	1 705	BPS-B
26	4	200	3 850	1 800	BPS-B
27	4	100	1 015	1 750	BPS-B/BPS-C
28	4	100	1 015	1 750	BPS-B/BPS-C
29	4	200	2 045	3 375	BPS-B/BPS-C
30	4	200	2 045	3 375	BPS-B/BPS-C
31	4	200	2 045	3 375	BPS-B/BPS-C
32	4	200	2 045	3 375	BPS-B/BPS-C
33	4	200	2 045	3 375	BPS-B/BPS-C
34	4	200	2 045	3 375	BPS-B/BPS-C
35	4	100	1 785		BPS-A
36	4	100	1 785		BPS-A

Water flow in the WDU

The water from WTW-A is pumped to all four BPSs. From the BPSs, water is distributed into the WDU network. Engine Room 1 at WTW-A pumps to BPS-A. BPS-A is situated at a head of 76 m from Engine Room 1 at WTW-A. Engine Room 2 pumps to BPS-C at a head of 145 m. Engine Room 3 can pump to BPS-B, at a head of 120 m, or to BPS-D at a head of 116 m. The last engine room, Engine Room 4, can pump to BPS-A, BPS-B or BPS-C. In total, WTW-A holds 36 pump sets that pump to the destinations mentioned.

The different pumping destinations in specific engine rooms depend on the operational needs due to water demands. There are valves that can be opened and closed to interlink the pipe network. Figure 25 shows a typical valve in the WDU pipeline network.

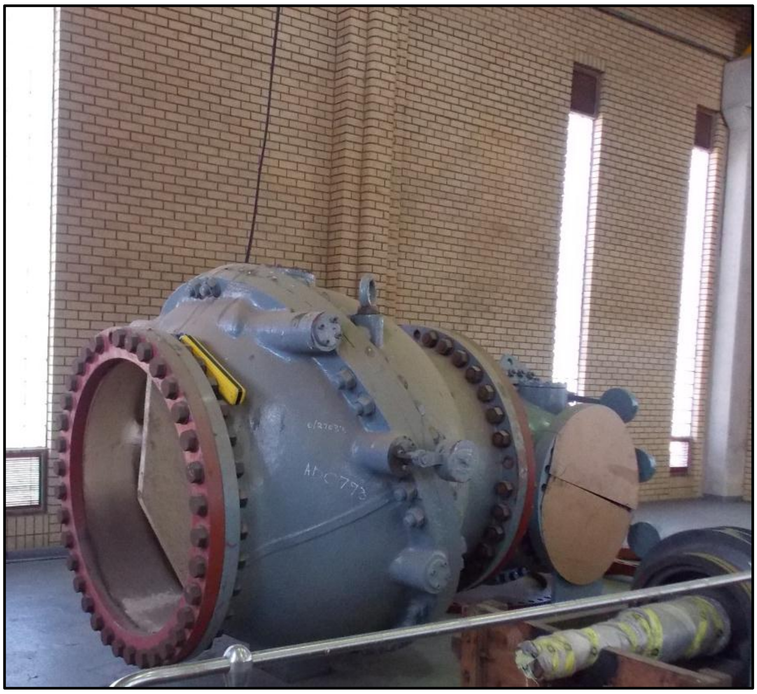


Figure 25: Typical valve out of commissioning

Water storage facilities

There are no reservoirs on WTW-A that serve as water storage facilities. A forebay is present where water is stored before the treatment process starts. There are also sumps that stores potable water before being pumped to the BPSs. The storage capacities of the sumps are very small. The purification process is not part of this dissertation and will, therefore, not be discussed in detail.

Typical power consumption

From the investigation it is now clear which elements of the water treatment works are the largest electricity consumers. The pumps that pump the potable water to the BPSs use the most electricity. Figure 26 shows a baseline of the average amount of power used on a weekday calculated over a three-month period. The baseline is around 72 000 kW and stays constant over a 24-hour period.

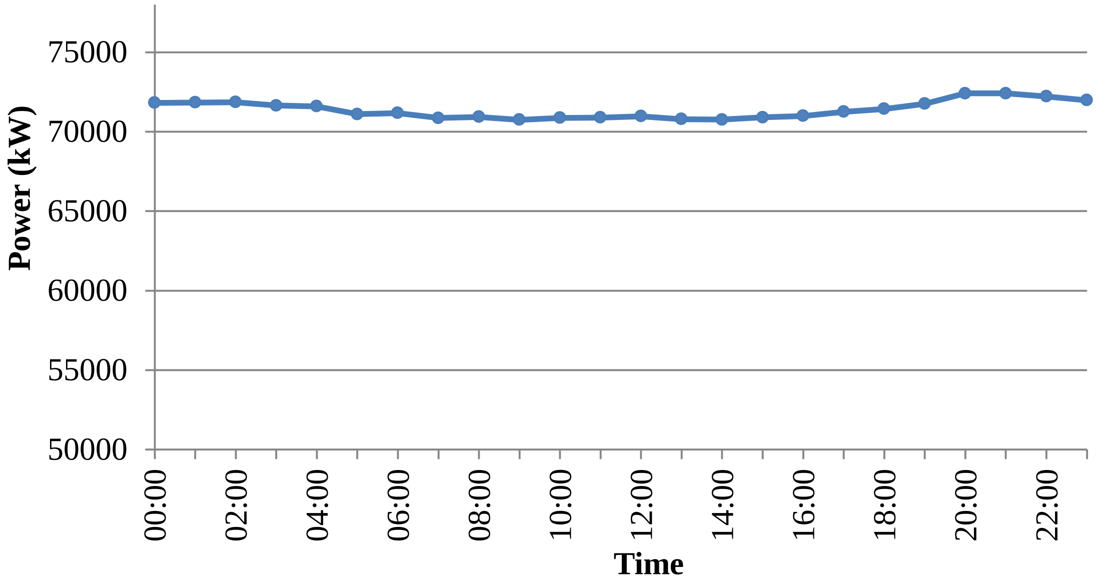


Figure 26: WTW-A average weekday power usage baseline

Tariff structure

WTW-A is on the Eskom Megaflex TOU structure. The current electricity prices as given in Section 5.3.2 are applicable. This tariff structure allows for cost saving potential if load shifting takes place as a DSM initiative.

Integrated layout

With all the information gathered, and on-site experience gained through the investigation, a layout of WTW-A can be drawn. The integrated layout of WTW-A is shown in Figure 27.

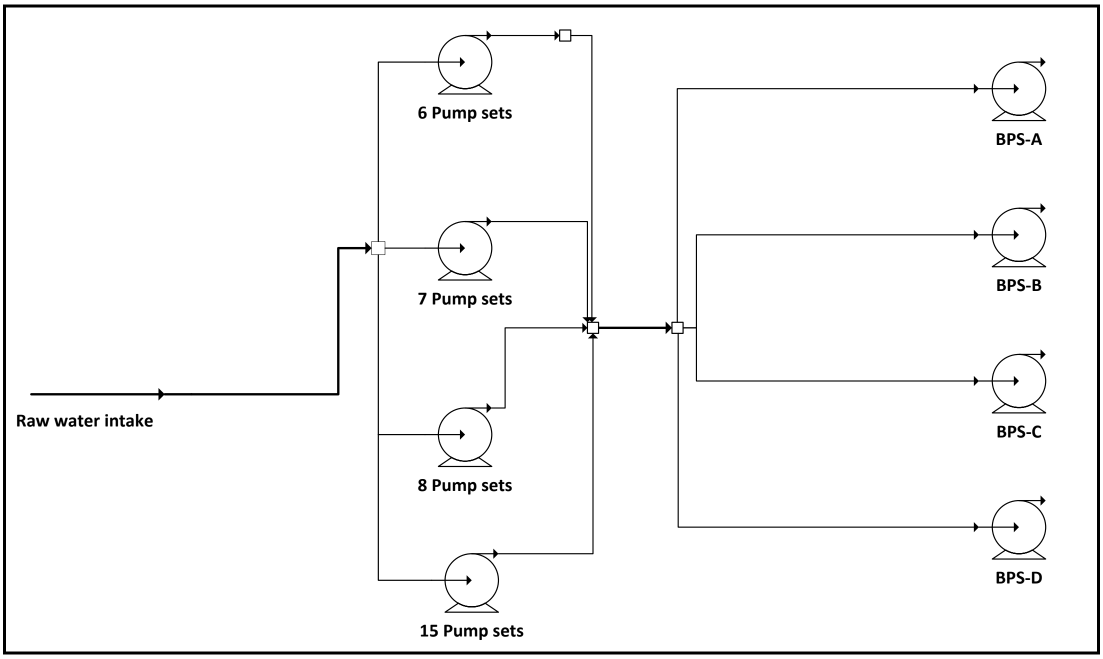


Figure 27: WTW-A simplified integrated layout

Water demand

The demand from WTW-A is primarily linked to the amount of water that the BPSs need. The water treatment works do not supply large distribution reservoirs directly but rather supply the BPSs with potable water. There are, however, nearby smaller reservoirs that can be supplied with water directly from the water treatment works. A fraction of the water is drawn off by secondary users, before water reaches the BPSs.

3.4.2 BPS-A

Pumping station

BPS-A pumps potable water received from the water treatment works to the distribution reservoirs. The balancing reservoir receives potable water from WTW-A and WTW-B. BPS-A has two engine rooms. Engine Room 1 has four pump sets and Engine Room 3 has seven pump sets. Table 5 shows all the pump sets with their sizes and other pump characteristics.

Table 5: BPS-A pump characteristics

Pump set	Engine room number	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Power – 3rd stage (kW)	Pumping destination
1	1	100	2 560	3 603	–	Res-A3
2	1	100	2 560	3 603	–	Res-A3
3	1	100	2 560	3 603	–	Res-A2

Pump set	Engine room number	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Power – 3rd stage (kW)	Pumping destination
4	1	100	2 560	3 603	–	Res-A2
14	3	100	1 500	2 030	2 030	Res-A1
15	3	100	1 500	2 030	2 030	Res-A1
18	3	100	1 475	1 475	2 700	Res-A1
19	3	100	1 475	1 475	2 700	Res-A5
20	3	100	1 475	1 475	2 700	Res-A5
21	3	100	1 475	1 475	2 700	Res-A5
22	3	100	1 475	1 475	2 700	Res-A5

Water flow in the WDU

BPS-A receives water from the balancing reservoir, which is supplied with potable water from WTW-A and WTW-B. BPS-A supplies mainly three distribution reservoirs of water, namely, Res-A2, Res-A3 and Res-A4. The pumps at BPS-A pump to the distribution reservoirs at heads of 1 792 m, 1 803 m, and 1 691 m respectively. Res-A1 and A-5 are also supplied by BPS-A, depending on the demand. BPS-A has two engine rooms. There are pumps dedicated to different distribution reservoirs. This is also shown in Table 5.

Water storage facilities

As discussed in the previous paragraph, the water from BPS-A is primarily pumped to Res-A2, Res-A3 and Res-A4 distribution reservoirs individually. The distribution reservoir capacities are:

- Res-A2: 90 000 m^3
- Res-A3: 36 000 m^3
- Res-A4: 200 000 m^3

Typical power consumption

The average power consumption for the pumps, which are the largest electricity users, can be seen in the baseline presented in Figure 28. The average daily power baseline is around 27 000 kW.

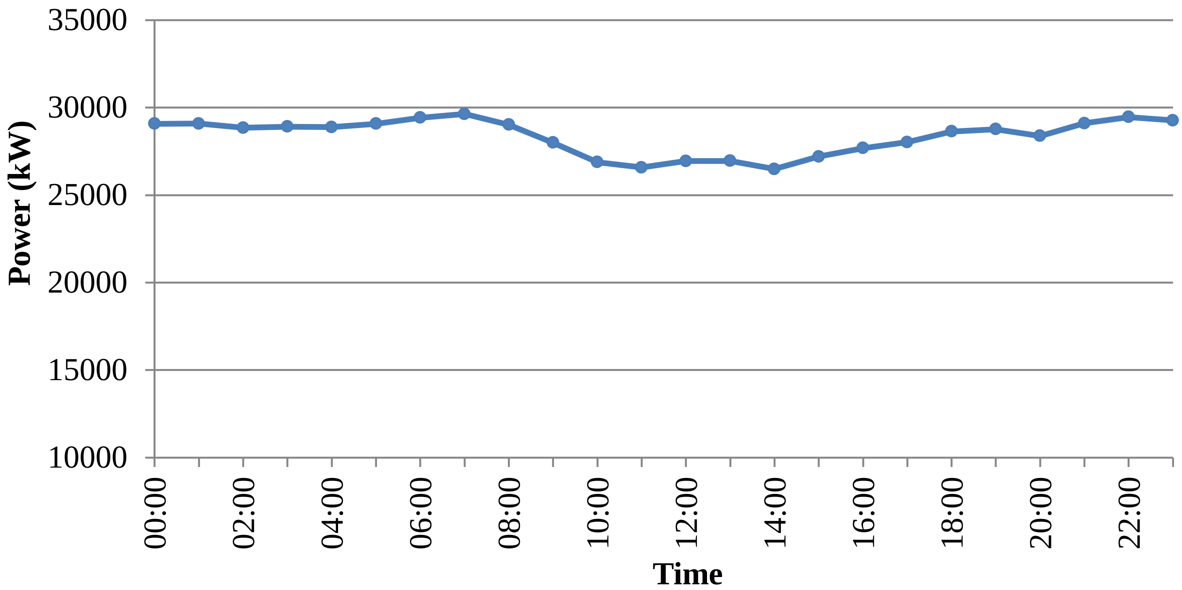


Figure 28: BPS-A average weekday power usage baseline

Tariff structure

The Eskom TOU tariff structure is used for BPS-A. The tariff price and the structure can be seen in Section 5.3.2.

System integrated layout

The layout for BPS-A is shown in Figure 29.

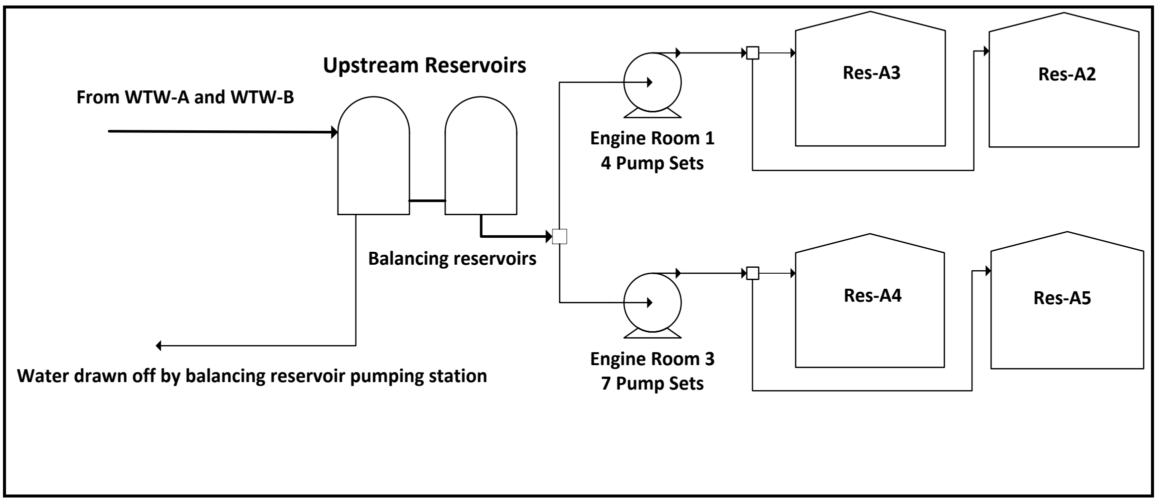


Figure 29: BPS-A simplified integrated layout

Figure 29 indicates each engine room using a pump symbol with a description including the number of pump sets in the engine room. The water intake as well as the water outlet is shown on the figure. Both the upstream and downstream reservoirs are indicated on the station-specific layout. It is important to note that at this pumping station water is drawn off by the balancing reservoir pumping station, before the water reaches BPS-A.

Demand

It was found during the investigation that the control philosophy of the WDU was based on the distribution reservoir level. Every eight hours a new water pumping target was calculated based on the distribution reservoir levels. This was the same for all of the BPS's distribution reservoirs. The distribution reservoir levels had to be maintained between 60–80%.

The influential reservoirs for the demand on the BPS-A system were Res-A2, Res-A3, Res-A4 and Res-A5. The client demand out of these reservoirs would, therefore, have the primary influence on the amount of water that needed to be pumped at the BPS.

Table 6 shows the demand calculated from historical data for the four distribution reservoirs that BPS-A supplied of water. The demand was calculated for four demand seasons. The demand is given in total flow (ℓ/s).

Table 6: Reservoir demands for BPS-A distribution reservoirs

		Res-A3	Res-A2	Res-A4	Res-A5
Summer	**Average**	**1 477.82**	**1 952.06**	**1 257.26**	**1 152.02**
	Maximum	1 911.11	3 030.09	1 967.59	2 018.75
	Minimum	1 206.94	552.08	196.76	134.26
Autumn	**Average**	**1 444.38**	**1 793.55**	**1 080.84**	**954.90**
	Maximum	1 911.11	2 599.54	2 175.93	1 356.48
	Minimum	801.39	1 281.25	254.63	567.13
Winter	**Average**	**1 443.65**	**1 558.43**	**783.33**	**1 045.32**
	Maximum	1 822.69	1 805.56	1 342.59	1 437.50
	Minimum	1 235.65	1 142.36	381.94	627.31
Spring	**Average**	**1 604.55**	**1 895.38**	**1 355.17**	**1 236.22**
	Maximum	2 050.00	2 310.19	2 071.76	1 629.63
	Minimum	1 243.98	1 511.57	625.00	791.67

3.4.3 WDU integrated layout

Figure 30 represents the integrated WDU-A layout. In this layout, all the subsystems with the BPSs and the reservoirs are included. The four blocks outline the four subsystems with their pumping stations, demand-balancing reservoirs and distribution reservoirs.

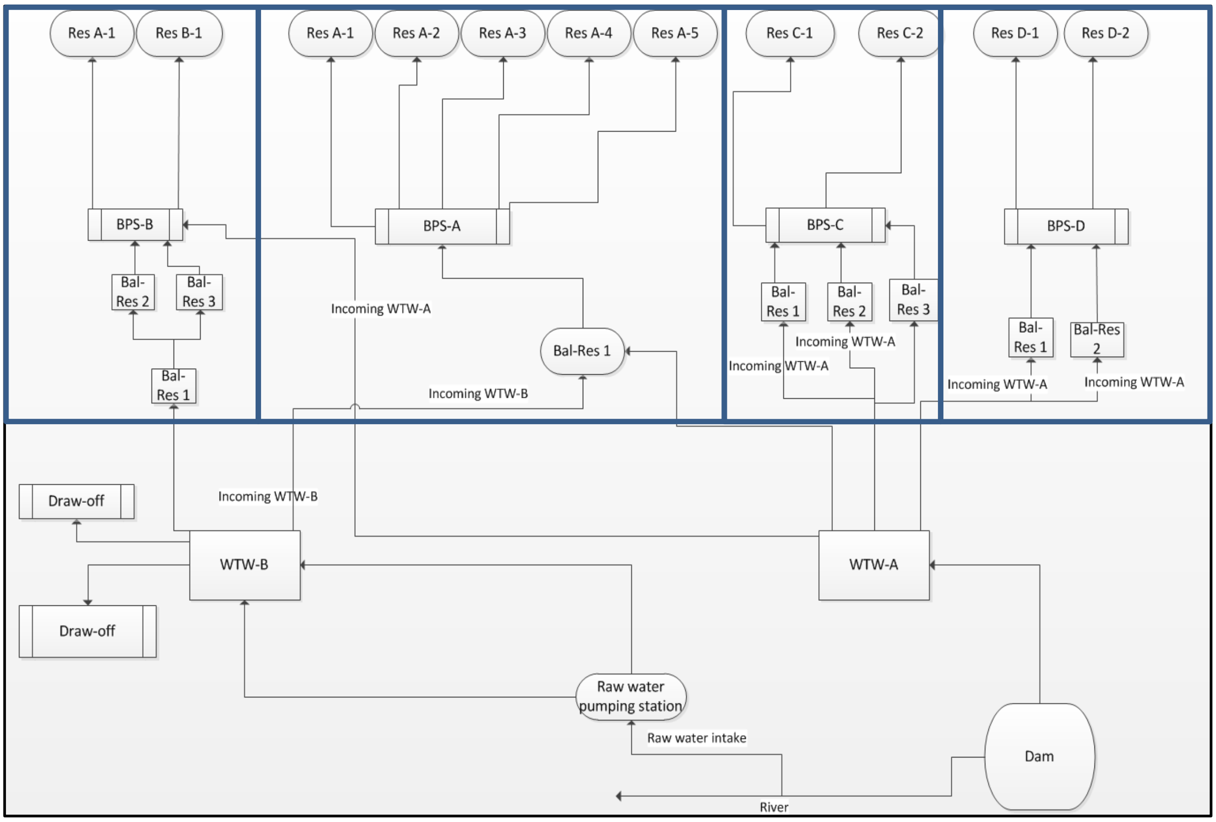


Figure 30: Integrated WDU-A network

3.5 Analysis of current operational philosophy

From the investigation, it is known that the utility has six main pumping stations. These pumping stations use the majority of the electricity on the WDU. It is important to understand how the specific WDU is operated in order to know how to implement the cost saving intervention.

3.5.1 Current control of the WDU – Holistic

The water treatment works supply the four BPSs in the four subsystems with potable water and from there it is distributed throughout the systems. Water is pumped to the distribution reservoirs from where it is distributed to the clients.

Distribution of water is either gravity-fed or pump-delivered. In the case of WDU-A, the clients are mostly smaller municipal reservoirs in the different municipal zones. Different municipalities buy the water from WDU-A, and it is their responsibility to distribute it to the users. The WDU, therefore, ends when it reaches the municipal reservoirs.

Current control is done holistically based on the following elements:

- ‘Daily call’;
- Voice communication;
- Distribution reservoir levels (60–80%) and demand-balancing reservoirs (40-80%);
- Pumping station-specific knowledge; and
- Central control of water flow.

Each of the pumping stations in the WDU is controlled separately. All operations are manual, and each pumping station is operated as a single entity. The communication between different pumping stations is via voice communication. Each pumping station receives a ‘daily call’ to pump. It is a target that the specific pumping station needs to pump in terms of potable water. These targets are relayed separately to all the relevant pumping stations. Figure 31 is a schematic representation of the current control operations.

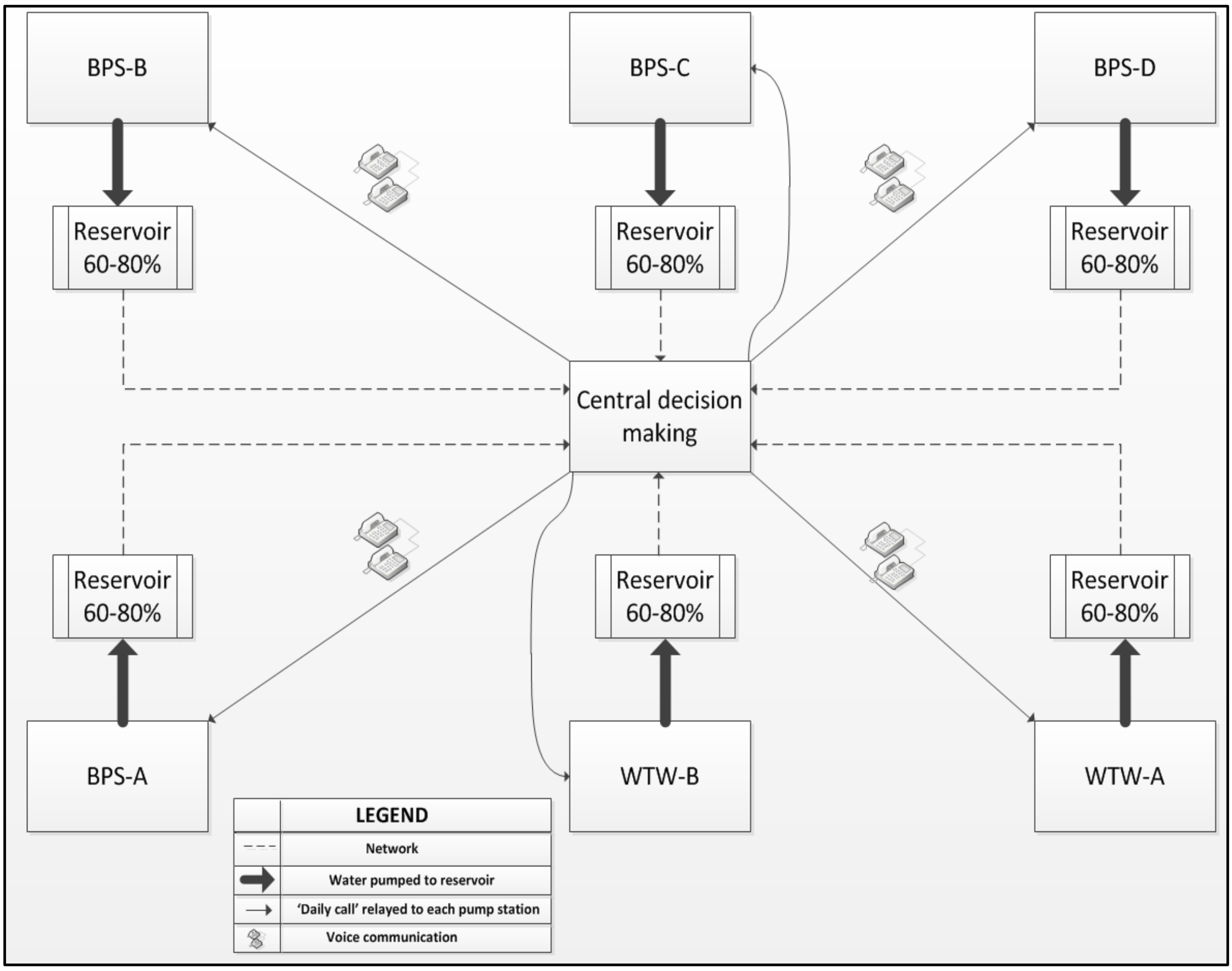


Figure 31: Current control operations on WDU-A

The target that the pumping station needs to pump is calculated using the distribution reservoir levels and the demand thereof (generally referred to as reservoir in Figure 31). The distribution reservoirs need to be maintained at a level between 60–80% of the allowed maximum as indicated in Figure 31. The target is adjusted according to the surplus or deficit of water.

This target is in Ml/day; this is the target that needs to be pumped to the distribution reservoir per day. It can be adjusted every 12 hours except when a drastic situation occurs. The reservoir readings are recorded every eight hours. The readings are sent to bulk water distribution where the daily targets are calculated.

Bulk water distribution also controls the flow of water. The pipelines in the WDU are interconnected at strategic places and equipped with valves. They are controlled from bulk water distribution and the destination of the water can change. The destination from the BPSs to specific distribution reservoirs can also change if necessary. If one of the reservoirs reaches its limits, the water can be drawn to a reservoir with a low water level.

In the WDU, each pumping station's operations team only knows what is happening at their specific pumping station. They cannot view other pumping stations. They also do not know the amount of water pumped from the other pumping stations in real time.

The distribution reservoir level, to which the pumping station pumps, is visible and known to that specific pumping station's operations team. But, the pumping station only reports the amount of water that is pumped at pre-set times. There is no knowledge of the WDU as an integrated utility. Each pumping station's operations team only focuses on controlling their pumps to meet the target.

3.5.2 Current control of the WDU – Locally

The following aspects form the basis of local control on the pumping stations in the WDU:

- Number of pumps matching the 'daily call';
- Balancing reservoirs handling inconsistent flow of water and reservoir control;
- Manual control from the PLC; and
- Manual readings.

The pumping station operator uses the target received from bulk water distribution to operate the pumps. The number of pumps running is directly equal to the target. The balancing reservoirs on the BPS sites are only used to handle the amount of water received and for emergencies such as pump or station trips.

The BPSs use balancing reservoir control when necessary. If more water reaches the pumping station than it needs to pump according to the target, then a balancing reservoir fills up. More pumps can be switched on to avoid the reservoir overflowing. This is called reservoir control.

Each of the pump sets at the engine rooms was controlled separately with a PLC equipped with a human machine interface (HMI). In some cases the SCADA was not functioning correctly, or it was not installed on all of the pumping stations. This resulted in data that was not readily available for use. The pumps were not controlled automatically and data not logged. Important data such as kWh, flow and pressures were obtained by personnel on-site with readings taken from HMIs. Hourly readings were taken using applicable instrumentation.

3.5.3 Constraints in the current control for integration of the WDU

As described already, there are definite control constraints with the current philosophy. The major constraint is that each pumping station operates on its own and not as part of an integrated system. During the investigation, it was found that it is an integrated system with pumping stations dependent on each other as well as the destination to where it is pumping.

The following points are a summary of the major constraints holistically and locally which will be elaborated in this section:

- Pumping station-specific control;
- Miscommunication;
- No centralised control, only decision making;
- No real-time monitoring of the WDU at the pumping stations; and
- Tariff structures and pumping optimisation not included in current control strategy.

The current strategy does not allow for real-time control of the WDU as a whole. Because all the communication is via voice communication, there is a time-lapse when reacting to information being relayed. This time-lapse may cause the WDU to operate suboptimally. If there is a station trip at one of the water treatment works, it may take time before it is communicated to the affected BPS, or the other way round. This may result in the distribution reservoir level dropping.

Lack of centralised control and real-time monitoring result in miscommunication and pump orders not being followed. The lack of displayed information is also a constraint that can lead to ineffective control. This may have an impact on the whole WDU, with more than one pumping station affected.

Because pumps are operated manually, there is no real-time monitoring of the pumps and other related instrumentation. This results in flow, pressure, power and efficiencies data from individual pump sets not being readily available. If all the information is available, a calculated decision can be made regarding which pumps to run. The most inefficient pump can be switched off and more efficient pumps can be operated and started. Real-time data and monitoring of pumps will also identify faulty equipment and precautions can be made to prevent damage.

There is no real-time control with the distribution reservoir as a constraint. The demand out of the reservoir is also not measured in real time. All of the distribution reservoirs have large capacities, and it takes time to see the effect of a higher or lower demand on the reservoir. The target that needs to be pumped at the engine room is only calculated every 12 hours. This time-lapse between static calculations can result in reservoir levels rising above the constraint level and also dropping below the constraint levels.

The current control philosophy makes it difficult to incorporate a load shift. A load shift will influence the WDU as a whole. If the water load is reduced on one pumping station, it will affect another pumping station. It will also affect the WDU when the water load is recovered, and more pumps have to be run. The reservoirs, both balancing and distribution, will also be affected by such a DSM intervention.

The current control philosophy does not take the tariff structures off the different pumping stations into account. As discussed in Section 3.2, there are different tariff structures that influence the cost of pumping. With optimised control, the largest amount of water can be shifted at the lowest costs.

3.6 Proposed control strategy for a water distribution utility

In the previous section, the shortcomings of the WDU-A control philosophy were discussed. In this section, the proposed control philosophy will be discussed in detail, stating a solution to integrate an electricity cost saving intervention on a WDU.

3.6.1 Integration of a WDU

The method proposed in this dissertation is to integrate the WDU as a whole. Instead of taking each pumping station as an individual element in the system, they need to be integrated. The integrated water distribution utility is presented as a simplified mass balance. The mass balance equation is as follows:

- Input + generation = output + consumption (Eq. 2)

Assumptions: The balance is on nonreactive species and total mass. This means that the generation and consumption terms equal zero. It is assumed that there is no water accumulated through the network and no consumption before the distribution reservoirs. The two approaches can now be simplified into:

- Each pump station separately with local control; and
- Integrated control of the WDU.

The first approach states the current control philosophy of WDU-A. The second approach is the proposed method of control. Figure 32 gives a simple representation of the proposed integrated control. There are three scenarios sketched for the model on a simplified WDU. The proposed approach is indicated on the right with a checkmark.

To sum up the proposed integrated control approach; the whole network will be operated and optimised as an integrated WDU network. This means that it will be connected from the water treatment works through the BPS to the distribution reservoirs.

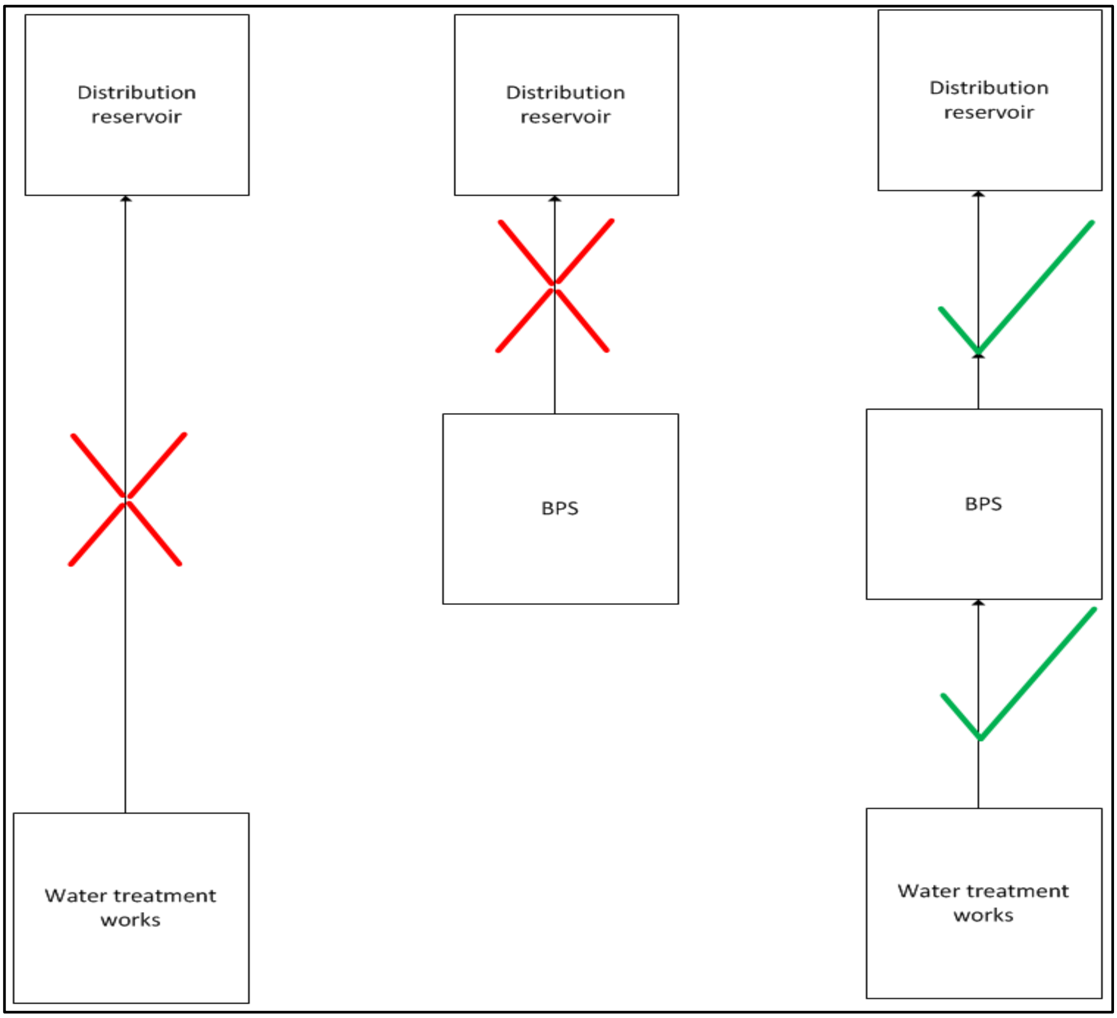


Figure 32: Proposed integrated control approach

This approach makes it possible to implement an electricity cost saving intervention. All the elements that are affected by implementing load shifting on the WDU are integrated into one strategy. Taking the WDU as a mass balance, the complicated network can be simplified.

The focus is on shifting the water from the water treatment works through to the distribution reservoirs. The following points state the important factors influencing the load shifting and form the basis of the control strategy:

- Pumping station;
- Demand-balancing reservoirs;
- Distribution reservoirs;
- Communication;
- Demand; and
- Tariff structures.

All of the above were part of the investigation methodology and now form part of the proposed strategy. It will be discussed in short below as part of the proposed strategy and the incentive to implement load shifting.

Pump station

Load shifting needs to take place simultaneously at the BPSs and the water treatment works. One pumping station affects another pumping station. For instance, the water treatment works will always be affected when load shifting takes place at a BPS, and the other way around. This is if demand-balancing reservoirs are not used as system capacitance for load shifting.

Using the simplified mass-balance equation, the effect of this load shifting in terms of water loss and gain can be calculated. With an integrated approach this equation can be satisfied easily without demand-balancing reservoirs in the WDU.

Demand-balancing reservoirs

Demand-balancing reservoirs are located on-site as discussed in Section 3.4. The balancing reservoirs form part of the integrated strategy. They function as buffers to absorb excess water from the water treatment works. In the integrated strategy, the balancing reservoirs will serve as backup and redundancy if load shifting cannot take place at the water treatment works. Load shifting can then continue to the BPSs even though the water treatment works are not load shifted. Water from the water treatment works can be absorbed in the balancing reservoirs during the two hours of load shifting.

The other way around, if the water treatment works cannot pump due to a breakdown or other process constraints, the BPSs have limited water in their balancing reservoirs. The BPSs can still continue pumping for a period of time. The size of the balancing reservoirs on-site will influence the amount of water that can be absorbed. To summarise, the balancing reservoirs can assist in load shifting if the water treatment works cannot participate in a load shift.

Distribution reservoirs

The distribution reservoirs are dependent on potable water from the BPSs. The distribution reservoirs are the final component in the mass balance of the process. It is the point where the water leaves the process. The outflow needs to match the inflow of the process. The amount of water flowing out of the reservoir due to demand needs to match water flowing into the reservoir. This water ultimately needs to be matched with the amount of water entering the process at the water treatment works.

The whole WDU needs to be integrated to satisfy the system mass balance. Even with the water treatment works not taking part in the integrated strategy for load shifting, it is important to know the availability of potable water in the system. The distribution reservoirs will, therefore, directly influence load shifting. The whole process mass balance needs to be satisfied. The distribution reservoirs are a constraint with the level of water in the reservoir that needs to be satisfied.

Demand

The demands form a critical part of the strategy. The demands influence the reservoir level. As demand varies, the reservoir level will drop or rise. It will then influence the whole WDU from the distribution reservoir down to the water treatment works. It plays an important role in the potential for load shifting.

Tariff structures

Tariff structures play an integral part of the WDU and the strategy for the integration of electricity cost saving intervention. With different tariff structures for different pumping stations, it will be better if more water is pumped from the pumping station with the lowest R/kWh tariff. This will only happen when the pumping station has spare capacity to pump more water and to take load from the station with the higher tariff rate.

3.6.2 Control strategy conclusion

With the important elements identified, the distribution reservoirs are the constraints in the WDU. The goal of the strategy is to satisfy the distribution reservoir constraints. This goal fits the mass-balance equation. This strategy uses the water target, set by WDU-A, as a minimum constraint in the strategy. Therefore, there will be no change in the amount of water pumped to the distribution reservoirs.

The implementation of this strategy will not result in automated control of the pumps. It is merely a tool for the operations personnel to make calculated decisions regarding load shifting. To test the feasibility of the strategy, a simulation package was used to develop an optimised integrated model.

3.7 Conclusion

Chapter 3 focused on the strategy for the integration of an electricity cost saving intervention on a WDU. It was emphasised that investigation was important. An investigation methodology was developed for a WDU. It was discussed how the data and a baseline was obtained.

In this chapter, WDU-A was introduced and the investigation methodology was applied in order to obtain the necessary information to develop the cost saving strategy.

The WDU under investigation was analysed to identify the current control strategy of the WDU and the shortcomings thereof. Finally, Chapter 3 concluded with the proposed control strategy for the integration of electricity cost saving interventions.

4 Optimisation and results

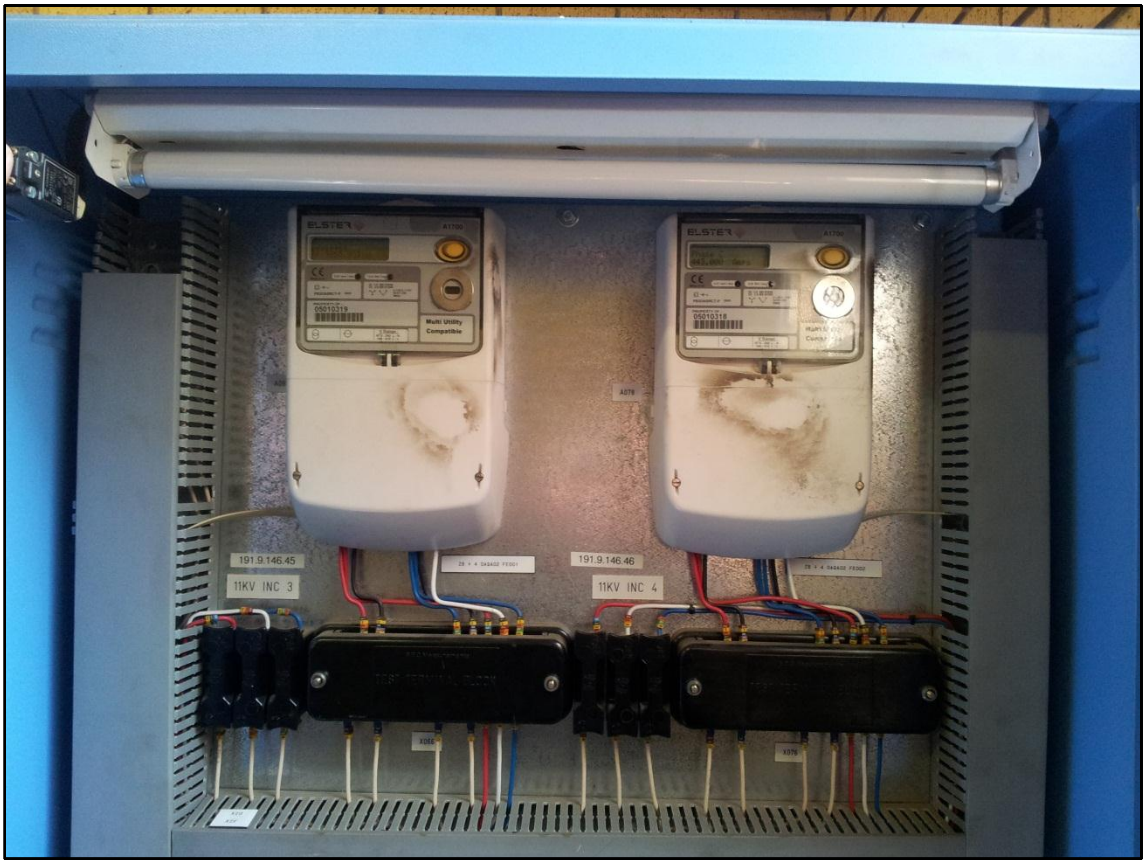


Figure 33: MOL panel with the mounted meters

MOL was used for the gathering of data to test the optimisation model.

4.1 Introduction

The optimisation model is an important step in the implementation and integration of an electricity cost saving intervention. It is used to study the opportunities for an electricity cost saving intervention on a WDU. In the previous sections it was explained that before the WDU can be simulated, a detailed investigation is needed.

After the investigation, the complex integrated network with all the equipment shall be known. The layout of the network will also be understood. The model is based on the control strategy proposed in Section 3.6. It will be tested with the model using all the important factors as stated. The goal of the model is to integrate the WDU into one optimised model to obtain the maximum electricity cost savings.

4.2 Process Toolbox modelling system

The core of the Process Toolbox (PTB) modelling system that operates within the larger computerised system is shown in Figure 34. Various characteristics have an influence on electricity consumption. In most cases, these are either directly or indirectly linked to the operation of the plant (discussed in Chapter 3). The modelling system, therefore, reflects various constraints that are integrated during modelling.

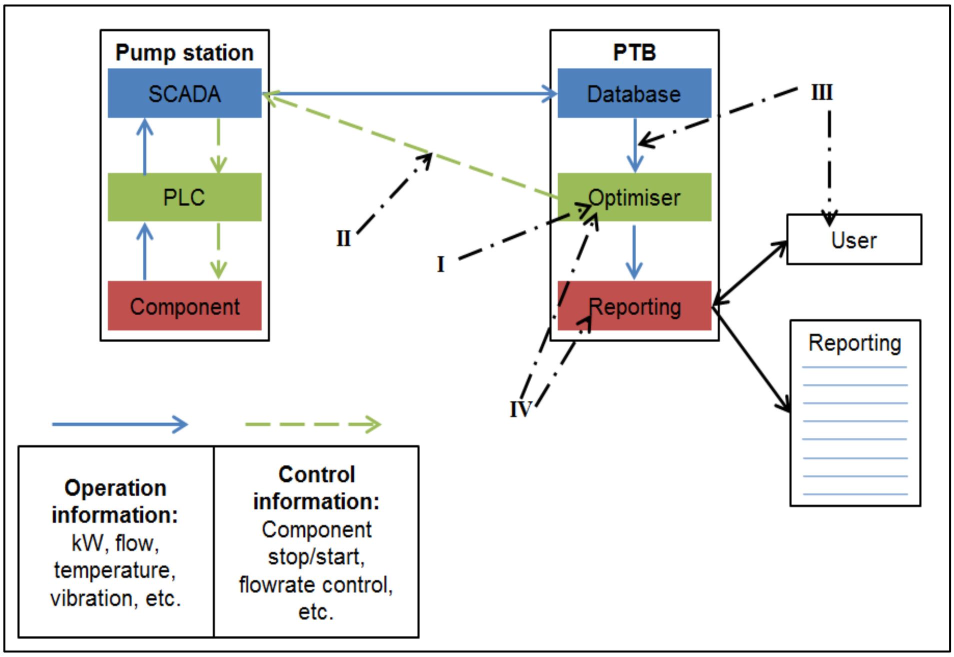


Figure 34: System communication layout

Various physical components and different pumping stations are integrated and modelled simultaneously in the simulation model. This allows for accurate prediction of the influences that different components have on the pumping network system and the final water distribution.

These components include pumps, line friction, static head and auxiliary components. They are essentially and functionally different, but are linked by the flow rates and electricity costs sustained during pumping. Using these two modelling properties – volumes pumped and cost – the components are integrated into a single, consolidated model. This allows for easy analysis of the influences these components have on the complete system.

To be able to construct an integrated model, the constraints of these components have been incorporated into the system. These include the daily constraints of the specific components, such as rate of pumping (constant or variable) and energy requirements.

This allows the integrated model to be a powerful tool that contributes significantly to accurately predicting and achieving the pumping system's potential cost and energy savings. The integrated simulation model does not only analyse the specific cost component (cost per litre pumped) but also optimises the total cost.

The developed system is dependent on accurate plant characteristics, which include component pumping rates, reservoir capacities, delivery targets, and so forth. This system is able to revise pumping automatically for a more accurate simulation. With the improved accuracy of the operations model, forecasting and prediction of pumping system characteristics (such as reservoir levels, distribution requirements, acquisition volumes and electricity requirements) are always available.

4.3 Model development

The proposed control strategy is used as basis for the development of the model. It is important to understand the WDU in detail. This was done during the investigation phase of the study. The information needed to start developing the model was:

- Data; and
- Layouts.

The layouts obtained in Section 3.4 were used to build the WDU model. It is important to know which data was specifically required. Table 7 indicates which data was required for the building of the model of a typical WDU.

Table 7: Data required for optimisation model

Data required	Description	Unit
Reservoir demand	Amount of water drawn from the distribution reservoir	Flow (ℓ/s)
Distribution reservoir	The total water capacity of the distribution reservoir	Volume (m^3)
Balancing reservoir	The total water capacity of the balancing reservoir	Volume (m^3)
Pump flow rating	The specific pump water flow rate	Flow (ℓ/s)
Pump motor power reading	The electrical absorbed power of the pump motor	Power (kW)
Pump efficiency rating	The pump efficiency	Percentage (%)
Pump motor efficiency rating	The pump motor efficiency	Percentage (%)
Pump elevation	Height to which pump is pumping	Height (m)
Pump schedule	Typical daily profile of a pump	Fraction

With both the data obtained and the layout understood it was possible to build the model. All the data was gathered from site investigations and MOL data (energy data) during the investigation phase.

It was already known that the WDU consisted of four subsystems. It was identified that each of the subsystems could implement an electricity cost saving separately. This was possible with buffer capacity available from the demand-balancing reservoirs. A separate simulation was built for each of the subsystems and implemented on the real-life WDU. It was an integrated approach implemented separately on the four subsystems. If the load shift was possible on the four subsystems, it could be quantified to one integrated simulation model.

A number of constraints were identified for the optimisation model (Table 8). These constraints needed to be satisfied in order for the model to be feasible. Constraints listed were all site-specific. The constraints were common to all the pumping stations in WDU-A.

Figure 35 is a summary of the four model levels that form the building blocks for the model. The development of the model will be discussed further later in this section.

Table 8: List of constraints

No.	Constraint
1	Dam levels (distribution and balancing)
2	Pump water capacity
3	Water source
4	Client water demand

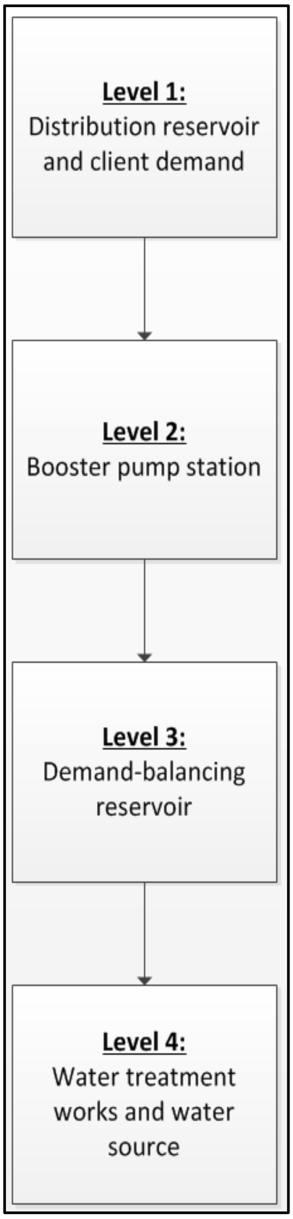


Figure 35: Summary of integrated optimisation model

Distribution reservoir and demand

As discussed in the previous section, the distribution reservoir had to meet its constraints. As shown in Figure 38, the reservoir had to be sustained between specified levels (60–80%). There are two factors that influence the water level in a reservoir; the demand out of the reservoir as well as the water supplied. For the purpose of the model and optimisation, the demand was given as a fixed value for a demand season.

At the time when this dissertation was written, there was no knowledge of the specific reservoir demands of the real-life WDU. The outgoing lines from the distribution reservoirs were not equipped with flow meters. A fixed demand was calculated using a mass-balance equation on the distribution reservoirs.

The daily targets pumped from the BPSs, the sizes of the reservoirs and the volumes were used to calculate the demand. The daily targets were limited in number of readings per day and, therefore, no dynamic calculation was done and only fixed values were calculated. The assumption was made that the water density stayed 100 kg/m^3 throughout for the distribution reservoir (water dam component).

The demands were simulated with a valve which was scheduled as 'open'. From the valve the water flowed into a water sink which simulated the end of the process. The water into the distribution reservoir was supplied from the feeding BPS. The distribution reservoir with the demand out was the first step in the model. It was, therefore, referred to as the first level (Figure 35).

Figure 36 represents the first level of the model with the reservoir; valve and water sink from top to bottom. The level is indicated with a red block on the figure. Figure 37 shows the inputs required for simulation of the reservoir in the integrated WDU model.

For the simulation of the WDU it was assumed that the heat transfer coefficient and surface area could be ignored. This assumption could be made because the model was a mass balance with no generation or consumption within the process and no mixing of species occurred. It is a water mass balance in a closed system. The initial temperature and ambient temperature were set according to the average ambient temperature in the province WDU-A was located in. The only values that needed to be specified were:

- Reservoir volume; and
- Initial reservoir level.

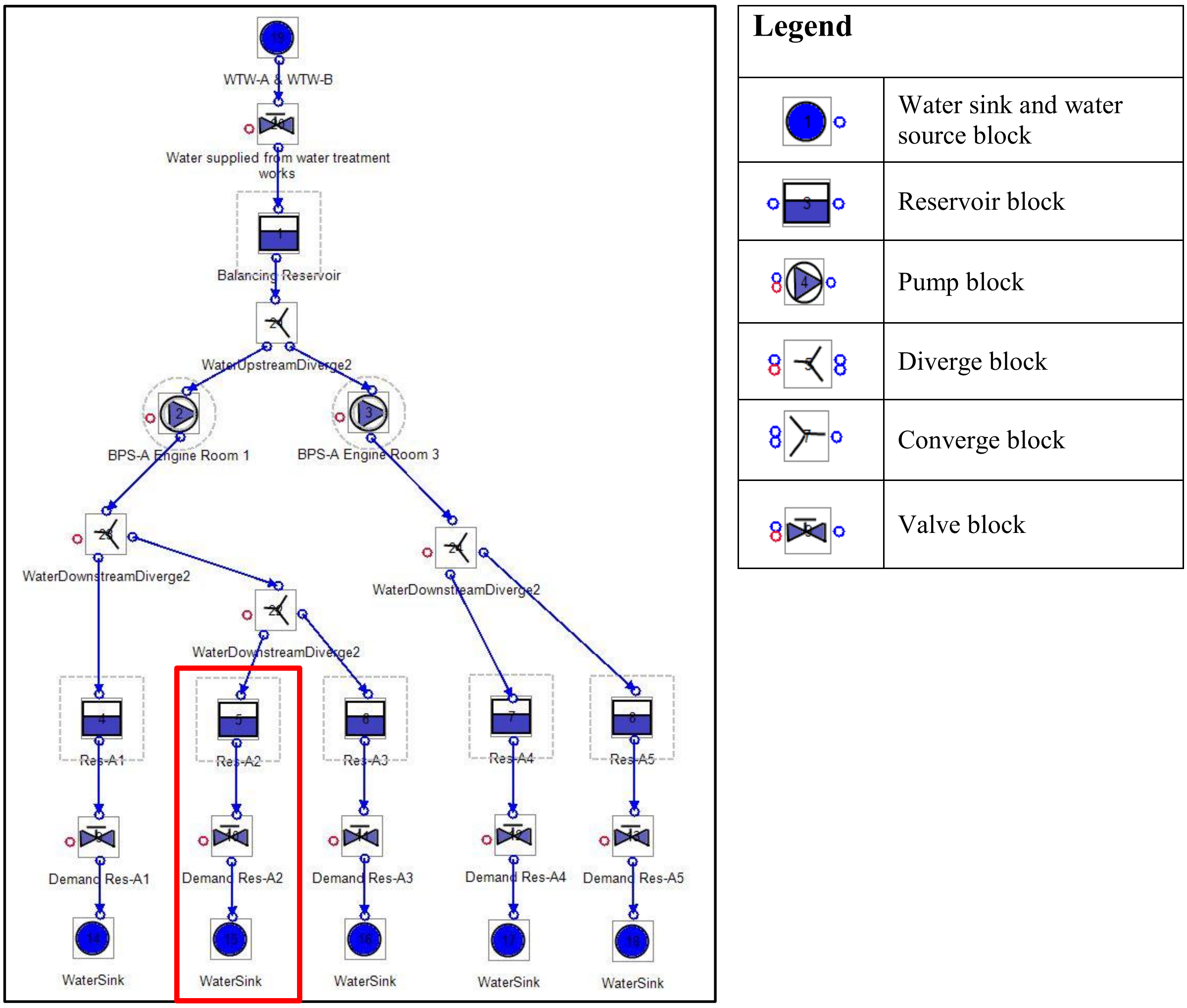


Figure 36: First level of the model

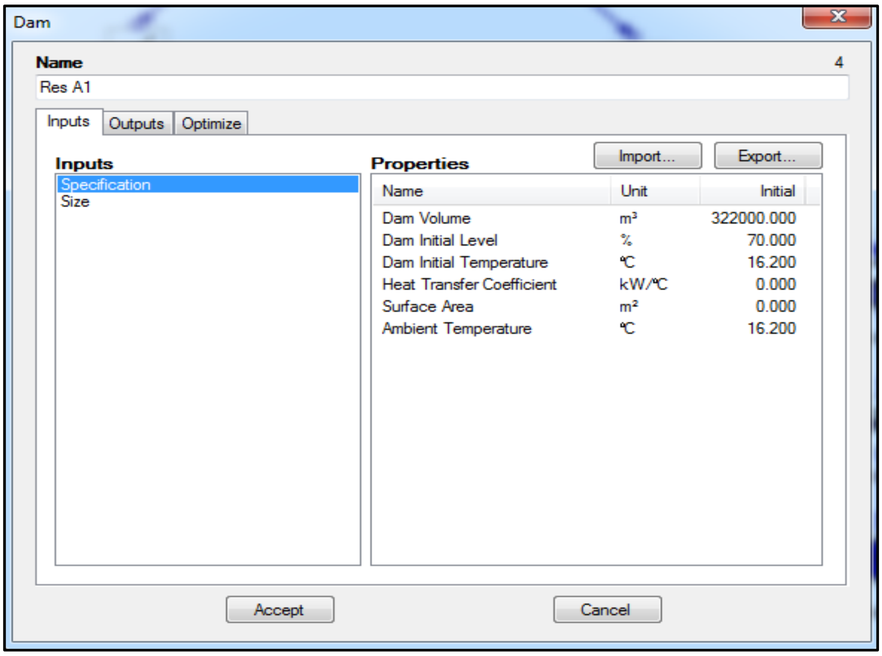


Figure 37: Reservoir inputs

Figure 38 shows the constraints as entered for the optimisation model integrating the distribution reservoir. It was the same for all the distribution reservoirs in the WDU. The reservoir level needed to be maintained between 60–80%.

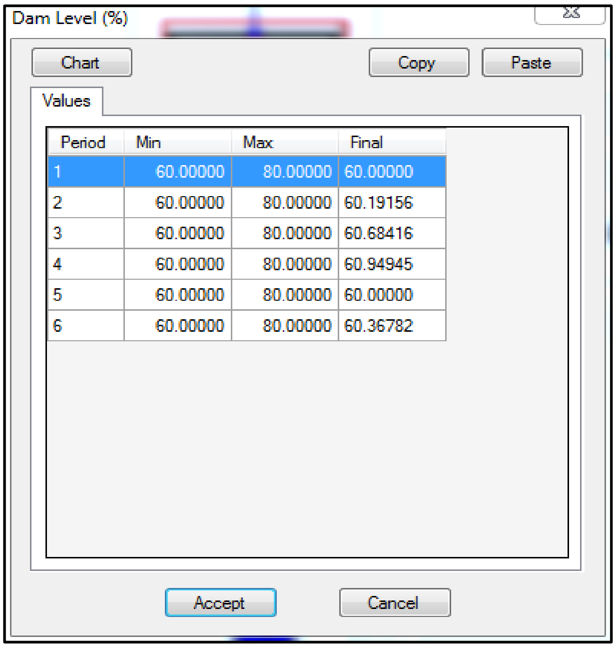


Figure 38: Dam level constraint for optimisation

Figure 39 specifies the inputs required to simulate the valve that served as the client demand for the WDU model.

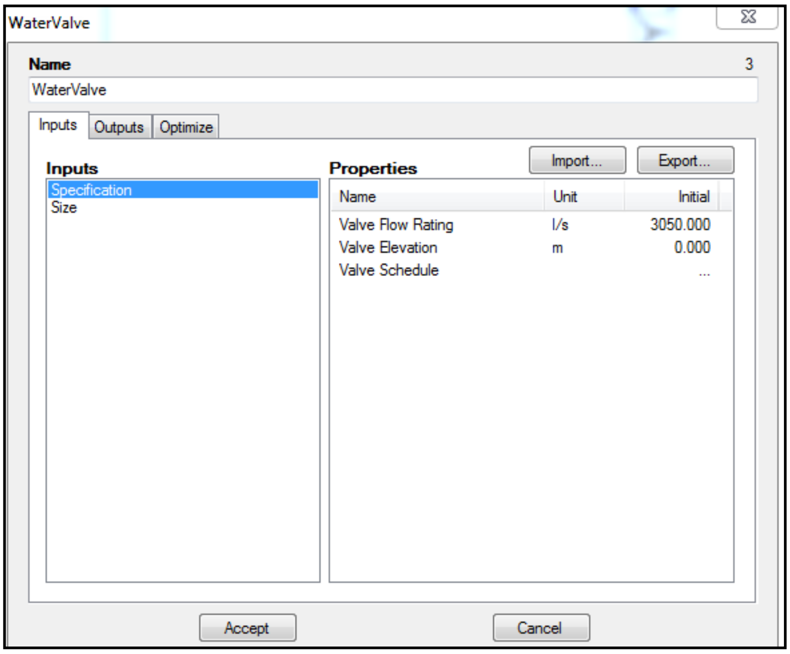


Figure 39: Valve inputs

For the WDU optimisation model, the only required fields were the valve flow rating and the valve schedule. The valve schedule would be the same for each time interval, which was a value of 1 for a fully open valve (Figure 40), otherwise it would be a fraction of 1. The reason for the value being set to 1 was that the valve had to be open to represent the fixed client demand.

No inputs were required for the water sink. It only served as the end of the process. The assumption was made that within a specific demand season, there would be no dynamic demand variations. The reason for this assumption was explained earlier in this section.

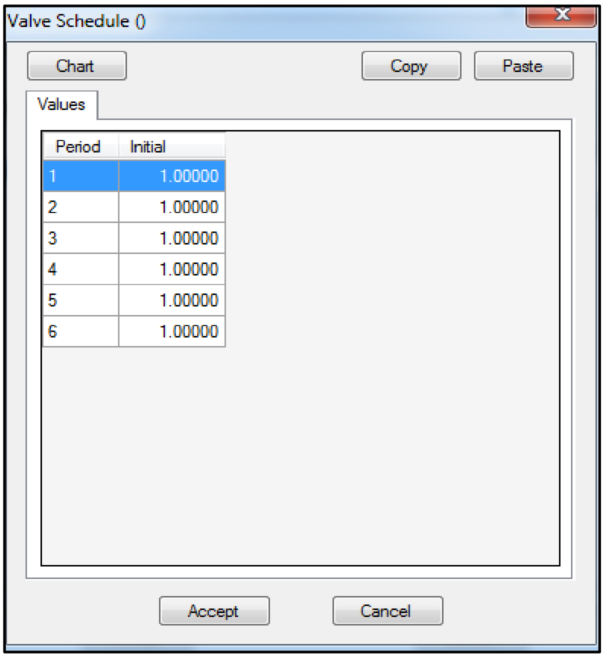
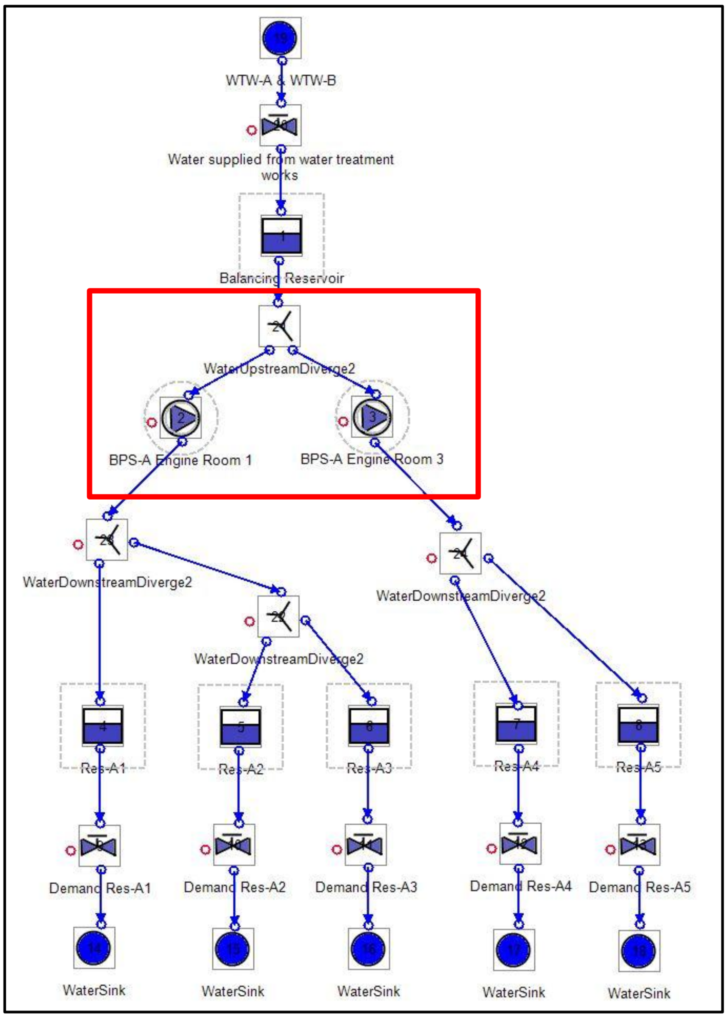


Figure 40: Valve schedule simulating water demand in the model

Booster pumping stations

The BPSs formed the second level of the model. It followed the distribution reservoirs and demand. The BPSs supplied the first level of the model with water. The minimum water that needed to be pumped from the BPSs depended on the first level of the model. The BPSs extracted water from balancing reservoirs which were directly filled with water from the water treatment works.

The second level of the model, consisting of BPSs, is indicated with a red block in Figure 41. An upstream diverge function block is also visible in Figure 41. Its function was to split one stream into two streams. Due to the size of a WDU and the number of pumps, certain pumps were grouped together to simplify the simulation. This assumption could be made due to the fact that several pump sets pumped together to a specific distribution reservoir.



Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

Figure 41: Second level of the model

The implication of this grouping of pumps was that pump-specific efficiency, pressures and flows could not be calculated. For this study it was not important since the goal was to calculate if and where there was capacity to switch off pumps during the Eskom peak tariff period and to verify the proposed strategy.

Figure 42 shows the inputs required to simulate the pumps. This was not only applicable to simulating the booster station pumps but also to the simulation of the water treatment works pumps as well. All the pumps used the same applicable assumptions for the optimisation model.

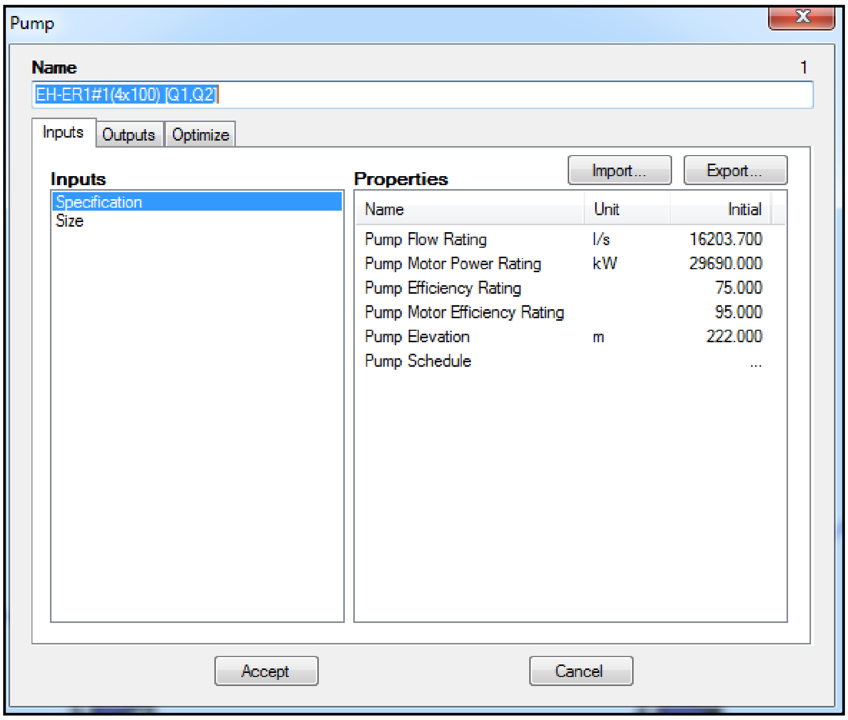


Figure 42: Pump inputs

All of the inputs specified were needed for the WDU optimisation. The following assumptions were made regarding the pump inputs:

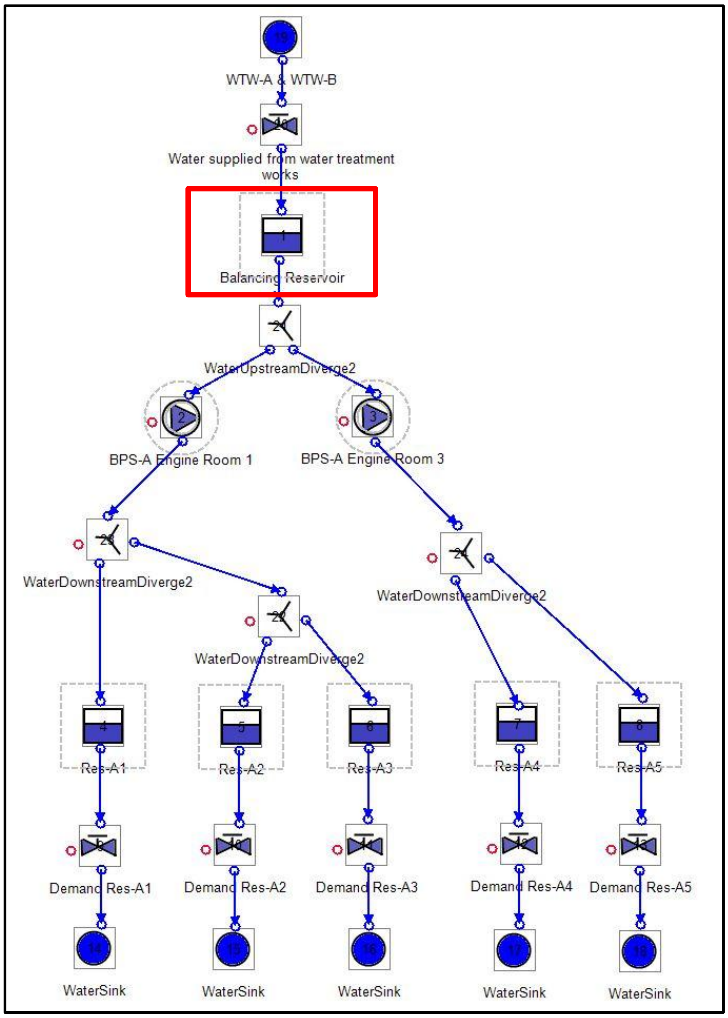
The pump efficiency rating would always be 75%, which was a good approximation. The pump motor efficiency rating would always be used as 95%. It would be more accurate to have three pressure readings and three flow readings on the pumps. It could be then calculated with a quadratic curve fit what the pump efficient fraction was. The data, however, was not available at the time of writing. The upstream diverge did not require any inputs.

Balancing reservoirs

Balancing reservoirs are the third level of the model. The balancing reservoirs in actual circumstances served as balance for excess water or shortage of water. The pumps received the water from direct pipeline surge. For the purpose of simulating the WDU, the balancing reservoirs were simulated in line with the pump sets since it formed part of the integrated strategy. This meant that the water flowed via the balancing reservoirs to the booster pumps.

The whole station was seen as a single entity. The amount of water entering would either be pumped away or accumulated in the balancing reservoir and pumped away at a later stage. There was no generation of water mass in the system after the water treatment works. It was only stored in the balancing reservoirs to be pumped onwards at a later stage. The constraint for the balancing reservoirs is the water level that needs to be kept between 40-80%. The lower level limit is 20% lower than is the case with the distribution reservoirs.

Figure 43 represents the third level of the simulation model, which only consists of the on-site demand-balancing reservoir. For the implementation of an electricity cost saving intervention, this is an important level. The balancing reservoirs serve as buffer capacity in the network and can be used for load shifting purposes.



Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

Figure 43: Third level of the model

The inputs for the balancing reservoirs in the model were the same as the inputs for the distribution reservoirs. Both of these were simulated as dams in the model. Refer to the paragraph on distribution reservoirs for required inputs and assumptions.

Water treatment works and water source

The water treatment works together with the water source completed the fourth level of the simulation model. This was where raw water was purified to potable water standard and was the start of the integrated process. The water source could be a dam or a river. The pumps at the water treatment works were also grouped into pump sets pumping to the same BPS.

The water treatment works were the input of water mass to the system. This together with the demand formed the boundaries of the process and the model. Figure 44 represents the fourth level of the model which consisted of the water source, water treatment works pumps and the downstream converge from top to bottom. The fourth level is indicated with two red blocks.

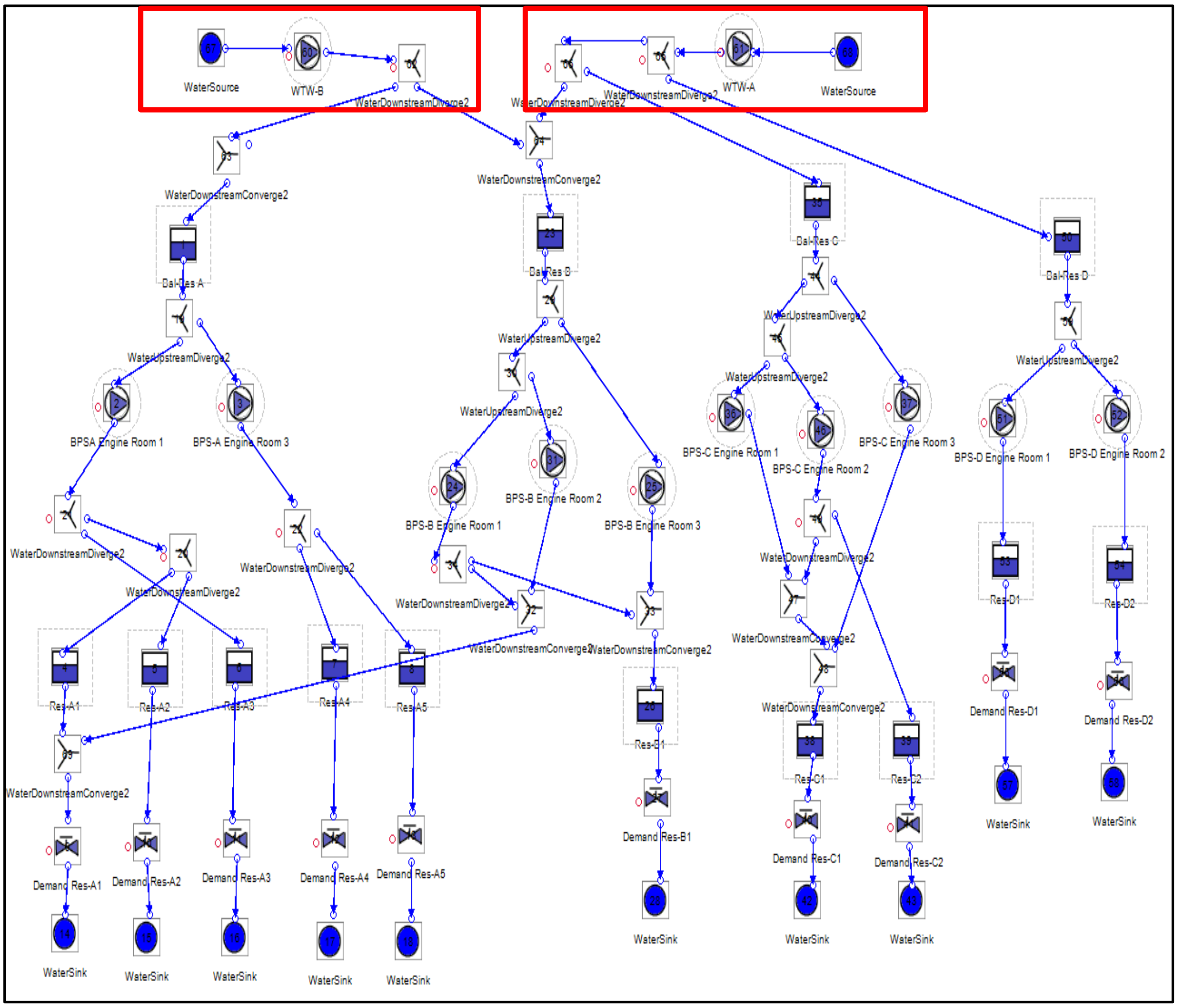


Figure 44: Fourth level of the model

Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

The downstream converge connected two incoming streams. It added the values from the two separate streams to give one output. The inputs for the water treatment works pumps were exactly the same as for the BPS pumps. The water source required no inputs and was assumed to be infinitely large with an infinite amount of water. The downstream converge also did not require any inputs. It only added two incoming flow rates. The fourth level would change with the modelling of the subsystems giving a fixed supply from the water treatment works. Figure 45 presents the change indicated with a red block.

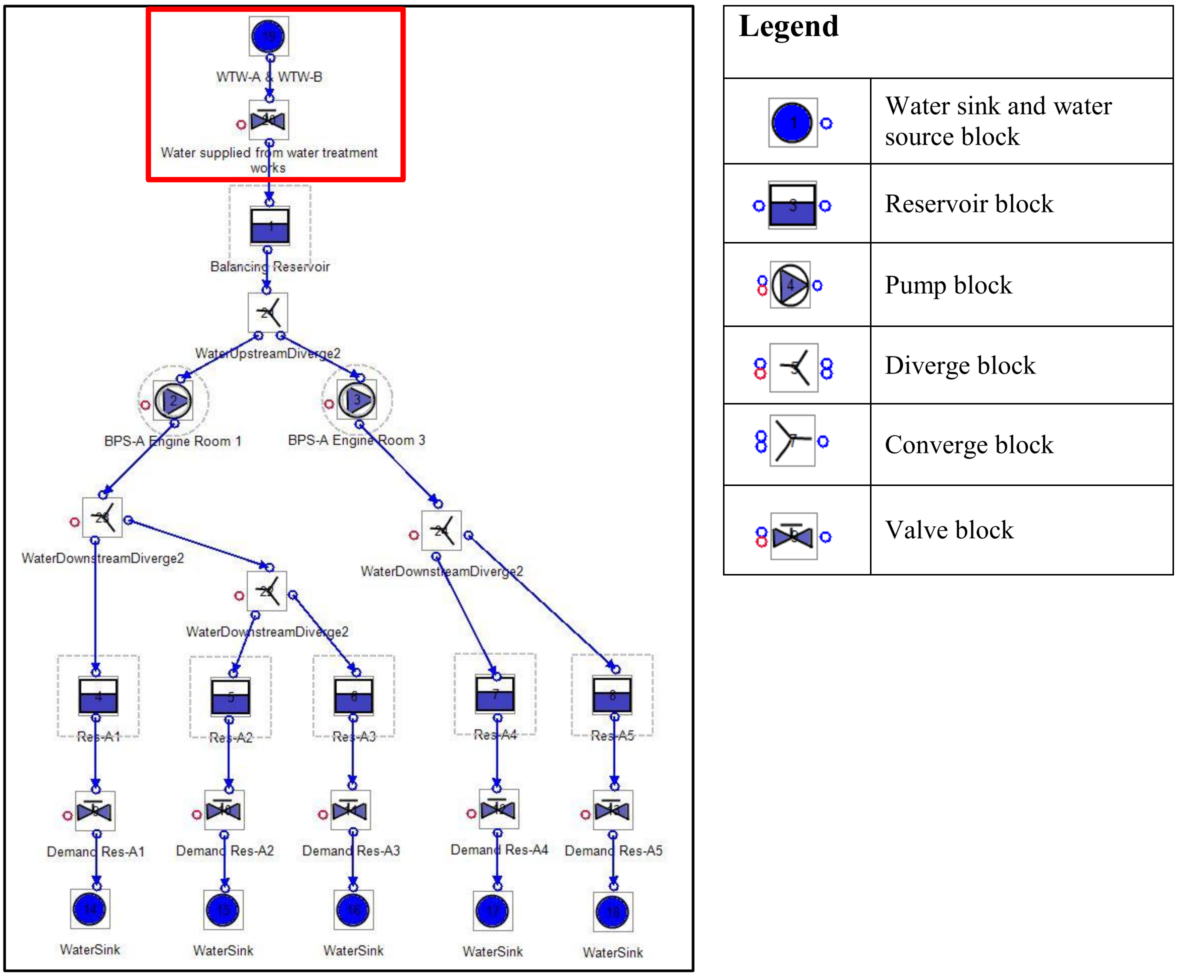


Figure 45: Fourth level of the simulation change – Fixed supply

Using the four levels is a simplified method to base the simulation and optimisation on for any WDU. It is a holistic and integrated approach to optimise a complex WDU and to simulate whether electricity cost savings can be obtained from implementing load shifting.

4.4 Optimisation

The purpose of optimisation was to control the operation in order to minimise total pumping cost and, in doing so, to minimise energy consumption during the peak Eskom periods. To do this, the model used an iterative optimiser that, whilst taking all the variables into account, iterated the operation of the components to obtain the most cost effective solution.

A solver was used for the optimisation. It optimised a specified objective value for steady-state systems taking all the optimisation variables and constraints for any number of time periods and period size into account. The system component inputs, optimisation variables, optimisation constraints and outputs automatically expanded to match the number of time periods.

The model was optimised for a typical day in a specific demand month. It was simulated using six different time periods. The six different time periods were adapted from the Eskom TOU tariff structure (refer to Section 1.3.1). Table 9 shows the different time periods as well as the time period size.

Table 9: Time period, duration and size of the tariff structure

Period	Period description	Time start	Time end	Size	
1	Off-peak	22:00	05:59	28 800s ⟶	8 h
2	Standard	06:00	06:59	3 600s ⟶	1 h
3	Peak	07:00	09:59	10 800s ⟶	3 h
4	Standard	10:00	17:59	28 800s ⟶	8 h
5	Peak	18:00	19:59	7 200s ⟶	2 h
6	Standard	20:00	21:59	7 200s ⟶	2 h

The focus of the cost saving intervention was on Time Period 3 and Time Period 5 which were the Eskom morning and evening peak periods with the highest tariff costs. The results only showed evening peak-period reduction. Time Period 3 was optimised for, and included in the optimisation results.

Every level of the model was optimised. The target of the optimisation was to schedule the operating time of the pumps to the less expensive time periods of the day. The target was to shift pumping from Time Period 3 and Time Period 5 to the cheaper periods such as Time Period 1, which was an off-peak period. The integration of all the factors on the whole WDU was important for the optimisation of the model. For optimisation, three inputs are required:

- Objective;
- Variables; and

- Constraints.

For the WDU model, the pumps were optimised. The objective and variable were specified for the pumps. The reservoirs could then serve as the constraint in the optimisation of the WDU as a whole. Table 10 shows the inputs for this specific application of the optimisation.

Table 10: Inputs required for optimisation of WDU model

Input	Description	Unit
Objective	Pump power cost	R/kWh
Variable	Pump schedule	Fraction
Constraints	Reservoir level	Percentage

The pump power costs were measured in R/kWh. It was the cost to run the motor of the pump per kWh (energy). The pump schedule was the fraction of the pump group running. The reservoir level resembled the amount of water in the reservoir. The outputs of the optimisation model required were:

- Pump power cost;
- Pump schedule; and
- Reservoir level.

The results obtained using the optimisation model was verified against a real-life case study. In the next section the results will be discussed.

4.5 Optimisation outputs and results

All the inputs into the model were historical data, collected on-site during investigations. The input data is available in Section 3.4 and Appendix A. The model was also limited to operational constraints such as the number of pumps available for pumping. This was all included in the model developed for each of the different subsections. The optimisation results do not include results for the water treatment works. It was left out on purpose, because the cost saving intervention could only be implemented on the four BPSs of WDU-A. It was included in the integrated model. The baseline was scaled energy neutral for all the pumping stations.

The optimised results will be discussed in this section including the following for each of the subsystems:

- Layout of the optimisation;
- Optimised power profile versus scaled baseline; and
- The reservoir outputs.

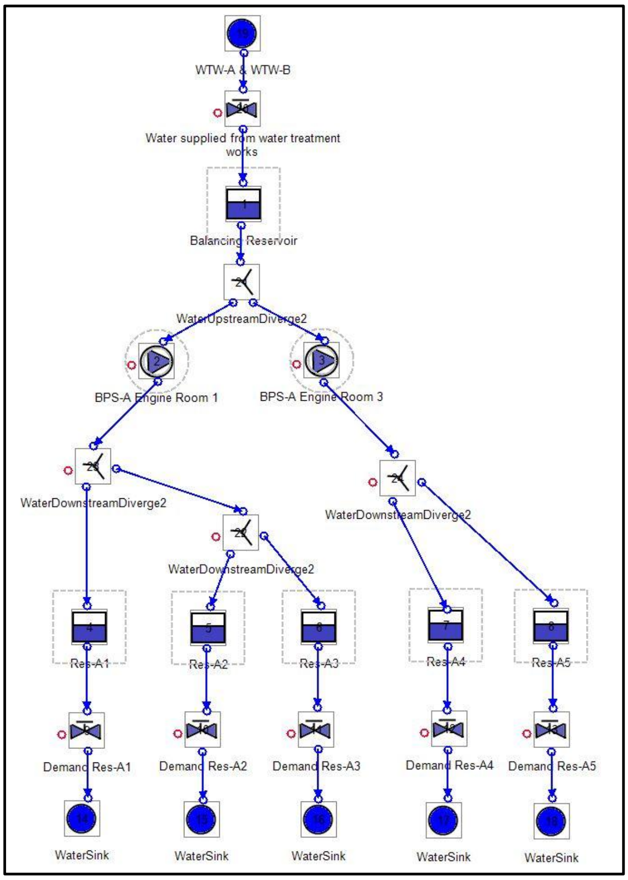
The goal is to identify the possibilities for load shifting keeping within the predetermined constraints:

- Maintain reservoir levels between 60–80%; and
- Maintain 25% spare capacity for standby.

4.5.1 BPS-A

Layout

Figure 46 represents the model for BPS-A. The model was based on the layouts obtained and discussed in Section 3.4. It is important to emphasise that the model was simplified. There could have been more reservoirs, but for the purpose of optimising the system these were the only reservoirs required.



Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

Figure 46: Integrated layout of BPS-A optimisation model

Optimised kW profile versus baseline

Figure 47 represents the optimised power profile versus the actual scaled baseline. The optimised power profile was obtained from the optimisation of the BPS-A model. The demand out of the distribution reservoir and the water received from the water treatment works were constant over a 24-hour day profile.

The average evening load shift result was 16.4 MW (3×100 Ml pumps) and the average morning load shift was 11 MW (2×100 Ml pumps). Indicated in brackets is the number of pumps that could be stopped in order to achieve the load shift (refer to Section 3.4 and Appendix A for pump sizes).

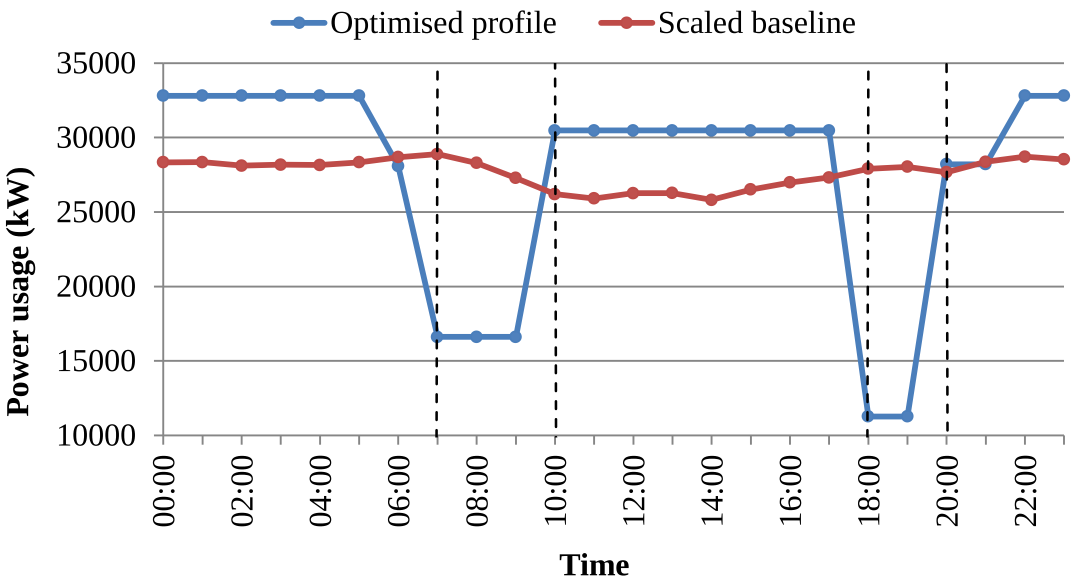


Figure 47: BPS-A optimised power profile versus scaled power usage baseline

Although the focus was on the evening peak period, the morning peak period was also included for all the optimised BPSs. It had a large effect on the total cost savings if load shifting was done during the morning peak period. Table 11 shows the total cost in Rand that could be saved during an average 24-hour weekday. The average saving that could be achieved per day was R30 534. If quantified to a week, the average electricity cost saving could add up to R152 670 per week.

Table 11: BPS-A optimised cost savings

TOU period	Tariff (R/kW)	Baseline pumping cost	Optimised profile pumping cost
Peak	0.6568	R92 218	R47 531
Standard	0.4520	R133 796	R137 697
Off-peak	0.2868	R65 027	R75 278
Total		**R291 041**	**R260 506**
Average saving per day: R30 534			

Reservoirs output

Figure 48 shows the graph for the balancing reservoirs acting as buffers for BPS-A. There were two 40 Ml reservoirs combined into one for the purpose of optimisation. The maximum and minimum boundaries are indicated on the graph as 40% and 80%. It can be seen that the boundary constraints were satisfied.

The reservoir level varied between the minimum of 40% and the maximum of 80%. Although it reached the maximum and the minimum for an average day profile, the boundaries were not exceeded. It is interpreted from the graph that the balancing reservoirs were able to absorb water from the water treatment works while the pumps at BPS-A were switched off during the peak periods.

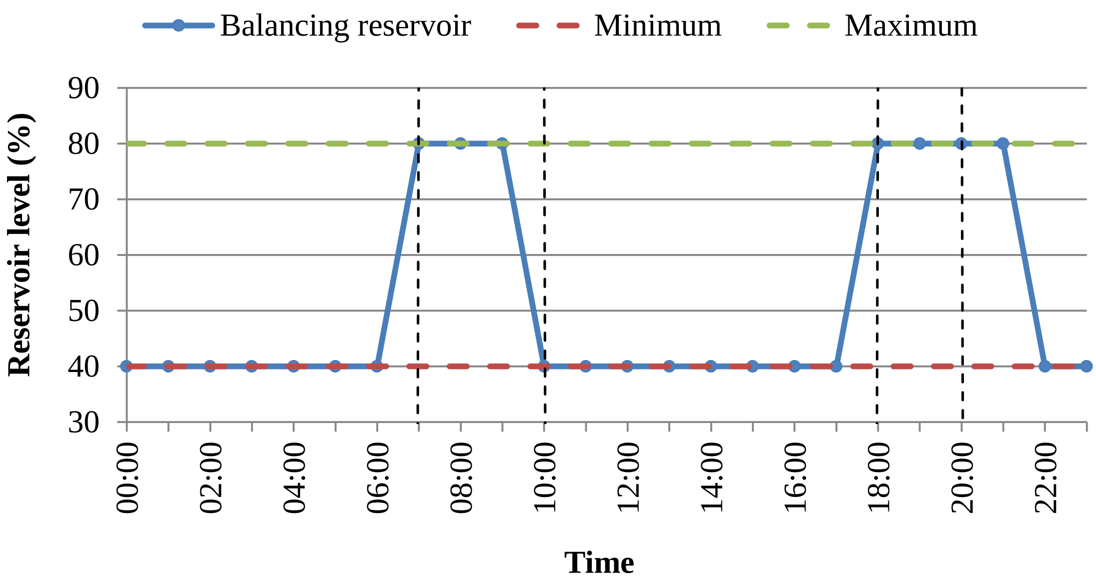


Figure 48: BPS-A demand-balancing reservoirs level percentage

Figure 49 to Figure 53 represent the distribution reservoir level for an average 24-hour weekday profile for BPS-A. The reservoirs that formed part of the model were Res-A1 to Res-A5 (distribution reservoirs). It can be seen from the graphs that all of the reservoirs were maintained between the 60–80% boundary limits and never exceeded those constraints.

From the results it is interpreted that the distribution reservoirs were able to recover even though the water levels were dropping when pumps were switched off at BPS-A. The pumps were switched off during the peak periods.

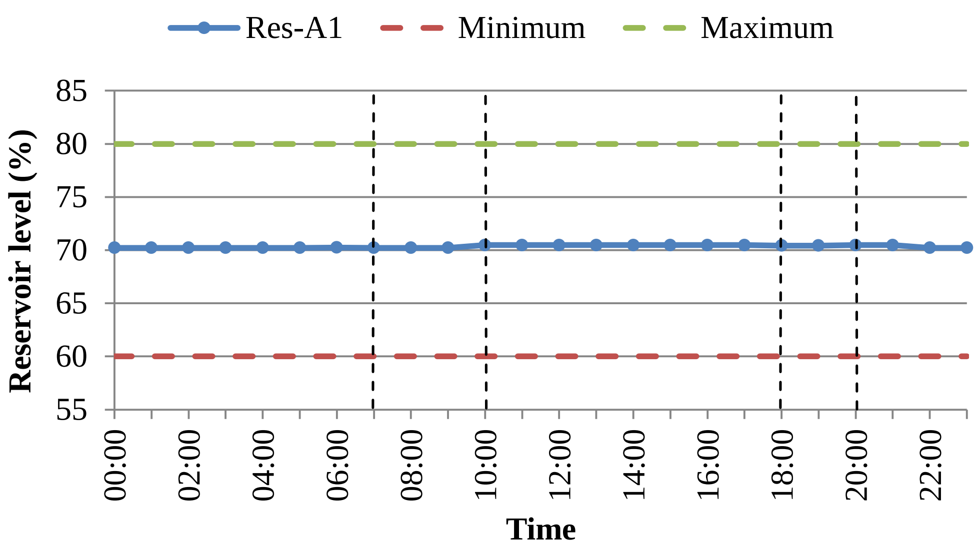


Figure 49: Reservoir level percentage of Res-A1

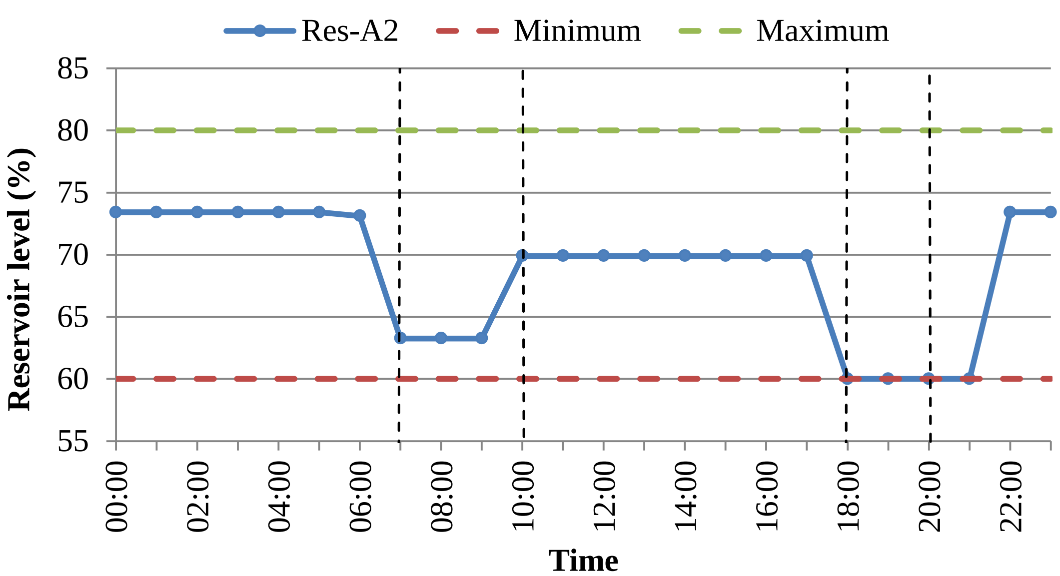


Figure 50: Reservoir level percentage of Res-A2

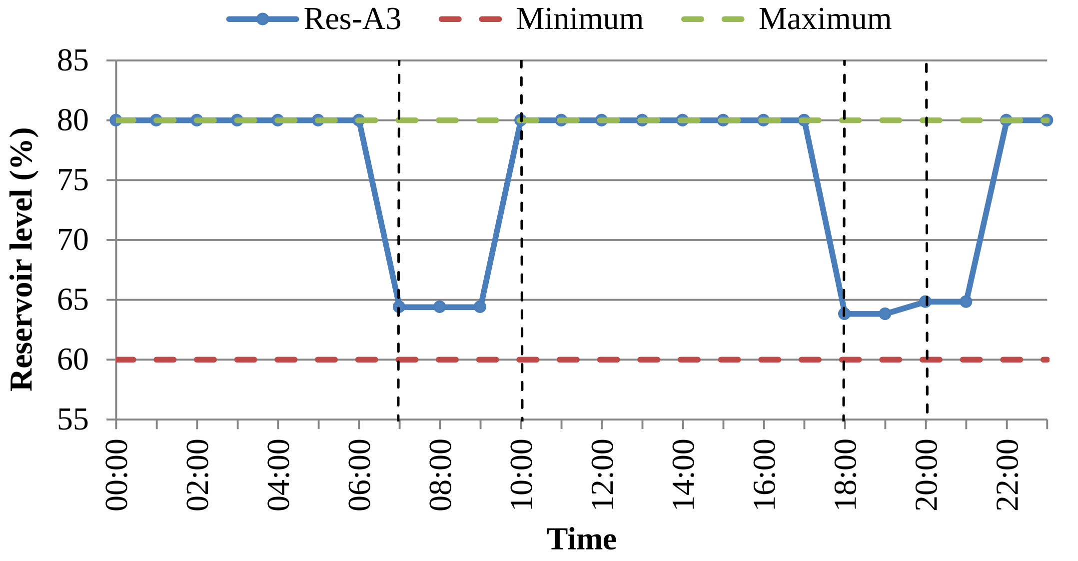


Figure 51: Reservoir level percentage of Res-A3

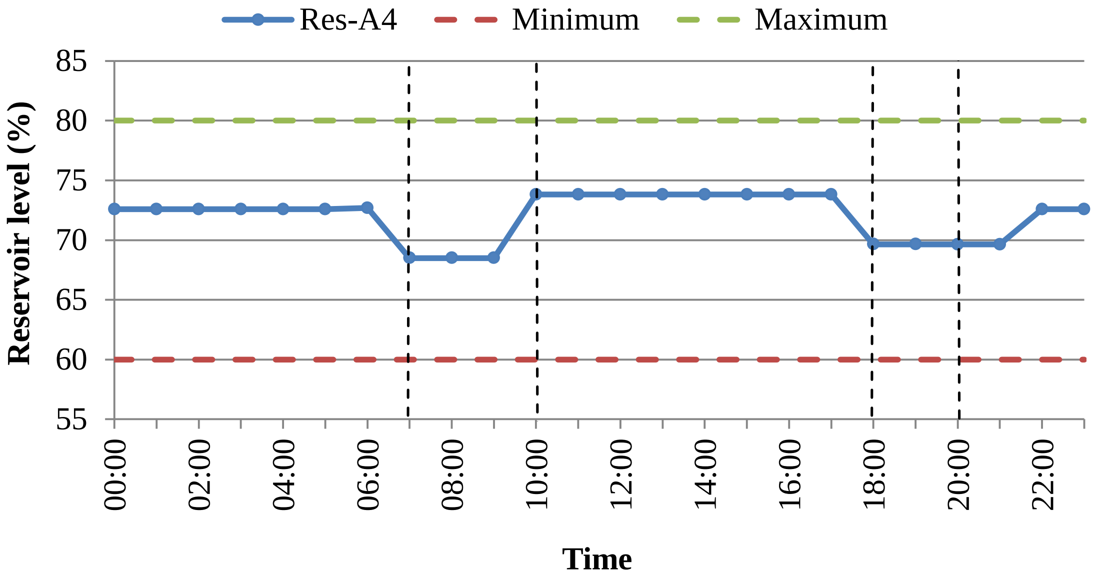


Figure 52: Reservoir level percentage of Res-A4

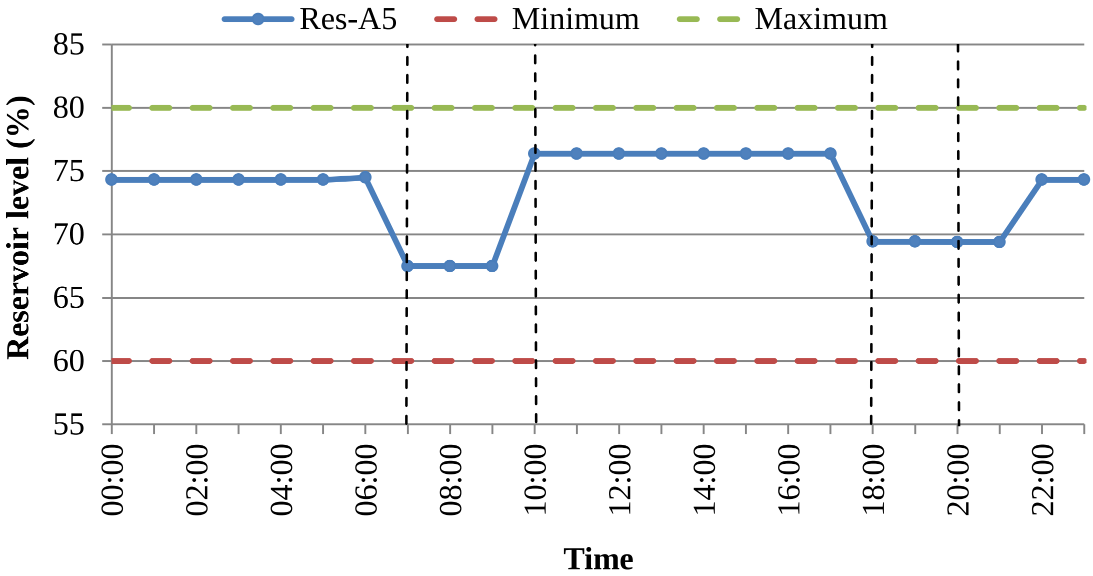


Figure 53: Reservoir level percentage of Res-A5

4.5.2 BPS-B

Layout

Figure 54 is a representation of the BPS-B model layout.

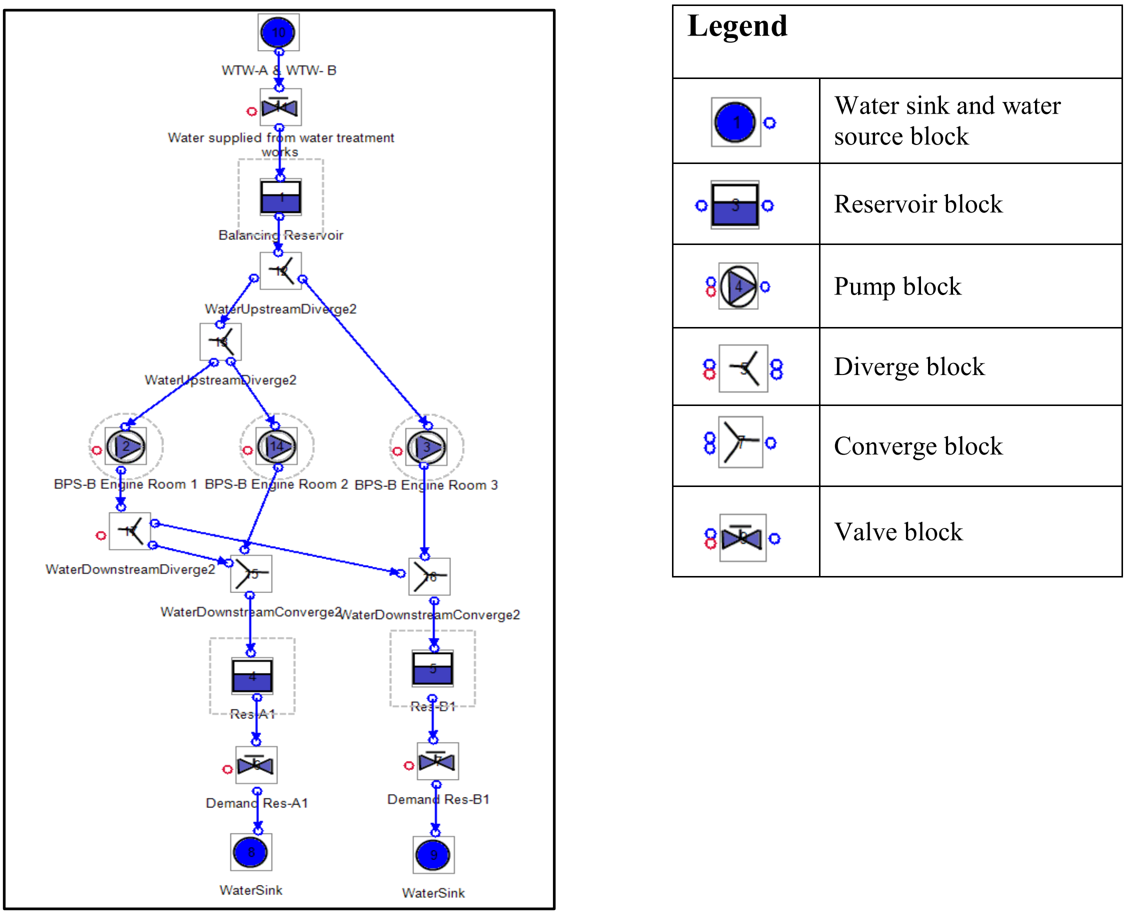


Figure 54: Integrated layout of BPS-B optimisation model

The model layout is based on the layouts obtained in Section 3.4 and Appendix A. It can be seen that Res-A1 was present in both the BPS-A and BPS-B layouts because both of these pumping stations pumped to the same distribution reservoir.

Optimised kW profile versus baseline

Figure 55 represents the optimised power profile versus the actual scaled baseline. The optimised power profile was obtained from the optimisation of the BPS-B model. The demand from the distribution reservoir and the water received from the water treatment works were kept constant over a 24-hour day.

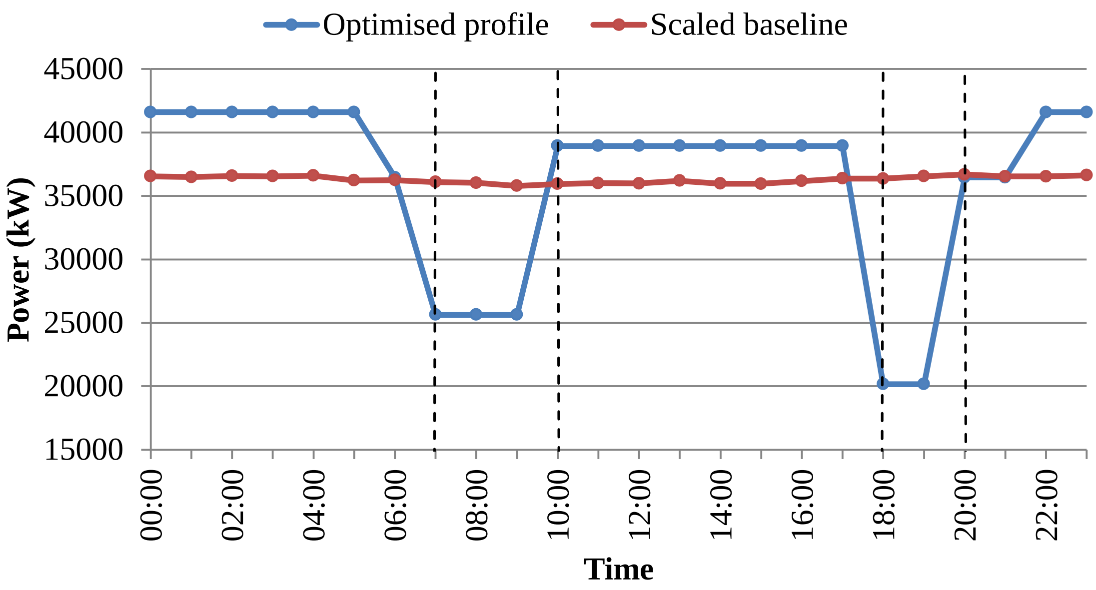


Figure 55: BPS-B optimised power profile versus scaled power usage baseline

The average evening load shift achieved was 16.1 MW (3×100 Ml or 3×200 Ml pumps) and the average morning load shift was 11 MW (2×100 Ml or 2×200 Ml pumps). Indicated in brackets is the number of pumps that would stop in order to achieve the load shift (refer to Section 3.4 and Appendix A for pump sizes).

The same as with BPS-A, the morning peak period load shifting was included to give a full optimised profile. Table 12 shows the total cost in Rand that could be saved during an average 24-hour weekday.

The total average saving was R92 094 per day. Although the average load shift amount was almost the same as BPS-A's, the R/kW values were higher when compared. This meant that for the same amount of load shift achieved, a higher electricity cost saving could be realised. A total of R460 470 could be saved during one week.

Table 12: BPS-B optimised cost savings

TOU period	Tariff (R/kW)	Baseline pumping cost	Optimised profile pumping cost
Peak	2.1221	R383 733	R248 823
Standard	0.8208	R326 743	R345 502
Off-peak	0.5908	R172 593	R196 650
Total		**R883 069**	**R790 975**
Average saving per day: R92 094			

Reservoir output

Figure 56 shows the graph for the balancing reservoirs acting as buffers to BPS-B. There were three 20 Ml reservoirs combined into one for the purposes of the model. The maximum and minimum boundaries as indicated on the graph were 40% and 80%.

It can be seen that the boundary constraints were satisfied. The reservoir level never exceeded the boundaries. It is interpreted from the graph that the balancing reservoirs were able to absorb water from the water treatment works while the pumps were switch off at BPS-B during the peak periods.

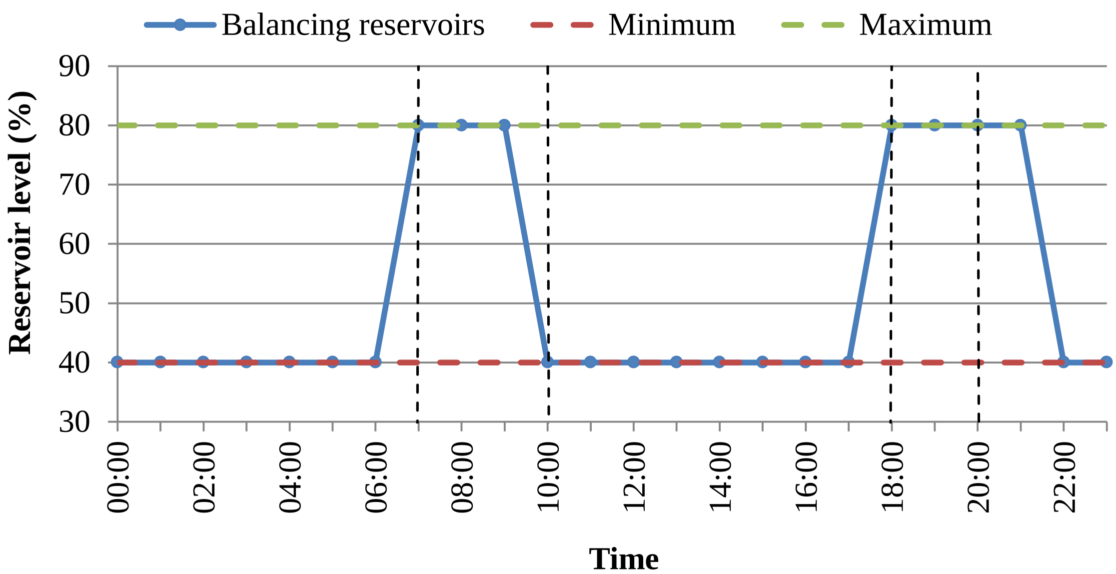


Figure 56: WTW-B balancing reservoirs' level percentage

Figure 57 and Figure 58 represent the distribution reservoir levels during an average 24-hour weekday for BPS-B. The reservoirs that formed part of the model were Res-A1 and Res-B1.

It can be seen from the graphs that all of the reservoirs were maintained between the 60–80% boundary limits and never exceeded those constraints for the distribution reservoirs.

From the results it was interpreted that the distribution reservoirs were able to recover after dropping when pumps were switched off at BPS-B. The pumps were switched off during the morning and evening peak periods.

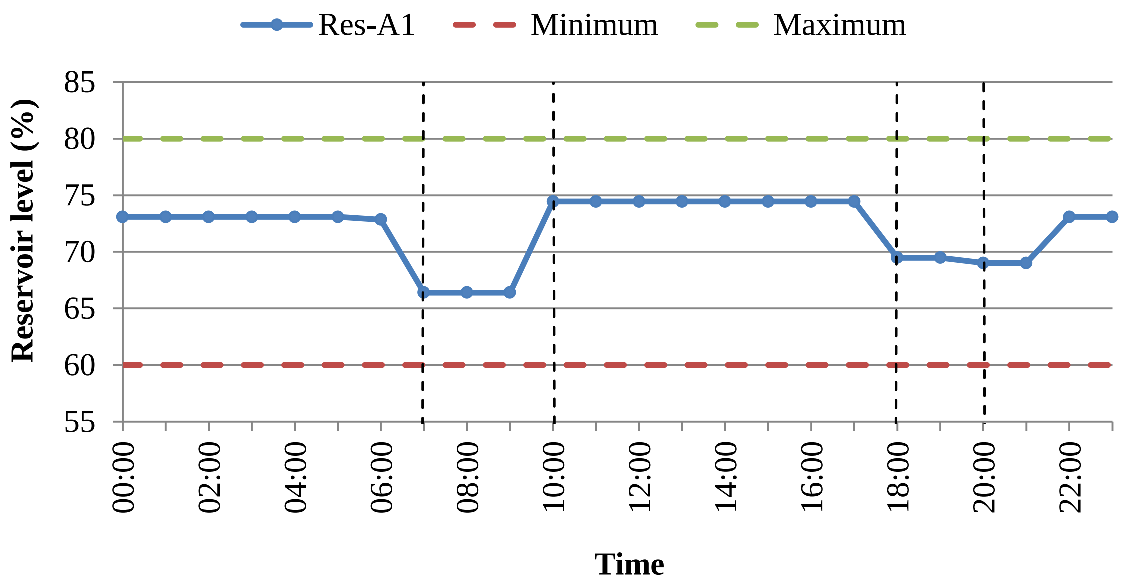


Figure 57: Reservoir level percentage of Res-A1

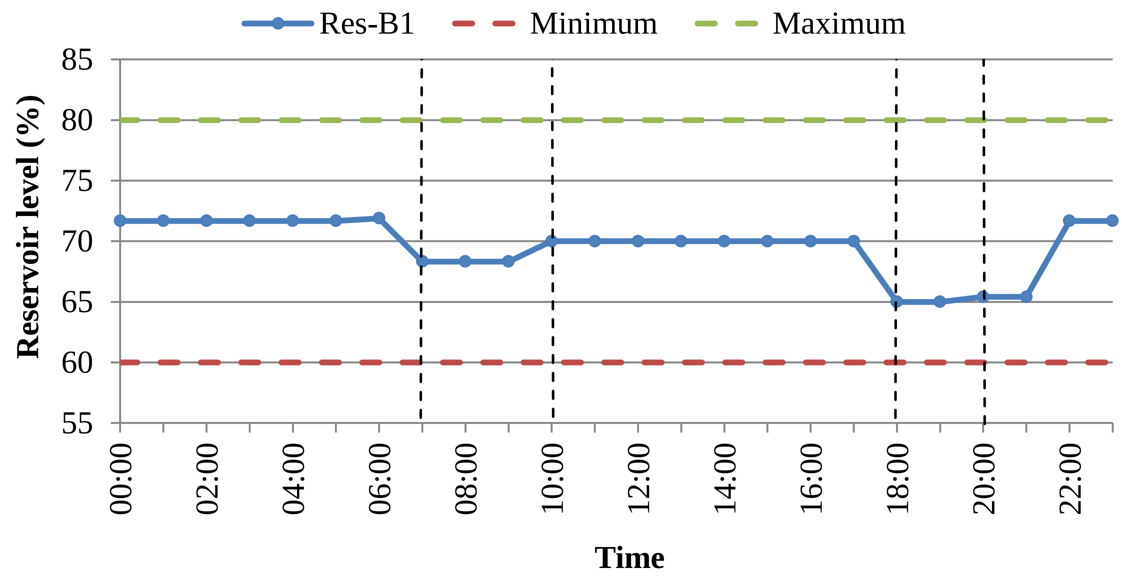
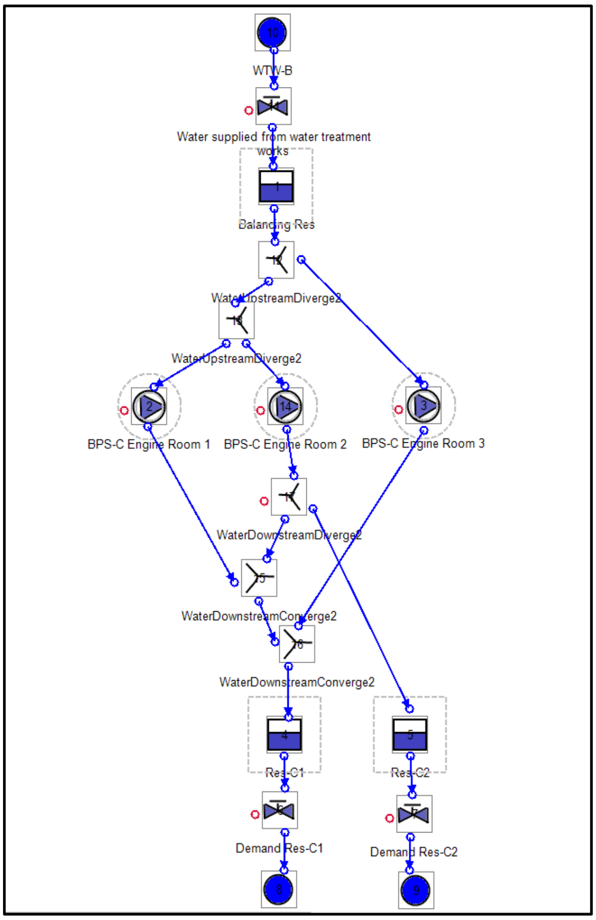


Figure 58: Reservoir level percentage of Res-B1

4.5.3 BPS-C

Layout

Figure 59 shows the layout of the optimisation model for BPS-C. The model layout was based on the layouts obtained in Section 3.4 and Appendix A. The two distribution reservoirs were Res-C1 and Res-C2. The balancing reservoir was a 60 Ml reservoir consisting of three 20 Ml reservoirs on-site.



Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

Figure 59: Integrated layout of BPS-C optimisation model

Optimised kW profile versus baseline

Figure 60 shows the optimised power profile versus the actual scaled baseline. The optimised power profile was obtained from the optimisation of the BPS-C model. The demand from the distribution reservoir and the water received from the water treatment works were kept constant over a 24-hour day period.

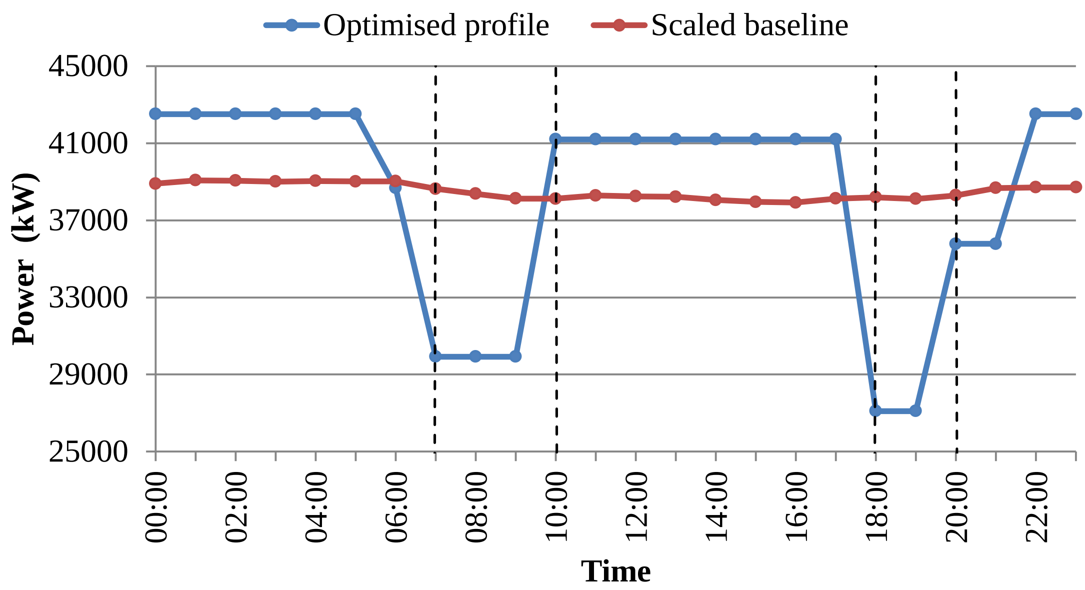


Figure 60: BPS-C optimised power profile versus scaled power usage baseline

The average evening load shift result was 11.4 MW (4×70 Ml or 2×200 Ml pumps). The average morning load shift result was 8.6 MW (3×70 Ml or 1×200 Ml pumps). Indicated in brackets is the number of pumps that would stop in order to achieve the load shift (refer to Section 3.4 and Appendix A for pump sizes).

The morning peak period load shifting was included to give a full optimised profile; the same as with BPS-A and BPS-B. Table 13 shows the total cost in Rand that could be saved during an average 24-hour weekday. The total average saving was R75 156 per day. A total of R375 780 could be saved during one week of optimal load shifting.

Table 13: BPS-C optimised cost saving

TOU period	Tariff (R/kW)	Baseline pumping cost	Optimised profile pumping cost
Peak	0.6568	R125 730	R94 567
Standard	0.4520	R190 242	R138 062
Off-peak	0.2868	R89 339	R97 526
Total		**R405 311**	**R330 155**
Average saving per day: R75 156			

Reservoir output

Figure 61 is the graph for the balancing reservoirs acting as buffers to BPS-C. Three 20 Ml reservoirs were combined into one for the purpose of the model. The maximum and minimum boundaries are indicated on the graph as 40% and 80%.

It can be seen that the boundary constraints were satisfied. The reservoir level never exceeded the boundaries. It is interpreted from the graph that the balancing reservoirs were able to absorb water from the water treatment works while the pumps were switched off at BPS-C during the peak periods.

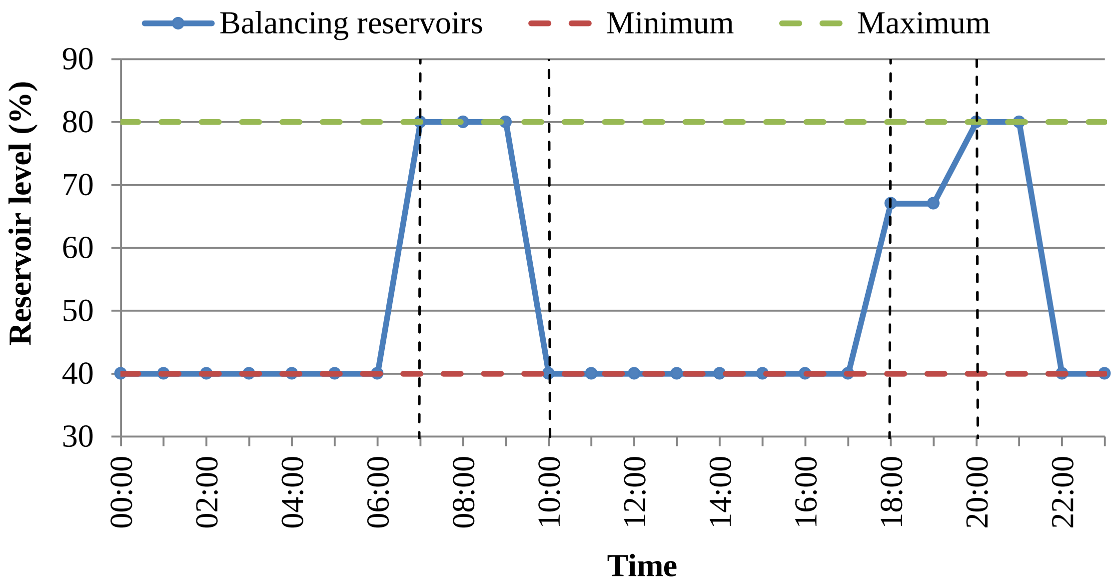


Figure 61: BPS-C balancing reservoirs level percentage

Figure 62 and Figure 63 represent the distribution reservoir level during an average 24-hour weekday for BPS-C. The reservoirs that formed part of the model were Res-C1 to Res-C2. It can be seen from the graphs that all of the reservoirs were maintained between the 60–80% boundary limits and never exceeded those constraints. From the results it can be interpreted that the distribution reservoirs were able to recover after levels dropping when pumps were switched off at BPS-C. The pumps were switched off during the morning and evening peak periods.

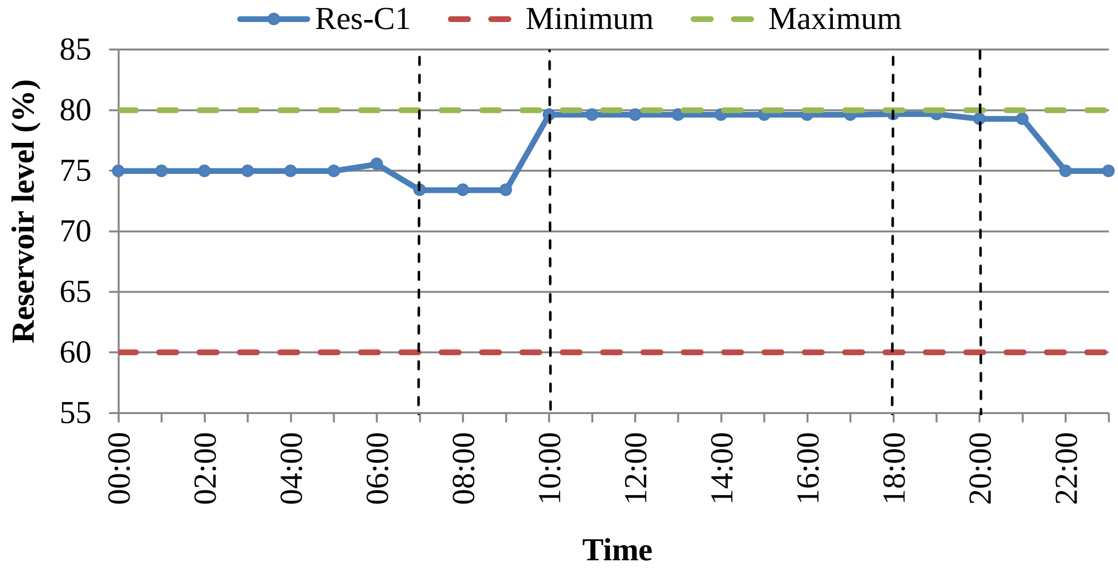


Figure 62: Reservoir level percentage of Res-C1

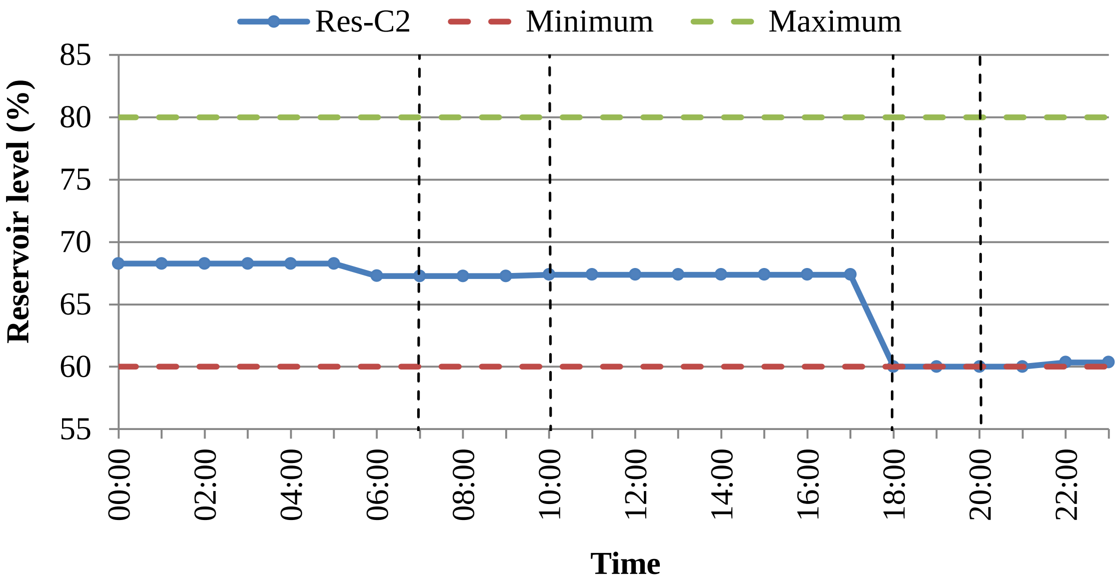
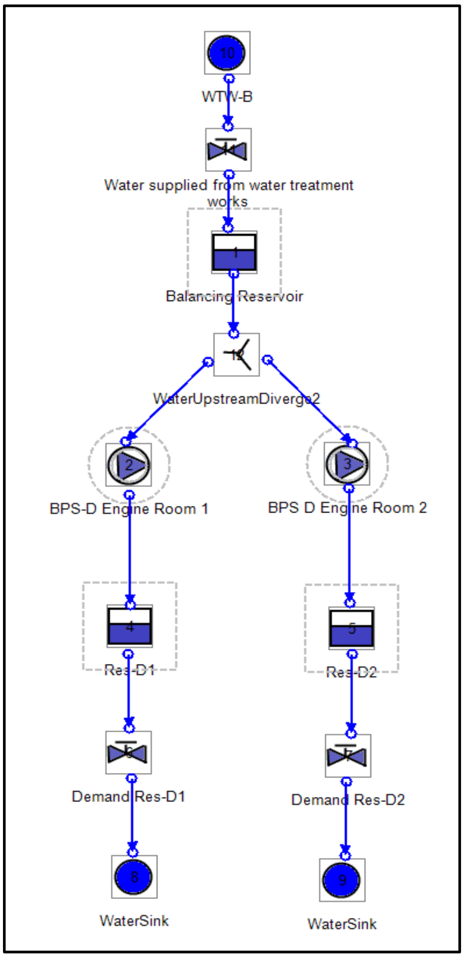


Figure 63: Reservoir level percentage of Res-C2

4.5.4 BPS-D

Layout

Figure 64 shows the layout of BPS-D.



Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

Figure 64: Integrated BPS-D layout of optimisation model

The model layout is based on the layouts obtained in Section 3.4 and Appendix A. The two distribution reservoirs were Res-D1 and Res-D2. The balancing reservoir was 60 Ml consisting of three 20 Ml reservoirs on-site.

Optimised kW profile versus baseline

Figure 65 represents the optimised power profile versus the actual scaled baseline. The optimised power profile was obtained from the optimisation of the BPS-D model. The demand out of the distribution reservoir and the water received from the water treatment works were kept constant over a 24-hour day period.

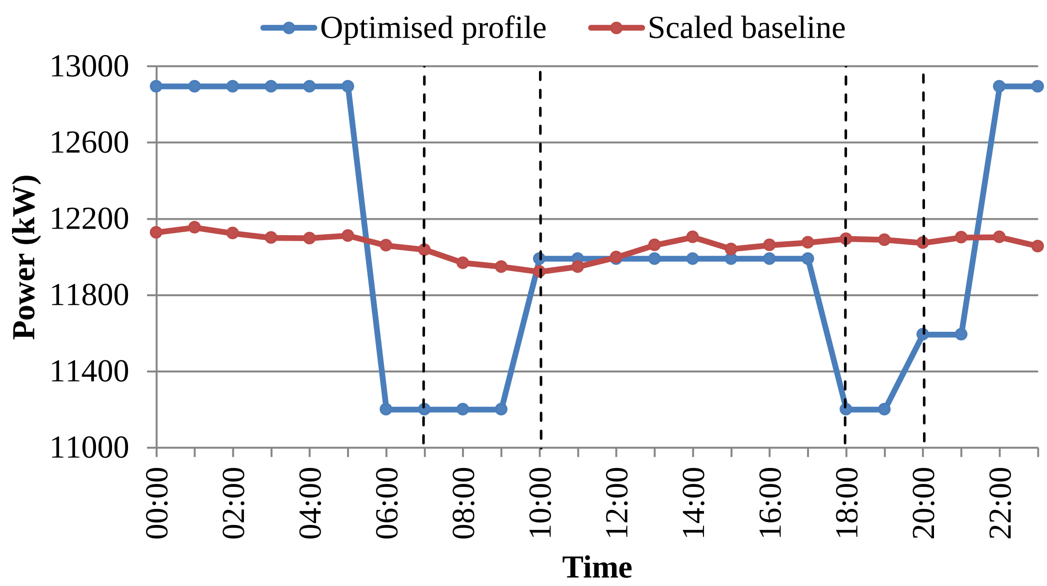


Figure 65: BPS-D optimised power profile versus scaled power usage baseline

The average evening load shift result was 0.8 MW (1×45 Ml pump) and the average morning load shift result was 0.8 MW (1×45 Ml pump). Indicated in brackets is the number of pumps that would be stopped in order to achieve the load shift (refer to Section 3.4 and Appendix A for pump sizes). The amount load shifted was less than the load shifted at other sites. The reason for the small load shift potential was due to the large demand on the distribution reservoirs and the small Res-D2.

The same as with BPS-B and BPS-C, the morning peak period load shifting was included to give a full optimised profile. Table 14 shows the total cost in Rand that could be saved during an average 24-hour weekday.

The total average saving was R2 287 per day. A total of R11 435 could be saved during one week of optimal load shifting. The tariff structure with a low R/kW ratio contributed to the low cost saving.

Table 14: BPS-D optimised cost savings

TOU period	Tariff (R/kW)	Baseline pumping cost	Optimised profile pumping cost
Peak	0.99	R59 538	R55 440
Standard	0.65	R86 091	R84 699
Off-peak	0.51	R49 406	R52 610
Total		**R195 035**	**R192 748**
Average saving per day: R2 287			

Reservoir output:

Figure 66 shows the graph for the balancing reservoirs acting as buffers for BPS-D. There were two 20 Ml reservoirs combined into one for the model. The maximum and minimum boundaries are indicated on the graph as 40% and 80%.

It can be seen that the boundary constraints were satisfied. The reservoir levels never exceeded the boundaries. It is interpreted from the graph that the balancing reservoirs were able to absorb water from the water treatment works while the pumps were switched off at BPS-D during the peak periods.

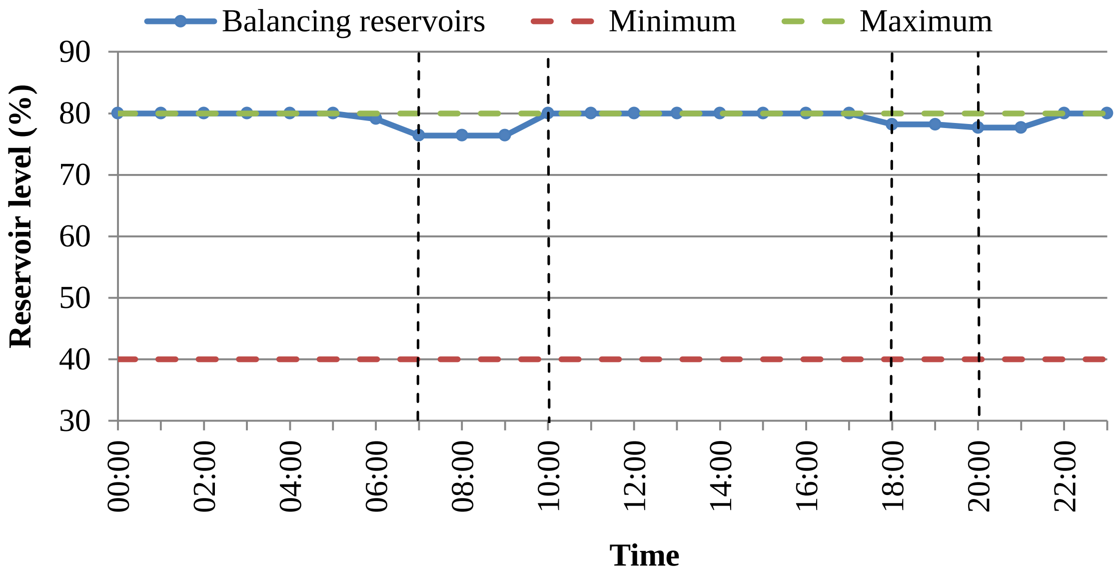


Figure 66: BPS-D balancing reservoirs percentage

Figure 67 and Figure 68 represent the distribution reservoir levels during an average 24-hour weekday for BPS-D. The reservoirs that formed part of the model were Res-D1 and Res-D2. It can be seen from the graphs that all of the reservoirs were maintained between the 60–80% boundary limits and never exceeded those constraints.

From the results it can be interpreted that the distribution reservoirs were able to recover after dropping when pumps were switched off at BPS-D. The pump was switched off during the peak periods in the morning and the peak periods in the evening. For Res-D2, the level remained constant.

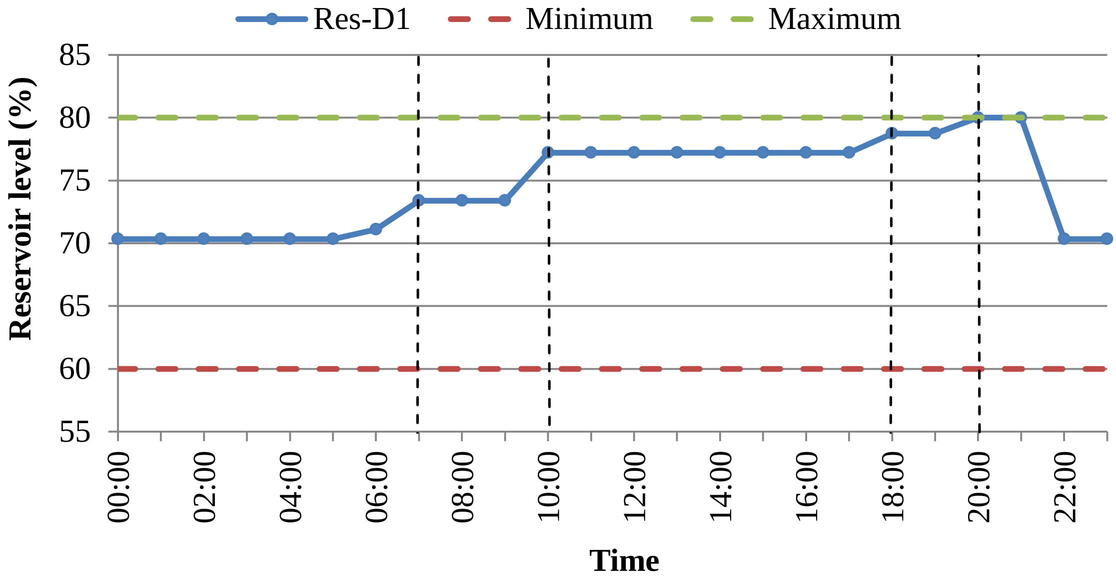


Figure 67: Reservoir level percentage of Res-D1

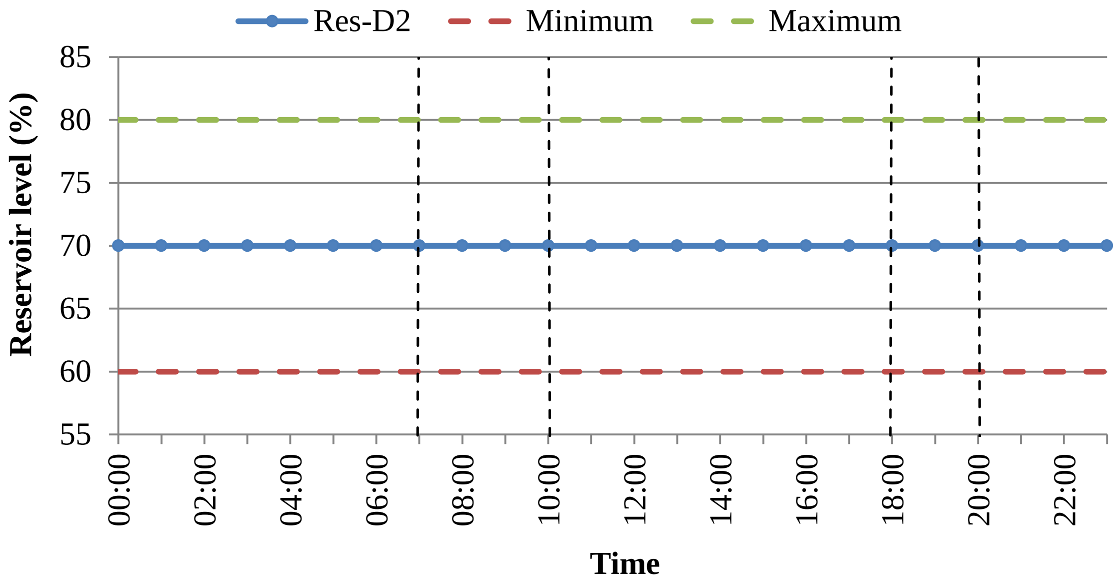


Figure 68: Reservoir level percentage of Res-D2

4.6 Verification of optimisation model

The optimisation model was verified with the data of the test done on WDU-A. Actual results were obtained. These results can be compared to the optimisation model results. The test results will be discussed in Chapter 5. Table 15 shows the comparison between the optimised average power profile and the actual average power profile as obtained from the test results.

Table 15: Comparison between optimised profile and actual profile

	BPS-A		BPS-B		BPS-C		BPS-D	
	Opt profile	Act profile	Opt profile	Act profile	Opt profile	Act profile	Opt profile	Act profile
00:00	32 809.6	28 693.4	41 606.7	33 923.2	42 506.2	31 602.8	12 894.5	5 533.2
01:00	32 809.6	28 990.9	41 606.7	34 029.6	42 506.2	31 717.4	12 894.5	5 766.0
02:00	32 809.6	29 311.8	41 606.7	34 062.7	42 506.2	32 543.8	12 894.5	5 981.6
03:00	32 809.6	29 769.3	41 606.7	34 033.6	42 506.2	31 850.8	12 894.5	5 991.5
04:00	32 809.6	30 040.5	41 606.7	34 047.1	42 506.2	31 623.5	12 894.5	5 979.0
05:00	32 809.6	30 048.1	41 606.7	34 361.5	42 506.2	32 132.7	12 894.5	5 982.2
06:00	28 089.5	30 278.2	36 459.7	34 073.8	38 673.4	32 233.9	11 200.0	7 623.7
07:00	16 610.6	30 262.4	25 637.8	34 069.8	29 926.9	32 211.9	11 200.0	11 419.0
08:00	16 610.6	30 261.4	25 637.8	34 024.5	29 926.9	31 931.8	11 200.0	11 184.6
09:00	16 610.6	30 089.5	25 637.8	34 203.9	29 926.9	31 749.1	11 200.0	11 032.4
10:00	30 475.3	28 183.6	38 944.2	34 060.0	41 195.6	31 201.2	11 990.1	10 943.7
11:00	30 475.3	27 106.2	38 944.2	34 109.5	41 195.6	29 666.8	11 990.1	7 489.9
12:00	30 475.3	26 375.3	38 944.2	34 116.4	41 195.6	30 186.0	11 990.1	7 677.6
13:00	30 475.3	26 903.1	38 944.2	34 128.8	41 195.6	29 820.7	11 990.1	7 617.6
14:00	30 475.3	28 174.6	38 944.2	34 052.9	41 195.6	29 542.9	11 990.1	6 544.6
15:00	30 475.3	28 161.5	38 944.2	34 067.8	41 195.6	30 422.0	11 990.1	7 434.3
16:00	30 475.3	29 151.9	38 944.2	34 090.3	41 195.6	31 728.9	11 990.1	7 399.3
17:00	30 475.3	29 642.8	38 944.2	32 780.5	41 195.6	31 474.4	11 990.1	7 237.0
18:00	11 268.2	22 846.8	20 170.1	27 429.1	27 100.0	28 927.2	11 200.0	9 866.7
19:00	11268.2	22 549.9	20 170.1	27 449.7	27 100.0	29 010.2	11 200.0	9 617.1
20:00	28 204.7	27345.4	36 459.7	31 307.1	35 775.2	31 402.2	11 592.8	6 784.5
21:00	28 204.7	28 646.8	36 459.7	34 184.0	35 775.2	32 362.1	11 592.8	6 869.9
22:00	32 809.6	28 633.6	41 606.7	34 147.3	42 506.2	32 162.7	12 894.5	5 517.7
23:00	32 809.6	29 039.9	41 606.7	34 131.6	42 506.2	31 566.7	12 894.5	5 442.2
Average	27 631.1	28 354.4	36 293.3	33 370.2	38 492.5	31 211.3	12 060.9	7 622.3
Percentage deviation	**3%**		**9%**		**23%**		**58%**	

From Table 15 it can be seen that the actual results from the optimisation of BPS-A only deviated with 3% from the optimised results, and can be considered accurate. BPS-B deviated with 9%, BPS-C with 23% and BPS-D with 58%. The deviation was calculated using the Equation 3:

$$\%\,difference = \frac{Optimised\ power\ profile\ total}{Actual\ power\ profile\ total} \times 100 \qquad \text{(Eq. 3)}$$

In Chapter 5 it will be explained why BPS-C and BPS-D did not have good optimal profiles. BPS-A and BPS-B will be used to verify the optimisation model. Figure 69 gives a representation of BPS-A's optimised power profile versus an actual tested power profile.

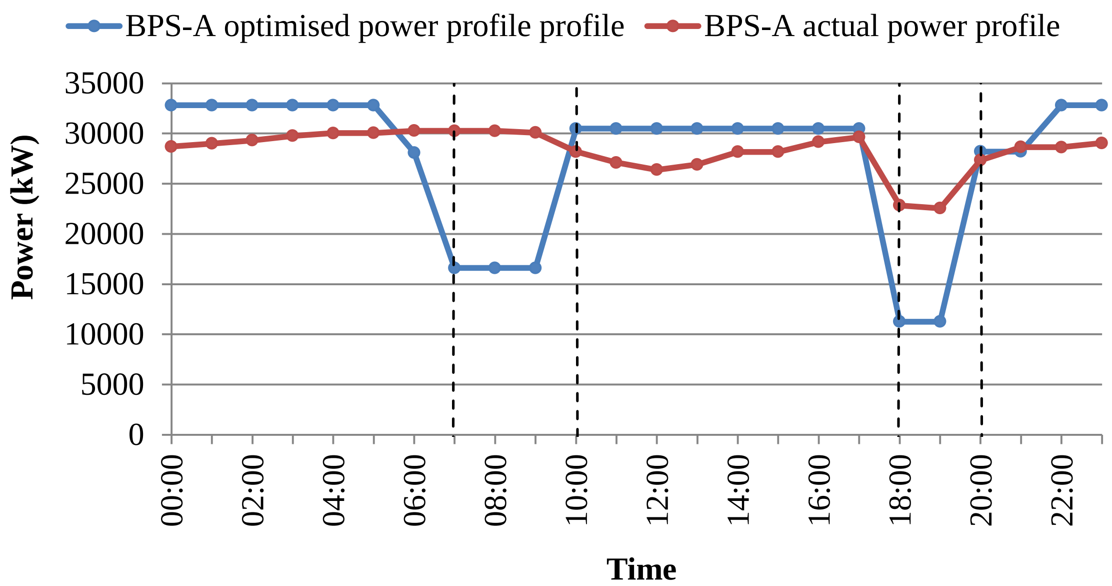


Figure 69: BPS-A optimised power profile versus actual power profile

Figure 70 gives a representation of BPS-B's optimised power profile versus an actual tested power profile.

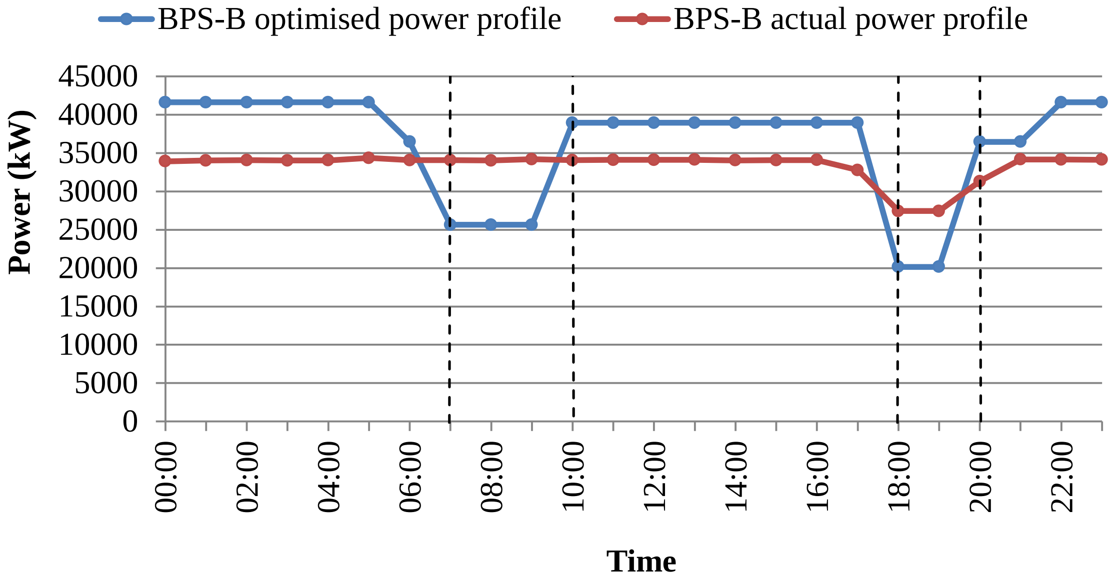


Figure 70: BPS-B optimised power profile versus actual power profile

It can be seen from Figure 69 and Figure 70 that the data points from the optimised and actual power profiles did not correlate completely. They were, however, in a range of 10%. There were a number of limitations that occurred with the optimisation model which might have influenced the accuracy of the model:

- No actual demand data was available. Demand was calculated using mass-balance equations. No single day's actual input could be used for the optimisation model to verify it accurately. There were not enough data available on WDU-A to simulate all of the inputs. The inputs were mostly calculated and an average day was used for the model.
- From the total pumping stations, 75% were programmed in the model to be available for possible load shifting.
- The objective was to reduce the pump power cost. With the morning peak on the same tariff rate as the evening peak, load shifting was scheduled for both periods. This, however, gave a total possible electricity cost saving which was the ultimate objective.

If more data becomes available, the optimisation model may become more accurate. As discussed previously in Chapter 4, this model serves as a tool to investigate load shifting possibilities and electricity cost savings. After the verification of BPS-A and BPS-B, the integrated model can be developed and results can be obtained. The verified subsystems form the building blocks for the integrated model.

4.7 Integrated model

After developing the individual models for the four subsystems, the integrated model could be developed. The model was large and complicated. The whole WDU was linked via distribution reservoirs as and the two water treatment works that was now part of the integrated model. The subsystems did not include load shifting on the water treatment works.

The results from the previous four models could be compared with the actual tested results. The integrated model had not been implemented by the time that the dissertation was completed. The model was developed to see what the potential load shift and electricity cost saving would be when implemented. This would also be the results discussed.

With the verified subsystem models, the results of the integrated optimisation model could be used as true results. This was because the model approach as well as the package used to do the optimisation was verified against the actual data.

The integrated model consisted of the subsystems connected with the water treatment works. It was only the water treatments works' pumping stations that were added to the model. The verification of the subsystem models follows at the end of Chapter 5. The test conducted on the four subsystems and the results will be discussed and the optimisation model will be verified.

Layout

Figure 71 represents the integrated optimised model.

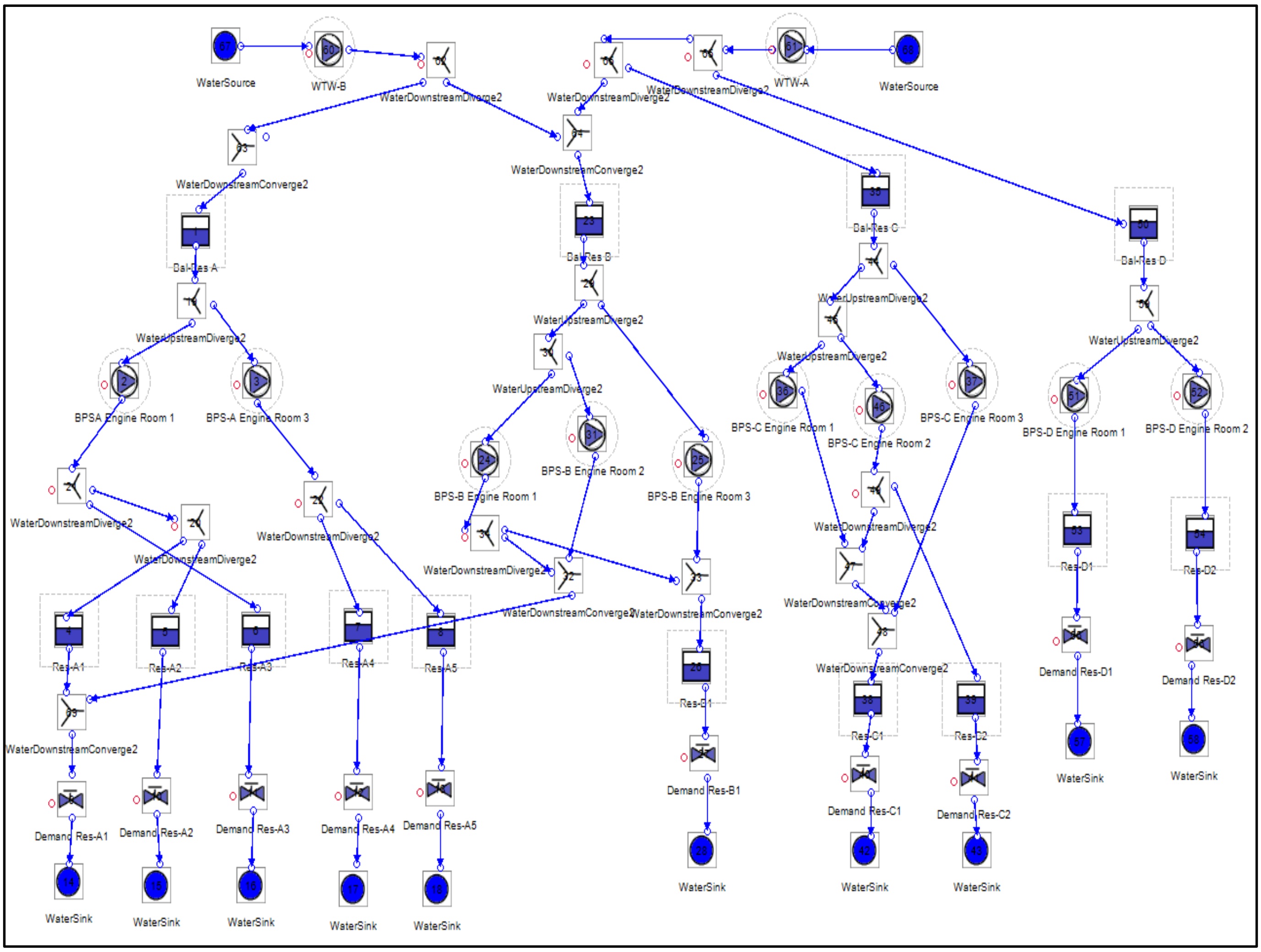
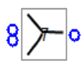


Figure 71: Total integrated optimisation model

Legend	
	Water sink and water source block
	Reservoir block
	Pump block
	Diverge block
	Converge block
	Valve block

Total optimised profile

Figure 72 shows the integrated optimised power profile for the whole WDU. A total load shift of 51.7 MW was simulated during the morning peak period and a load shift of 67.1 MW was simulated for the evening peak period.

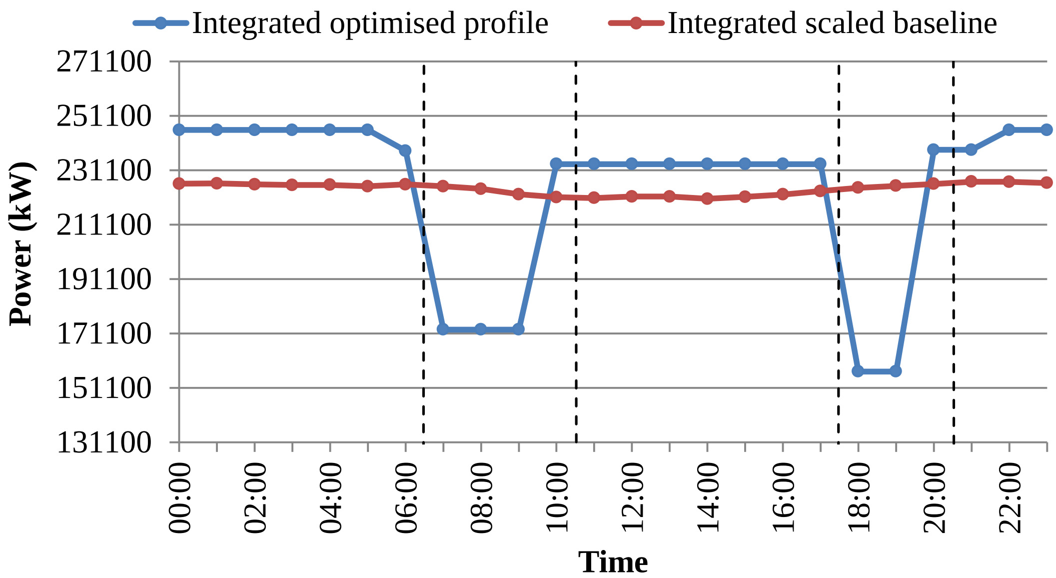


Figure 72: Integrated optimised power profile

4.8 Conclusion

In Chapter 4, the proposed strategy was developed into an optimisation model. An optimisation model was built for each of the four subsystems in the real-life WDU. Chapter 4 focused on the development of this model as well as the results obtained from the optimisation. It was discussed in detail.

The results obtained from the optimisation were compared with actual data obtained from tests done on the real-life WDU to verify the optimisation results.

5 Case study, implementation and results

Figure 73: Analogue pump sequence panel

Analogue pump sequence panel for manual operations.

5.1 Introduction

After the investigation, data collection, analysis, proposed strategy and optimisation of the model, the implementation of the cost saving intervention started. With the optimisation results of the WDU, the prediction for the possible amount of cost savings was known. The integrated strategy for the implementation of load shifting on a WDU had also been established.

The simulation and the integrated strategy were verified with the implementation of the cost saving intervention on a WDU. WDU-A has already been discussed in depth in order to build the optimisation model. In this section, there is no description of the real-life WDU. Refer to Chapter 3 and Appendix A for a description of each site that forms part of the four subsystems of WDU-A and the two water treatment works.

5.2 Integrating the water distribution utility pumping stations

To integrate the WDU and implement the DSM intervention on WDU-A, upgrades and installations were required. These installations were necessary in order to have all the important data available on the local SCADA.

5.2.1 Installations

The data, as stipulated in Chapter 4, needed for the optimisation of the WDU was the objective for installing equipment on-site. To obtain the data, it needed to be logged in real time. REMS3-Pumps were used to log the required data. The software package was installed on a server that connected to the local SCADA. This software was installed on all six of the WDU's pumping stations. The installations and upgrades, which are described in the subsections below, were necessary in order to get the required data on the SCADA.

BPS-A

BPS-A was well equipped with minor upgrades that included:

- New HMIs and PLCs for Engine Room 3;
- SCADA upgrade with new pictures and blocks;
- Number of EGX converters to get the data on the SCADA; and
- New fibre cables.

BPS-B

The Engine Room 2 of BPS-B was not well equipped. The following installations and upgrades were needed:

- New flow meters on outgoing pipelines;
- New level measurements on the balancing reservoirs; and
- New multilines on the incomers to measure kilowatts.

BPS-C

BPS-C required the same number of upgrades needed as BPS-B, but the upgrades were slightly different:

- New flow meters on pumps replacing analogue measurements;
- New level measurements on the balancing reservoirs; and
- SCADA upgrade.

BPS-D

BPS-D was well equipped and the only upgrade required included:

- New level measurement sensors in order to obtain all the needed information from the pumping station on the SCADA.

WTW-A and WTW-B

WTW-A and WTW-B were well equipped. The only upgrades needed were:

- SCADA upgrades; and
- Fibre upgrades.

5.2.2 Pump scheduling

Hermes-Pumps were installed on the servers. It is a webmail application that allows for the sending of large amounts of data to different clients. It sent logged data to the PTB server located at the ESCo's offices. The data was then used in the optimisation of the WDU. Integrating the electricity cost saving intervention with all six pumping stations was now possible. This optimisation of the WDU was based on the optimisation of the simulation model as explained in Chapter 4.

The schedule, obtained after the optimisation, was relayed back to the control room of the specific pumping station and displayed on a computer screen with remote viewing software. A pump schedule was displayed on the screen at the pumping station. Depending on the pumping schedule, the pumping station operator could decide to switch one or more pumps off.

The following data needed to be available on the SCADA:

- Pump power;
- Pump pressure;
- Water flow through the pump; and
- Running status of the pump.

The pressures, flows and pump power were used to calculate the pump efficiency.

Figure 74 shows the simplified communication overview for the WDU. All of the data was centralised at the WDU head office. The Galaxy repository was situated at the head office. A server was installed on all six of these sites. The server was used to host the Historian for data logging as well as the SCADA and REMS3-P.

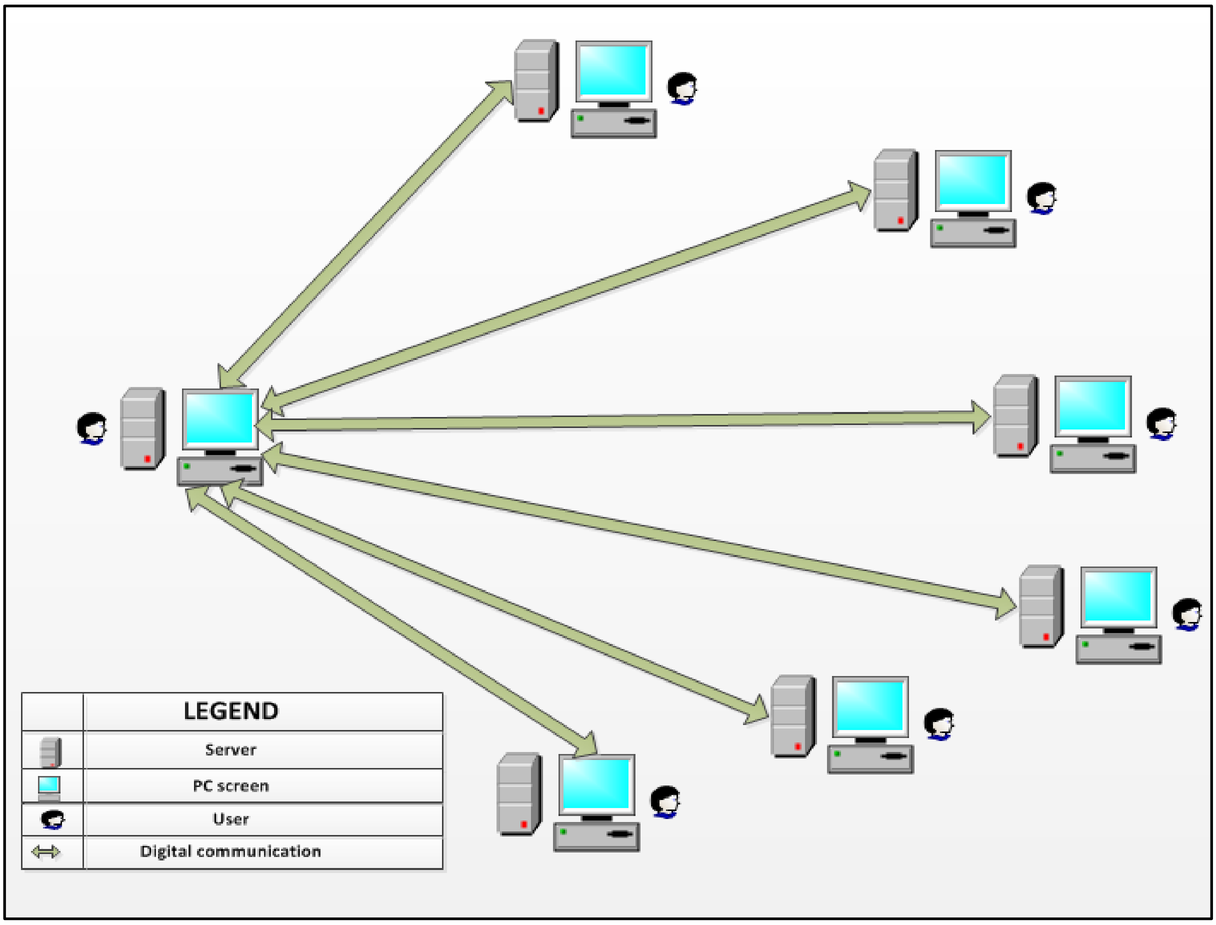


Figure 74: WDU communication overview

5.3 Case study

5.3.1 Constraints for implementation of integrated strategy

When the case study was implemented, numerous constraints arose that disrupted the implementation of the proposed integrated strategy. The following constraints were the major causes of the disruption:

- High- and increasing water demand;
- Delay in pumping station capacity upgrade at WTW-A Engine Room 5; and
- Delay in SCADA upgrades and installations on the six pumping stations.

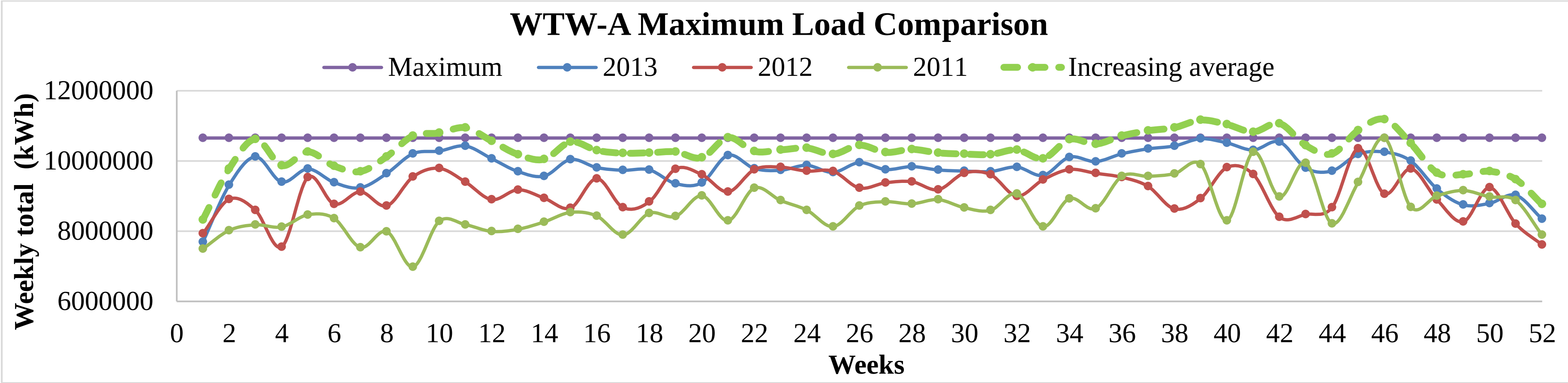
The high demand caused a strain on the WDU and the system struggled to meet the demand. Since the initial investigation in 2011, the demand increased as indicated in Figure 75.

Figure 75 compares the maximum load for 2011 to 2013. The average kWh per week was plotted for each of the three years. Also, an increasing maximum line was plotted that predicted the growth in pumping station loads. The maximum line showed the notified maximum demand of the pumping stations. Table 16 shows the changes in load as calculated for WTW-A and WTW-B.

Table 16: Percentage load increase and decrease results

Time period	Percentage increased load – WTW-A	Percentage increased load – WTW-B
2011–2012	5.3	3.9
2012–2013	4.9	−4.3
Increasing maximum predicted for 2014	5.0	5.0

From the results in Table 16 and the graphs in Figure 75, it is clear that since 2011 there has been a rise in load for WTW-A, at approximately 5% per year. Although the load on WTW-B decreased from 2012 to 2013, the maximum load will be reached with the sudden increase of 5% predicted for 2014.



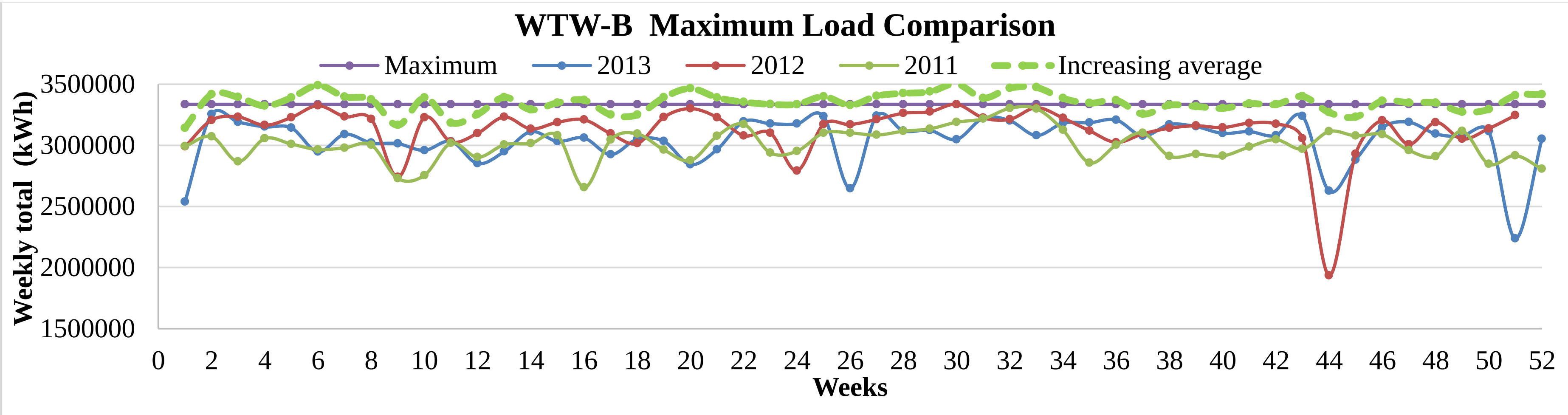


Figure 75: WTW-A and WTW-B maximum load comparison

Both of these water treatment works were near their maximum capacity available for pumping. This meant that the stations ran at full capacity and that there was no spare capacity available for load shifting. For this reason, no load shifting could be implemented at WTW-A and WTW-B. WDU-A forecasted that the capacity would be increased by a new engine room to be built by 2016.

As mentioned in Section 3.6, demand-balancing reservoirs could be used for load shifting on the BPSs when load shifting could not be implemented on the water treatment works. If integrated load shifting could not take place, load shifting on the BPSs could continue and electricity cost savings could be obtained. Therefore, the demand-balancing reservoirs were used to implement an electricity cost saving intervention on the BPSs.

The goal was to measure the impact of load shifting on the pumping stations and the amount of cost savings that could be achieved. The water level variation in the demand-balancing reservoirs was closely monitored to assess whether these reservoirs could be used as capacitance for load shifting.

Each of the tests on the separate pumping stations was discussed further on in this chapter. The success of the load shifting, as well as the constraints on the load shifting, was addressed.

5.3.2 BPS-A

During the period of 13–17 January 2014, a test was conducted on BPS-A. Although data was captured for a seven day period from 13-19 January 2014, the test focusses on the weekdays only. Two pump sets, with ratings of 100Ml/day in Engine Room 3 and Engine Room 1, were switched off at 17:55. The installed capacities of the pump sets were 5 650 kW and 6 163 kW respectively.

After the Eskom evening peak period, the pump operator was instructed to continue with operations as usual. During this test, the focus was on the downstream (distribution) reservoir with the highest water level before 17:00. This meant that the pumps, which were pumping to the reservoir with the highest water level, were scheduled to be switched off.

The downstream reservoirs were alternated during the week to reduce the possibility of the downstream reservoirs reaching the minimum level during testing. The pumps were switched off from 17:55 to 20:30 as shown in Figure 76. The average evening peak load shift achieved was 6.2 MW over the period of five weekdays.

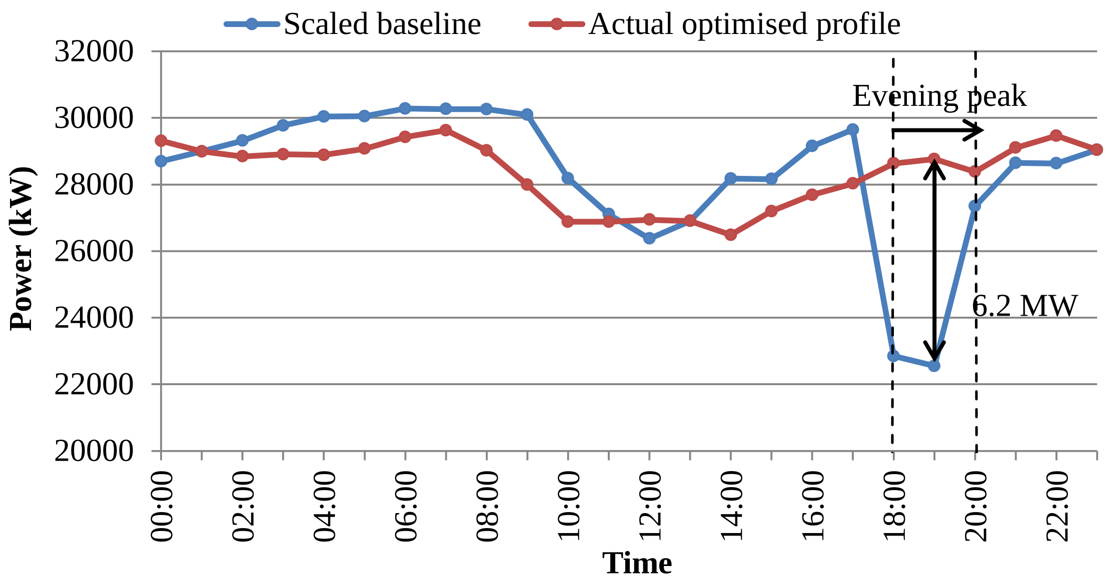


Figure 76: BPS-A average daily power baseline versus actual average daily power profile (13–17 January 2014)

Impact on reservoirs

During the two-hour Eskom evening peak period, two 100 Ml/day pump sets were switched off. One pump set was switched off in Engine Room 1; the other pump set was switched off in Engine Room 3. The pump set from Engine Room 1 supplied potable water to the Res-A2 and Res-A3 reservoirs. The pump set from Engine Room 3 supplied potable water to the Res-A4 and the Res-A5 reservoirs. Figure 77 shows the influence on the balancing reservoirs, which are the upstream reservoirs and functioned as capacitance from WTW-A and WTW-B to BPS-A.

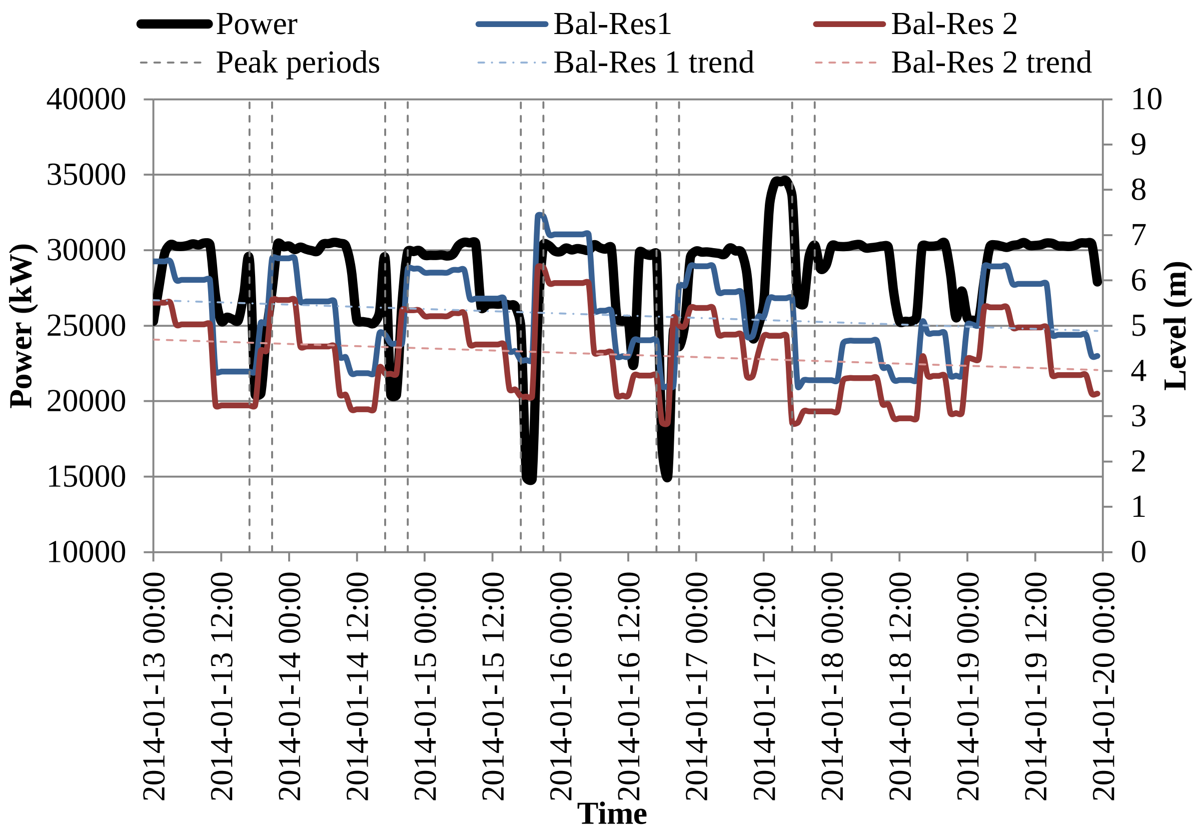


Figure 77: Distribution reservoir levels (13–19 January 2014)

The pumping station at the BPS-A balancing reservoirs had 30 Ml/day pumps which started automatically when triggered by the downstream reservoir levels. Before reaching the balancing reservoirs, water was drawn by other users. This was indicated on a daily water balance sheet. On average, from the 700 Ml/day pumped to BPS-A, only 560 Ml/day would reach the pumping station.

On 17 January 2014 the daily target was changed to 700 Ml/day (maximum pumping capacity). BPS-A increased output to 700 Ml/day, but could only do so for three hours due to the low level of the balancing reservoirs. The pumping station at the balancing reservoirs needed enough water to supply its users. It was scheduled to do a load shift, since the levels of the balancing reservoirs were too low to continue pumping at 700 Ml/day. The balancing reservoirs pumping station had two 40 Ml reservoirs and had a direct influence on the pumping at BPS-A.

During the load shift at BPS-A, the balancing reservoir could increase its water volume. The low inflow to BPS-A was due to restrictions at the WTW-A Engine Room 1. The effect on the Res-A2 level, when the supply was reduced by 100 Ml/day for two hours during Eskom evening peak period, is shown in Figure 78. The decline in the Res-A2 level was attributed to the sharp rise in demand after 15 January 2014. The increased demand was a direct result of a heatwave that Gauteng experienced.

As shown in Figure 78, from 13–15 January 2014 the load was recovered during the night. If the daily target increased earlier, the sharp decline in the level of the Res-A2 could have been avoided. The daily target was met every day of the week. It will be discussed later on in this section.

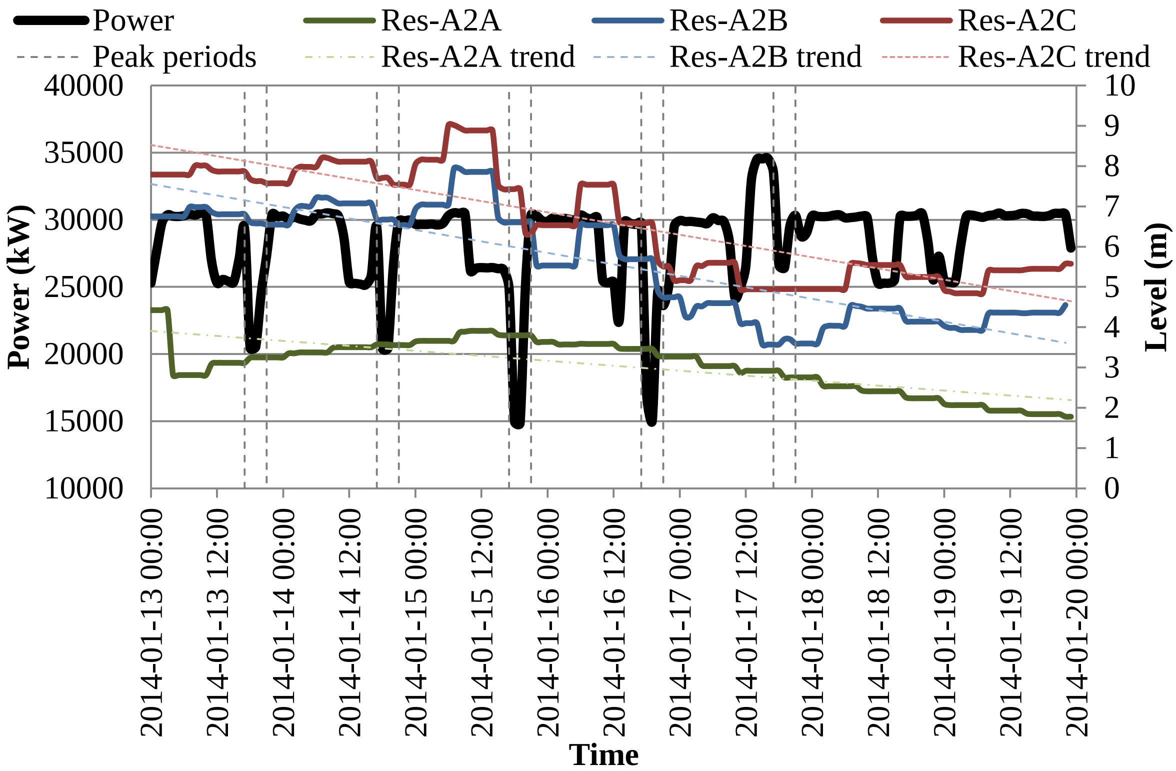


Figure 78: Res-A2 distribution reservoir levels (13–19 January 2014)

Figure 79 shows the effects on the remaining reservoirs that BPS-A pumped water to. The decline during the week was attributed to a rise in demand. On 17 January 2014, an electrical fault resulted in a pump trip at BPS-D. This influenced the Res-A5 level since Res-A5 also supplemented the BPS-D subsystem.

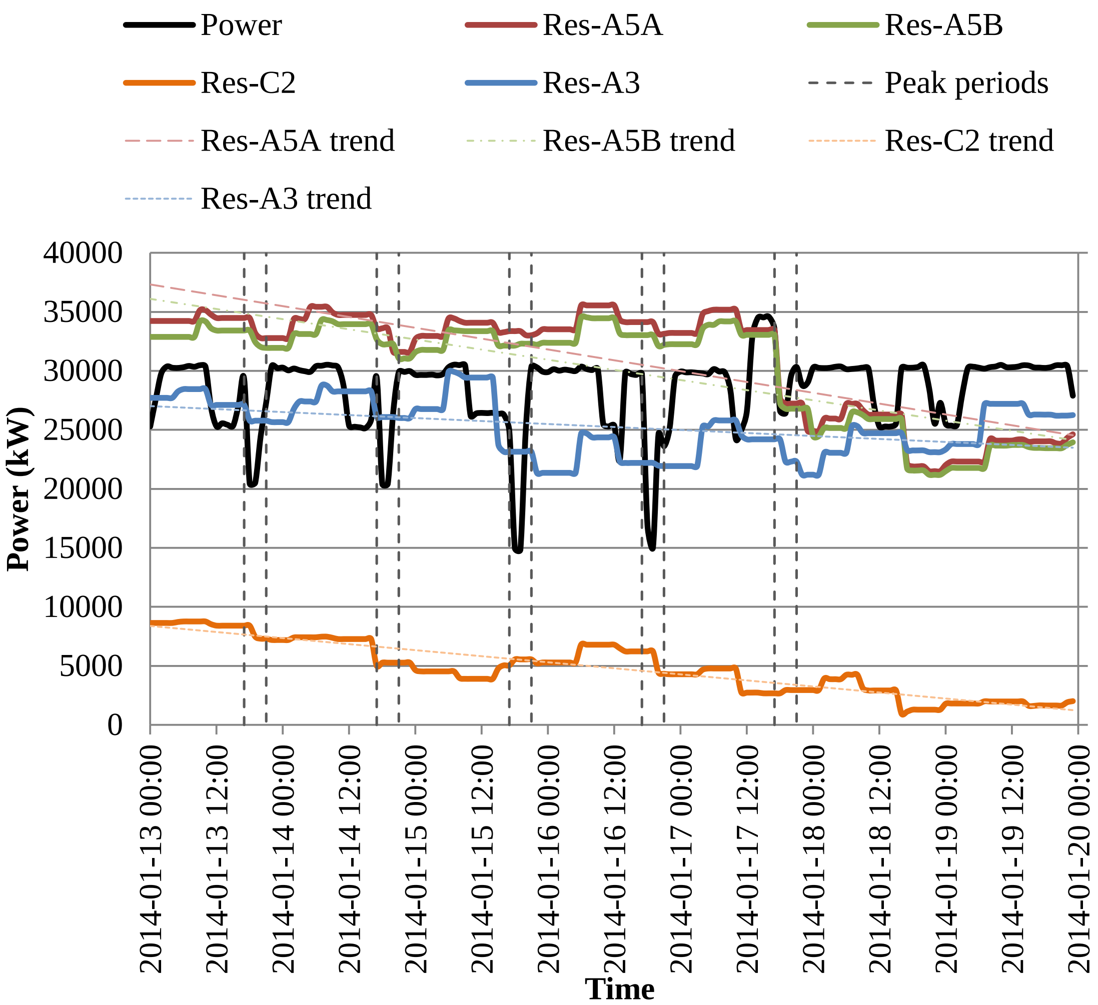


Figure 79: Res-A5, Res-A3 and Res-C2 distribution reservoir levels (13–19 January 2014)

The BPS-C system had problems during the week which led to a major decrease in the level of Res-C1. BPS-A was obliged to supply the Res-A2, Res-A3 and Res-A5 reservoirs. Increased pumping to the Res-A4 reservoir only took place when additional water volumes were required in the BPS-C subsystem. The sharp rise in demand, as well as the problems experienced in the BPS-C subsystem, was responsible for the decline of the water level of Res-A4.

The water load was recovered during the week nights. The load shift had no effect on the reservoir other than the effect of normal operations. The effects of the heatwave showed no visible effect on the reservoir levels.

Figure 77, Figure 78 and Figure 79 show that the weeklong test had a negligible effect on the reservoirs when compared with normal operations. Load shifting was done by optimising the pumping schedule utilising the balancing reservoirs as capacitance during the process. This verified the model discussed in Section 4.5.

The balancing reservoirs could absorb water from the water treatment works while load shifting took place if used in the optimisation of the WDU. No pump sets at WTW-A and WTW-B were switched off due to process constraints at the water treatment works and high demand in the WDU system. The water treatment works pumped at maximum capacity during the test week.

Daily target

Figure 80 shows the daily targets for the week as well as the actual volumes water that were pumped. It can be seen in the trend that the water pumped into and the water pumped out of BPS-A were equal.

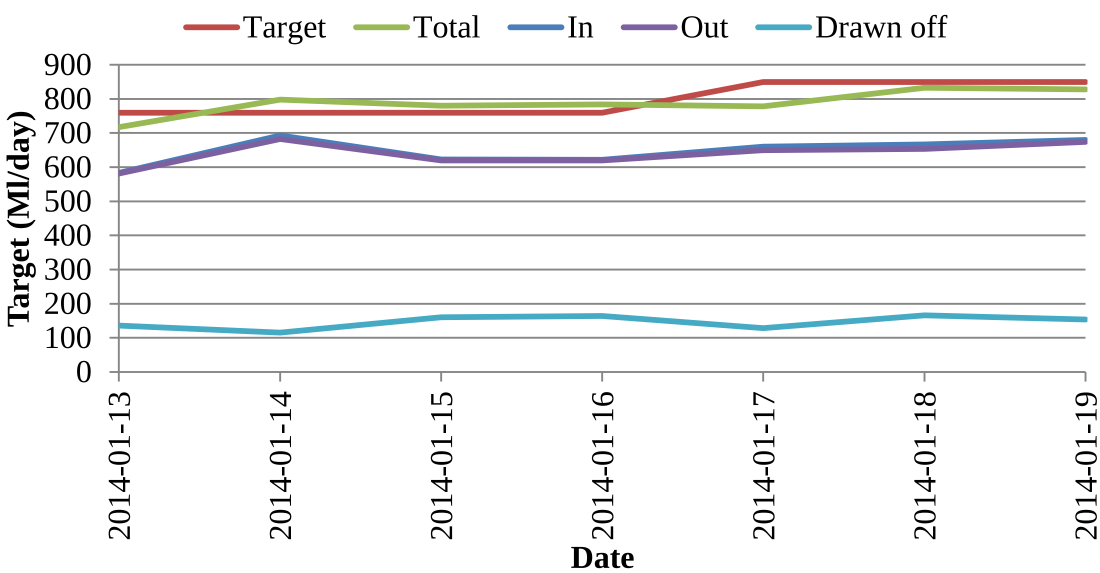


Figure 80: BPS-A pumping target (13–19 January 2014)

It is important to note that a 100 Ml/day pump that was switched off for two hours equated to 8.3 Ml during that period. When compared with the daily target it amounted to approximately 1.18% of the water pumped. This was absorbed by the pump efficiencies; water was also lost in the system. By using the balancing reservoirs, no water was lost to the downstream reservoirs.

Cost savings

The cost savings as a result of the week's testing can be seen in Table 17. R3 664 was saved on average per weekday. The cumulative saving for the week was R18 300.

Table 17: BPS-A costs savings

TOU period	R/kW (Megaflex, Eskom low demand season)	Baseline pumping cost	Optimised profile pumping cost
Peak	0.6568	R93 432	R85 303
Standard	0.452	R135 557	R138 062
Off-peak	0.2868	R65 949	R67 909
Total		**R294 937**	**R291 273**
Average saving per day: R3 664			

5.3.3 BPS-B

During the 24–28 February 2014 time period, a test was conducted on BPS-B. Although data was captured for a seven day period from 24 January to 2 March 2014, the test focusses on the weekdays only. It was scheduled to switch off pump sets in Engine Room 3 because Engine Room 3 had the best instruments and was the easiest place to switch off a pump. The installed capacity of these pump sets were 6 800 kW.

The pump was switched off at 17:45, before the Eskom evening peak period. After the Eskom evening peak period, the pump operator was instructed to continue operations as usual. During testing, the Res-A1 downstream distribution reservoir was used as storage capacity. The pump set was switched off from 18:00 to 20:30 as shown in Figure 82. The baseline was adjusted to be energy neutral. The average evening peak saving achieved was 5.9 MW.

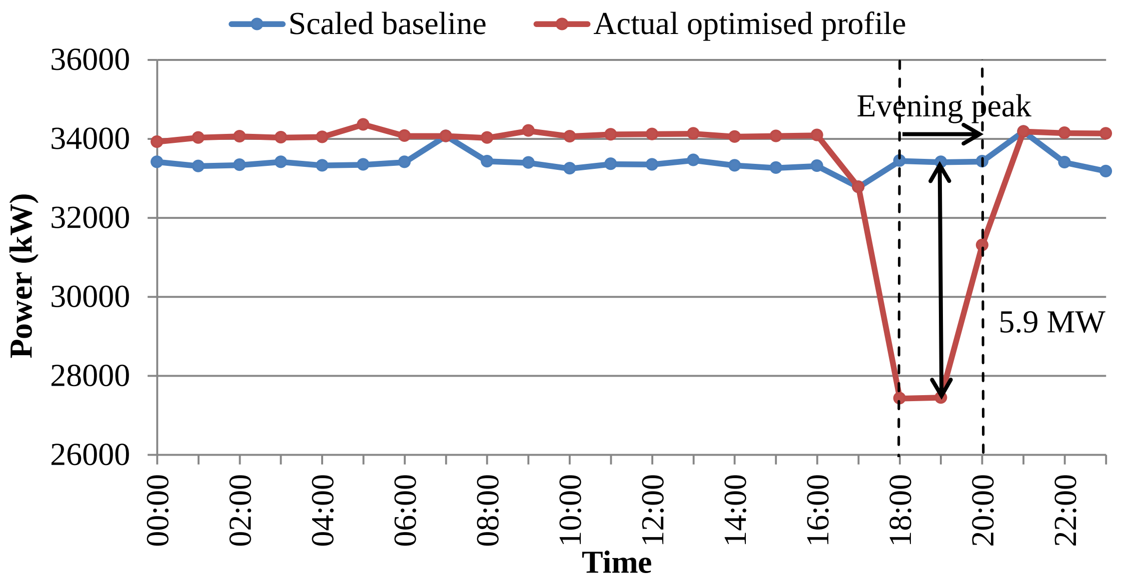


Figure 81: BPS-B average daily power baseline versus actual average daily power profile (24–28 February 2014)

Impact on reservoirs

One 200Ml/day pump set was switched off during the Eskom evening peak period. This pump set supplied water to Res-A1. Figure 83 shows the impact of the 200 Ml/day reduction on the balancing reservoirs' level.

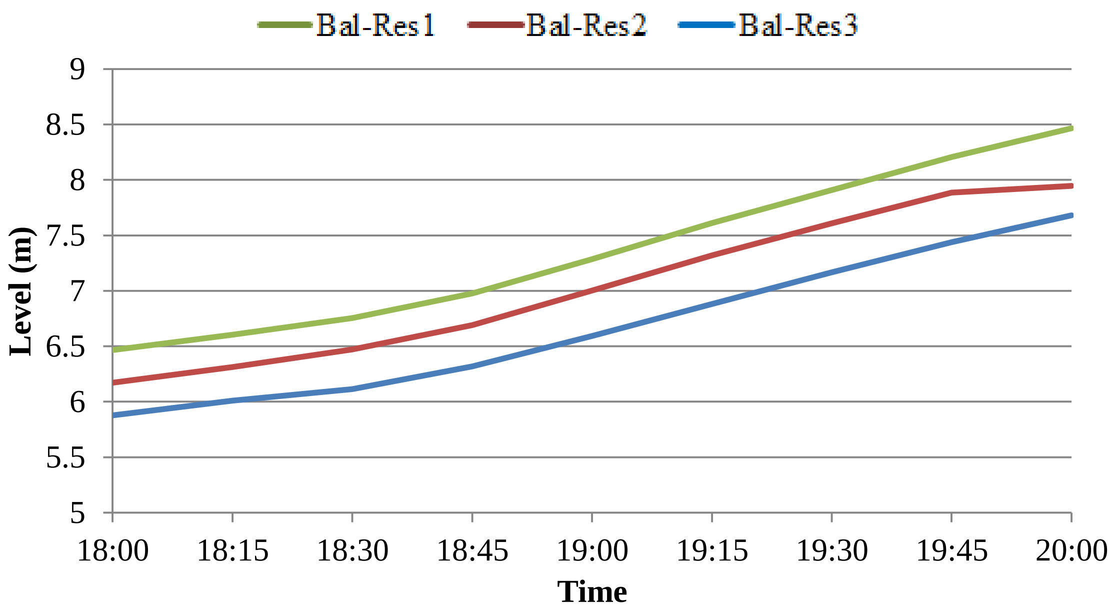


Figure 82: Average balancing reservoir levels during peak periods for the test days (24–28 February 2014)

As confirmed by the simulation, the balancing reservoirs had the capacity to absorb the excess flow from the water treatment works. The high balancing reservoirs' levels ensured that pumping capacity could be safely increased during the night to take advantage of the less expensive off-peak period.

Figure 84 shows the reduction in the water level of Res-A1A. This was caused by the load reduction of 200 Ml/day, but it can be seen that the load was recovered during the night. On 24 February 2014, Res-A1 was at 90%. The upper limit for all reservoirs is 80%. Pumping to Res-A1 was reduced to bring the reservoir level within allowable limits.

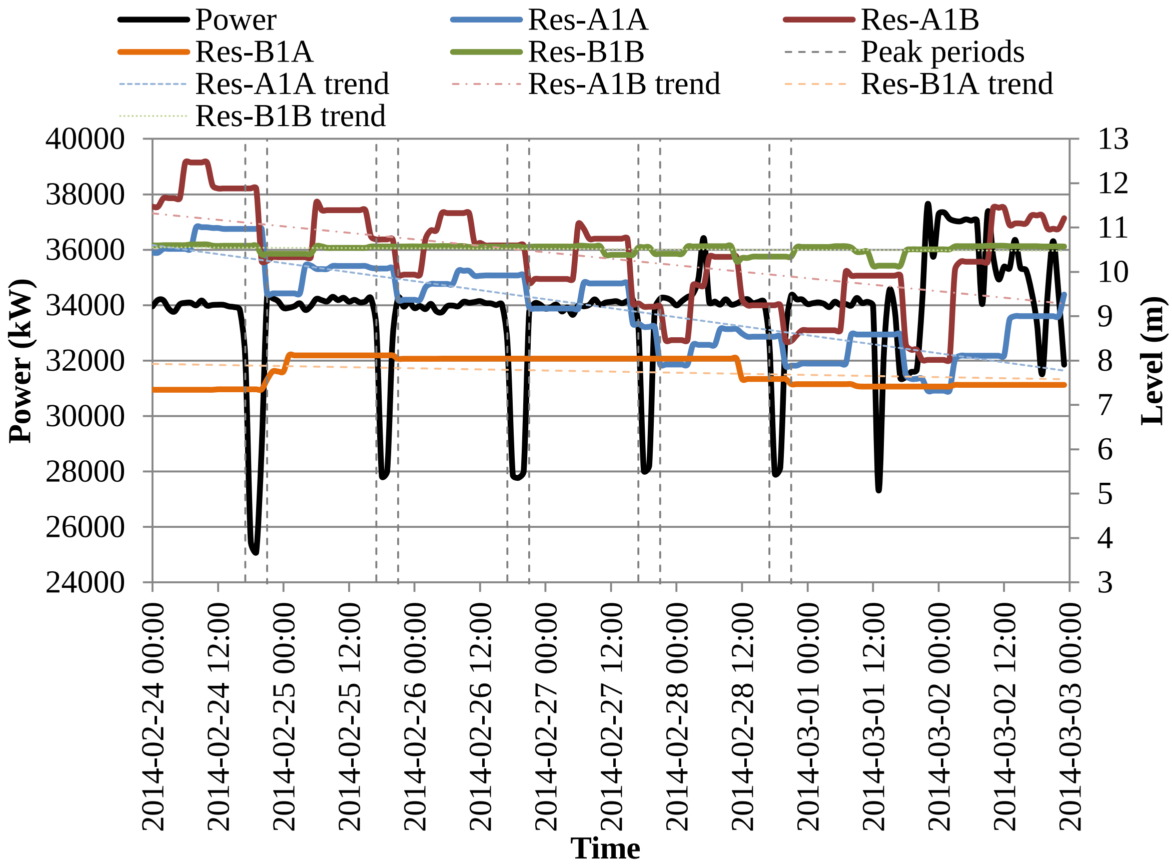


Figure 83: Distribution reservoir levels (24 February 2014 to 2 March 2014)

On 28 February 2014, a pump set supplying Res-B1 was switched off for the evening peak period. The load was recovered over the weekend as well as during the evenings. Throughout the week the reservoirs remained between the minimum and maximum levels.

Daily target

Throughout the week the daily targets were met as seen in Figure 85.

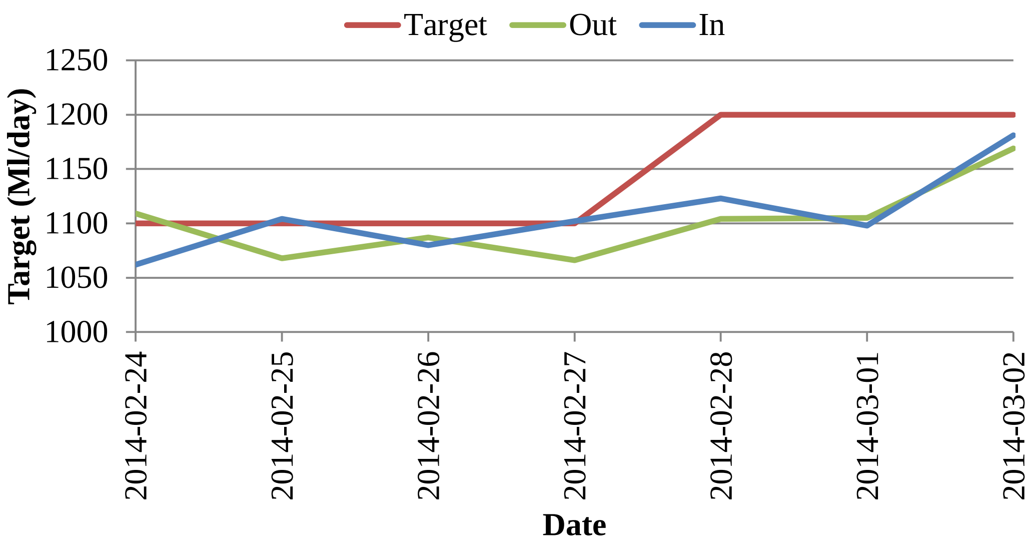


Figure 84: BPS-B daily pumping target (24 February 2014 to 2 March 2014)

It can be seen in the trend that the amount of water pumped into BPS-B and the amount of water pumped out of BPS-B were equal. The load shift had little effect on the downstream reservoirs' levels when compared with the demand and the daily target.

Cost savings

The cost savings as a result of the week's testing can be seen in Table 18.

Table 18: BPS-B cost savings

TOU period	R/kW (Eskom low demand season)	Baseline pumping cost	Optimised profile pumping cost
Peak	2.1221	R354 845	R333 545
Standard	0.8208	R344 462	R348 815
Off-peak	0.5908	R157 579	R161 134
Total		**R856 885**	**R 843 494**
Average saving per day: R13 391			

As shown in Table 18, R13 391 was saved on average per weekday. The cumulative saving was R66 950.

5.3.4 BPS-C

During the period of 3–7 March 2014, a test was conducted on BPS-C. Although data was captured for a seven day period from 3-9 March 2014, the test focusses on the weekdays only. A decision was made to switch off a pump set in Engine Room 3 that was dedicated to Res-C1. The pump was switched off at 17:55, just before the Eskom evening peak period.

After the Eskom evening peak period, the pump operator was instructed to continue with operations as usual. This test used the Res-C1 downstream reservoir as storage capacity. A pump set was switched off from 17:55 to 20:00 as seen in Figure 85. The evening peak average saving achieved was 2 MW.

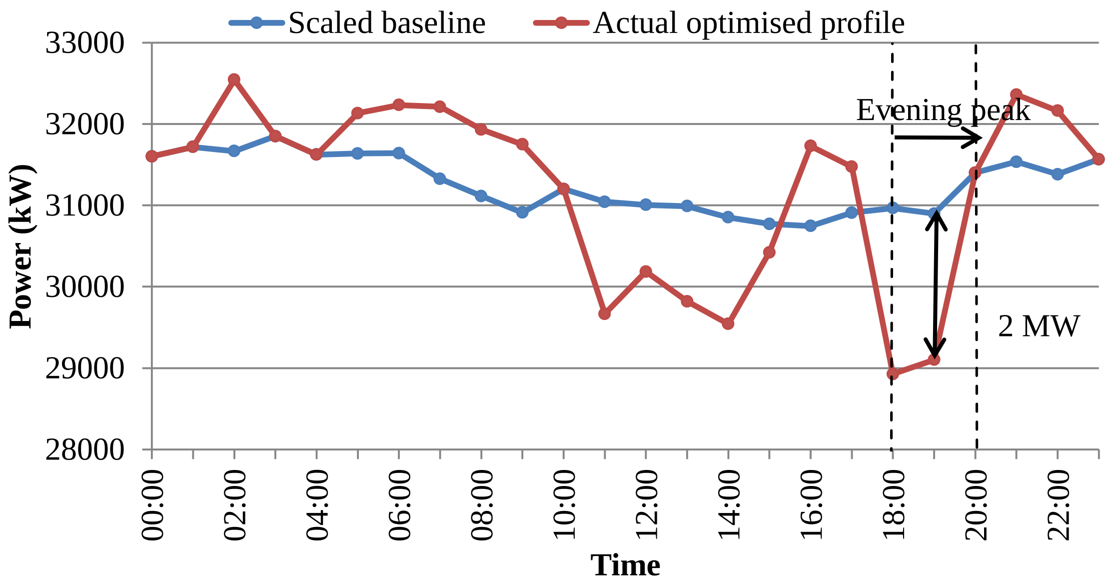


Figure 85: BPS-C average daily power baseline versus actual average daily power profile (3–7 March 2014)

Impact on reservoirs

The load shift test consisted of switching off one 200 M l/day pump set that supplied water to Res-C1. Figure 86 shows the impact on the water levels of the balancing reservoirs.

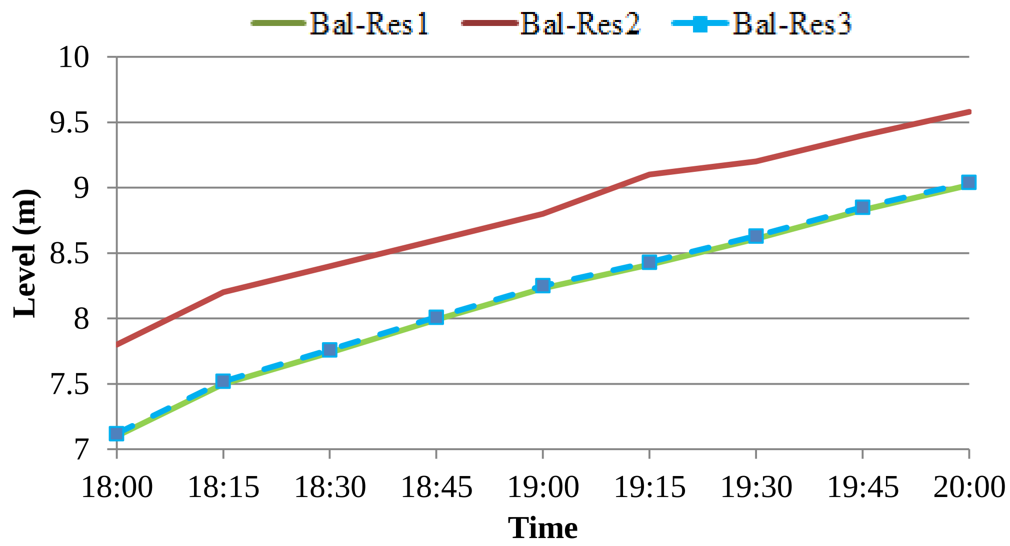


Figure 86: Average balancing reservoir levels during peak periods for the test days (3–5 March 2014 and 7 March 2014)

As confirmed by the simulation, the balancing reservoirs had the capacity to absorb the excess flow from the water treatment works. Figure 87 shows the impact on Res-C1 as well as the power usage of BPS-C.

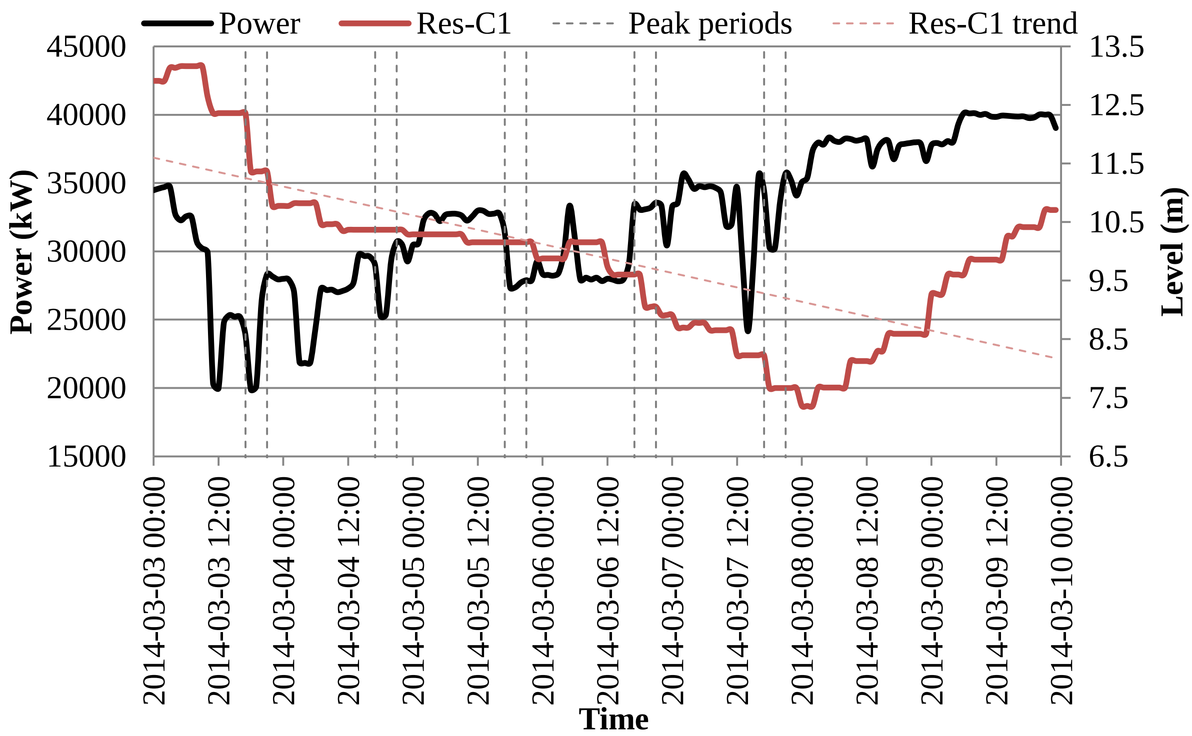


Figure 87: Distribution reservoir levels (3–10 March 2014)

On 7 March 2014, BPS-B was offline for five hours due to Eskom load shedding in the area. This made it impossible to do a safe load shift on BPS-C. Water was sent from BPS-C to the BPS-B balancing reservoirs to help BPS-B maintain the distribution reservoir levels. No load shifting took place that evening because the levels of the balancing reservoir levels were high and the power profile would show no significant saving on the baseline.

This could be contributed to the fact that the pumps were only started at 17:00 to compensate for the problems at BPS-B. Figure 87 also reflects this. Although Res-C1 has two reservoirs, only one level indicator can be seen. The second level indicator has been out of commission since the beginning of the 2014.

The effect of load shifting on the water levels of the reservoir was small when compared with the demand and other problems experienced throughout the week. On 3 March 2014, the Res-C1 level was above the upper limit and pumping to the reservoir was decreased. Figure 86 shows that on 4 and 5 March 2014 the load shift had no effect on Res-C1.

Daily target

The daily targets were met throughout the week as shown in Figure 88. The water that reached BPS-C was pumped away on the same day.

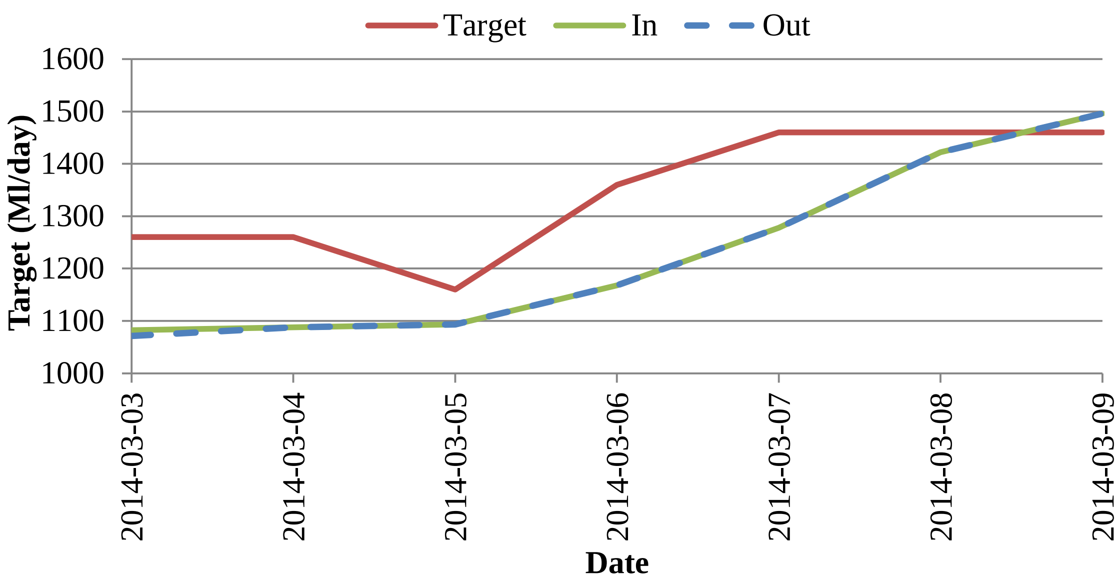


Figure 88: BPS-C daily pumping target (3–10 March 2014)

It can be seen in the trend that the amount of water pumped into BPS-C and the amount of water pumped out of BPS-C were equal. Demand and the daily target had a greater effect on the downstream reservoirs than load shifting.

Cost savings

The cost savings as a result of the week's testing can be seen in Table 19.

Table 19: BPS-C cost savings

TOU period	R/kW (Megaflex, Eskom low demand season)	Baseline pumping cost	Optimised profile pumping cost
Peak	0.6568	R101 947	R101 035
Standard	0.4520	R154 256	R153 698
Off-peak	0.2868	R72 439	R73 191
Total		**R328 643**	**R327 925**
Average saving per day: R717			

As shown in Table 19, R717 was saved on average per weekday. The cumulative saving was R3 585 for the week.

5.3.5 BPS-D

During the period of 3–7 February 2014, a test was conducted on BPS-D. Although data was captured for a seven day period from 3-9 February 2014, the test focusses on the weekdays only It was decided to switch off a pump set (1 900 kW) in Engine Room 1, which are dedicated to Res-D1. Only one pump was switched off at 17:50 before the Eskom evening peak period commenced.

After the Eskom evening peak period, the pump operator was instructed to continue with operations as usual. This test used the Res-D1 distribution reservoir as storage capacity. A pump set was switched off from 17:50 to 20:00 as shown in Figure 89. The baseline was adjusted to energy neutral. The evening peak average saving achieved was 1.3 MW.

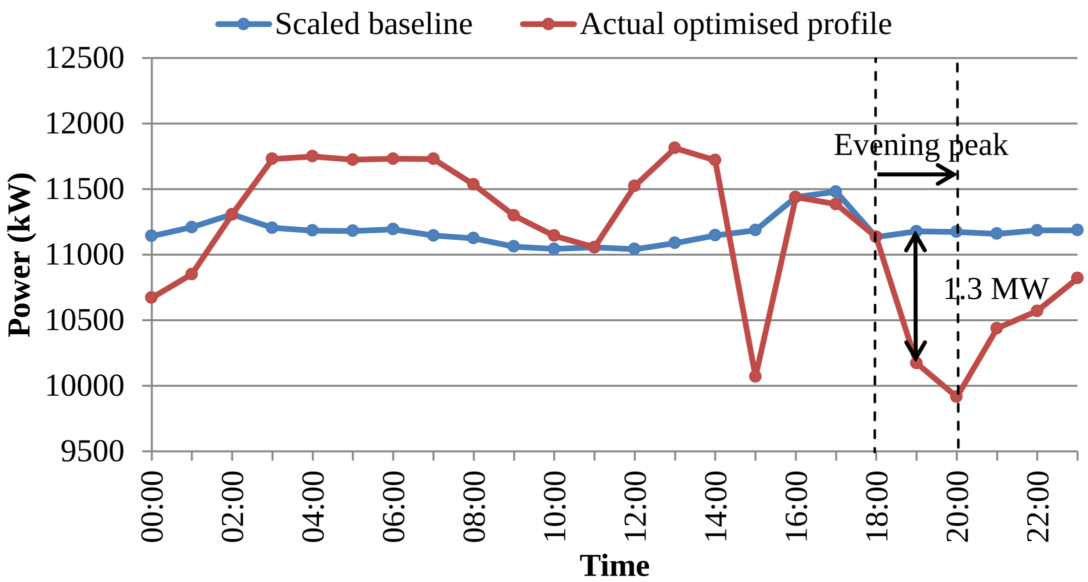


Figure 89: BPS-D average daily power baseline versus actual average daily power profile (3–7 February 2014)

Impact on reservoirs

The load shift test consisted of switching off one 100 Ml/day pump set that supplied water to Res-D1. Figure 90 shows the impact on the balancing reservoirs.

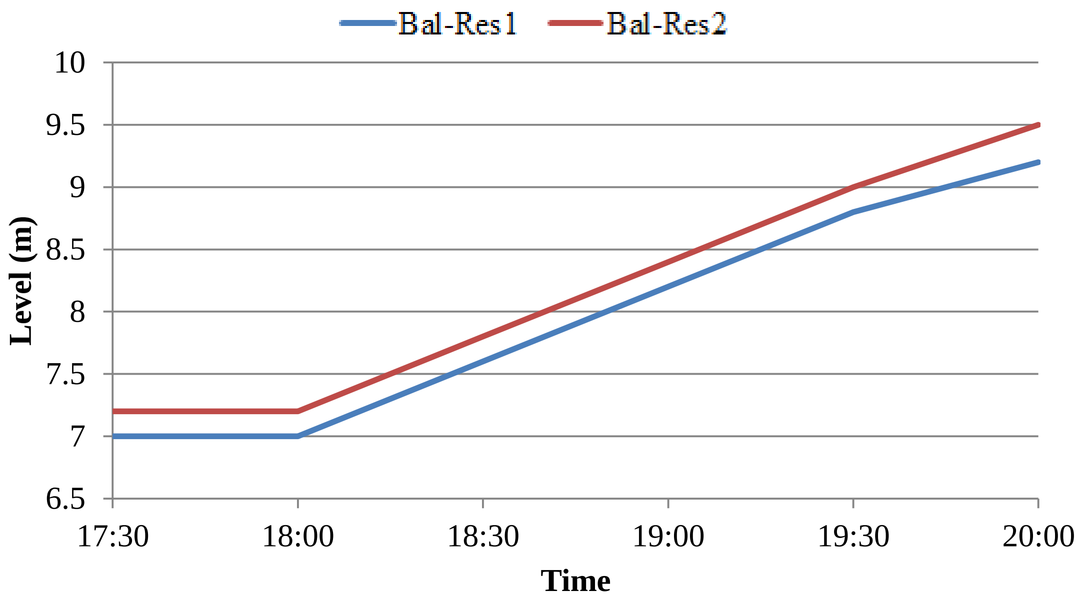


Figure 90: BPS-D Average balancing reservoir levels during peak periods for the test days (3–9 February 2014)

As confirmed by the simulation, the balancing reservoirs had the capacity to absorb the excess flow from WTW-A as shown in the optimisation model. The high balancing reservoir levels ensured that pumping capacity could be increased safely during the night to take advantage of the less expensive off-peak period. Figure 91 shows the effect on Res-D1.

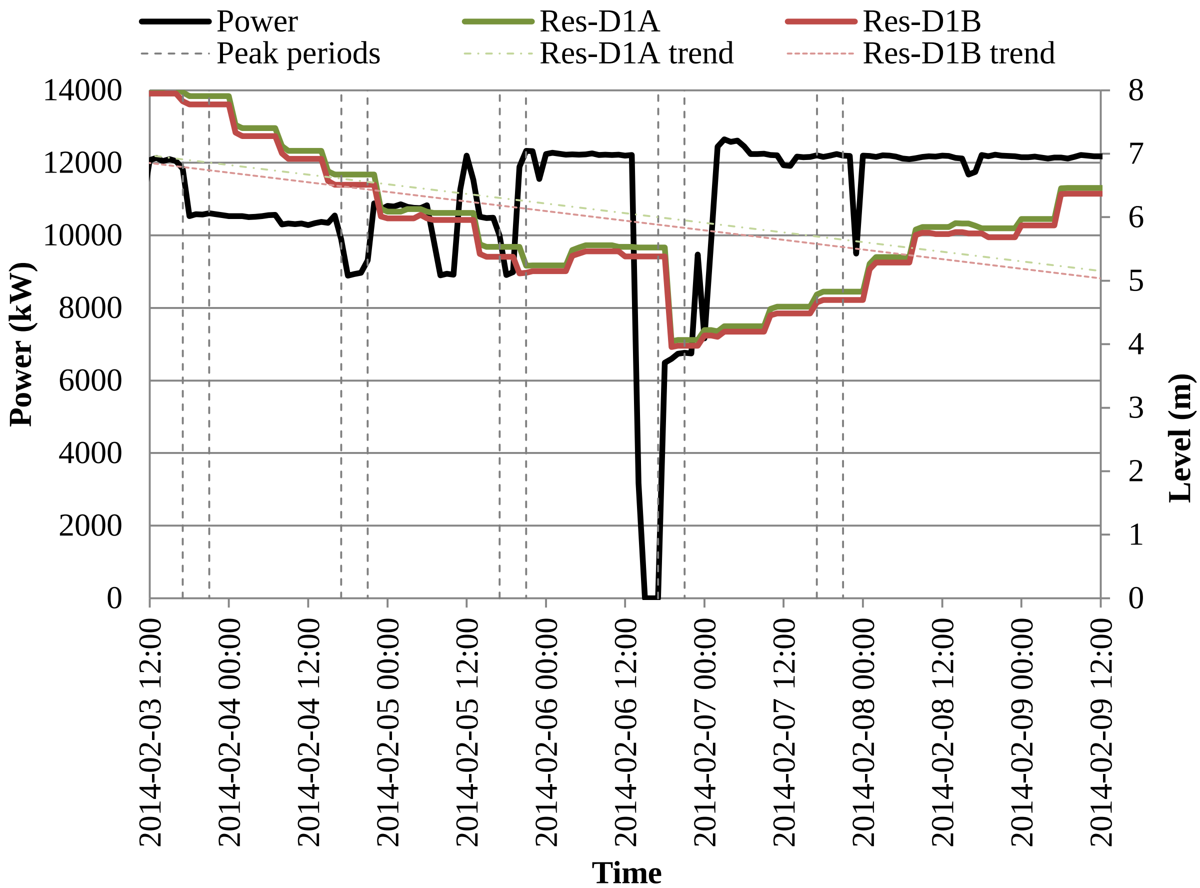


Figure 91: Distribution reservoir levels (3–9 February 2014)

After a trip occurred on 6 February 2014, it was decided to stop the tests for the rest of the week. During the week the demand increased and the trip that occurred was responsible for the downward curve of the Res-D1 level.

Daily target

The daily targets were met throughout the week as shown in Figure 92. The water that reached BPS-D was pumped away on the same day.

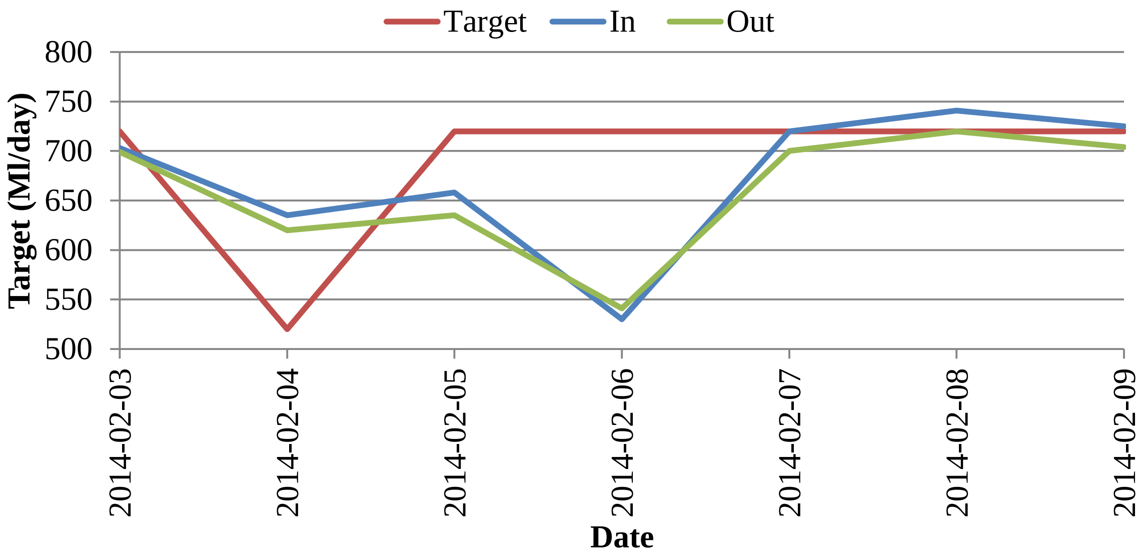


Figure 92: BPS-D daily pumping target (3–9 February 2014)

It can be seen in the trend that the amount of water pumped into BPS-D and the amount of water pumped out of BPS-D were equal. The daily target and demand had a greater effect on the reservoir level than the load shift had.

Cost savings

The cost savings as a result of the week's testing can be seen in Table 20. As shown in Table 20, R604 was saved on average per weekday. The cumulative saving was R3 020 for the week.

Table 20: BPS-D cost savings

TOU period	R/kW (Ekurhuleni, Eskom low demand season)	Baseline pumping cost	Optimised profile pumping cost
Peak	0.99	R65 481	R64 063
Standard	0.65	R72 399	R72 678
Off-peak	0.51	R45 658	R46 193
Total		**R183 539**	**R182 935**
Average saving per day: R604			

5.4 Conclusion

All the data for the load shift tests that were conducted was obtained from MOL. The test performed on BPS-A was a success and the set target was exceeded. It was established that balancing reservoirs could be used to optimise the pumping schedule. The daily target was met throughout the week.

The test done on BPS-B was a success and the target was exceeded. As confirmed by the simulation, the balancing reservoirs would absorb the excess flow. Using the balancing reservoirs, the load shift could be scheduled. The daily target was met throughout the week and no water was lost. It was confirmed that load shifting could be done even though the daily target was 1 200 Ml/day.

The test on BPS-C was challenging. As confirmed by the simulation, the balancing reservoirs would absorb the excess flow. Using the balancing reservoirs, the load shift could be scheduled. The daily target was met throughout the week. If the daily target for BPS-C was below 1 560 Ml/day, a saving of 2.4 MW was achievable.

The test on BPS-D was challenging. As confirmed by the simulation, the balancing reservoirs would absorb the excess flow. Using the balancing reservoirs, the load shift could be scheduled. The daily target was met throughout the week and no water was lost.

All the tests showed that load shifting had a negligible effect on the water level of the downstream reservoirs when compared with the demand and the daily target. Generally, the tests were completed successfully.

The outcome of the results was that load shifting could be done on all four subsystems in WDU-A by using the demand-balancing reservoirs. Electricity cost savings were achieved on the individual subsystems. Due to the constraints discussed with rising demand and so forth, the integrated model could not be implemented. As a result, the simultaneous load shifts on all six the pumping stations could not take place. The integrated optimisation model gave a forecast of the possible electricity cost savings that could be achieved if implemented.

6 Conclusion

Figure 93: Engine Room from the outside

The outside of an Engine Room located at WTW-A.

6.1 Summary

In South Africa, rising electricity prices and a shortage in electricity supply create a need for electricity cost saving interventions such as DSM initiatives. Eskom introduced the DSM programme, which focuses on reducing electrical energy demand during peak periods of the day. The reader was informed about the benefits of an electricity cost saving intervention of such a nature.

It was shown in Chapter 2 that there is an information shortage regarding energy and energy efficiency in the water industry. These aspects, in the light of electricity cost savings, were discussed in this dissertation. It was also found that there is not much research done, regarding energy used by large WDUs that consists of more than one pumping station and more than one reservoir.

An investigation methodology for the integration of electricity cost saving intervention on WDU was developed. A real-life WDU (WDU-A) in South Africa was selected as a case study. The case study was used to test the methodologies and strategies developed in this dissertation. The investigation methodology was applied to WDU-A and information was gathered.

WDU-A was analysed in terms of its control strategy. Problems for the intervention were identified. An integrated intervention strategy was developed and, with the aid of an optimisation model, tested. Infrastructure needed for the success of the integrated strategy was mentioned. A great deal of infrastructure is necessary in order to see all the required information and to obtain good data.

Due to the vulnerability of WDU-A, the integrated strategy could not be tested fully. The strategy required load shifting to take place on all the pumping station in WDU-A at the same time. Load shift tests were conducted on all four BPSs in the four subsystems of WDU-A, but not on one of the water treatment works. A total of 15.4 MW load shift was achieved using the demand-balancing reservoirs. An integrated electricity cost saving of R18 376 for an average day was achieved during the load shift tests.

Integration of electricity cost saving interventions on a WDU is viable and beneficial if implemented. If the water capacity of WDU-A increases, it can be fully tested and verified if the optimisation model predictions are correct.

6.2 Recommendations

In this study, it was found that it is possible to integrate electricity cost saving interventions on the integrated subsystems of a WDU. It was shown that the interventions quantified to the total WDU. The methodology and strategies discussed in this dissertation can be rolled out to other large WDUs in South Africa.

Considering the constraints listed in Section 5.3 regarding the implementation of the proposed strategy, it is recommended that more data is obtained. To obtain more data, certain upgrades are needed on the case study WDU. Each project and each WDU has its own constraints and limitations and more in-depth investigations are required.

To solve the problem of available data and information, large infrastructure upgrades and SCADA upgrades are required. At the time of completion of this dissertation, the upgrades were being implemented. Better available data needs to be verified against the optimisation model to validate the entire study.

It is suggested that the study is tested for different demand seasons with actual demand data. Long-term effects also need to be established through monitoring of the implemented intervention.

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Appendix A – Additional data and information from investigation

1.1 WTW-B

Pumping station

WTW-B is a water treatment works site. It consists of a water purification system and two associated engine rooms from where the potable water is distributed throughout the WDU. WTW-B pumps the water to BPS-A at a head of 87 m, and to BPS-B at a head of 131 m. As is the case for WTW-A, WTW-B is also situated close to the river for easy access to raw water. There are sixteen pump sets at WTW-B. These pumps are situated in Engine Room 2 and Engine Room 4. The number of pumps, and their sizes, can be seen in Table 23.

There are a pump houses that supply raw water to the WTW-B station, namely, Intake Pump House A (IPH-A). IPH-A operates with two engine rooms. The Vaal River is the raw water source for WTW-B. The water treatment process followed at WTW-B station is similar to the process followed at WTW-A. The characteristics of the process components are summarised in Table 21. The total installed capacity of the filtration system's infrastructure is 1 285 kW.

Table 21: Filtration system characteristics

Component	Rated power (kW)
Air blowers	4×90
Wash water pumps	2×75 1×55 1×45
Wash water recovery pumps	3×225

The investigation also included the sludge pumping on the water treatment works to investigate the potential for energy or electricity cost savings. Central sludge receives sludge from three different work areas, two located at WTW-A and one located at WTW-B respectively. From there, the sludge is pumped to the sludge pumping station at a daily average of 2 000 Ml.

Initial information indicated that the sump at central sludge would overflow within one hour if all the pumps at central sludge were turned off. Table 22 shows the characteristics of the sludge pumps.

Table 22: Sludge pumps

Installed capacity	4×300 kW, 12×220 kW
Voltage	400 V
VSDs	Yes

The total installed capacity of the sludge pumps at central sludge was 3 840 kW. The sludge pumping station at WTW-B had two pumps. These pumps were used to convey sludge to the central sludge plant at the WTW-B station. Both these pumps had rated power specifications of 300 kW and were fitted with VSDs.

Table 23: WTW-B pump characteristics

Pump set number	Description	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Pumping destination
10	Smelter pump	33.5	460	–	Smelters
11	Smelter pump	33.5	460	–	Smelters
12	Smelter pump	33.5	460	–	Smelters
13	Low pressure	100	1 950	–	BPS-B
14	Low pressure	100	2 250	–	BPS-B
15	Low pressure	100	1 950	–	BPS-B
16	Low pressure	100	1 950	–	BPS-B
17	Low pressure	100	2 250	–	BPS-B
19	High pressure	200	1 650	3 720	BPS-A
20	High pressure	200	2 072	3 720	BPS-A
21	High pressure	200	1 650	3 720	BPS-A
22	High pressure	200	2 072	3 720	BPS-A
23	High pressure	200	1 650	3 720	BPS-A
23	High pressure	200	2 150	4 100	BPS-A
23	High pressure	200	2 150	4 100	BPS-A
23	High pressure	100	820	2 520	BPS-A

Water flow in the WDU

Five low-pressure pump sets supplied the areas surrounding WTW-B with water. Eight high-pressure pump sets were used to pump water to BPS-A and BPS-B. The high-pressure pumps were sufficient to overcome the head to the BPSs. The remaining three pump sets pumped raw water to a nearby smelter. There were four VSDs, of which two VSDs were connected to low-pressure pumps and two VSDs were connected to high-pressure pumps.

From the information obtained during the investigation, it was found that there was always one high-pressure and one low-pressure line on standby in case of pump breakdowns. The pump characteristics of the WTW-B pumps can be seen in Table 23.

Water storage facilities

As was the case with WTW-A, there were no reservoirs at WTW-B that served as water storage facilities. The raw water was pumped directly from the intake pumps to WTW-B, where it entered the purification process. The potable water was then stored in a sump before it was pumped to the BPSs.

Typical power consumption

It was identified that the pumps were the largest electricity users at the water treatment works. An average power profile was obtained for the pumps' energy usage during weekdays. The profile is shown in Figure 94. The power baseline for an average weekday was just above 25 000 kW.

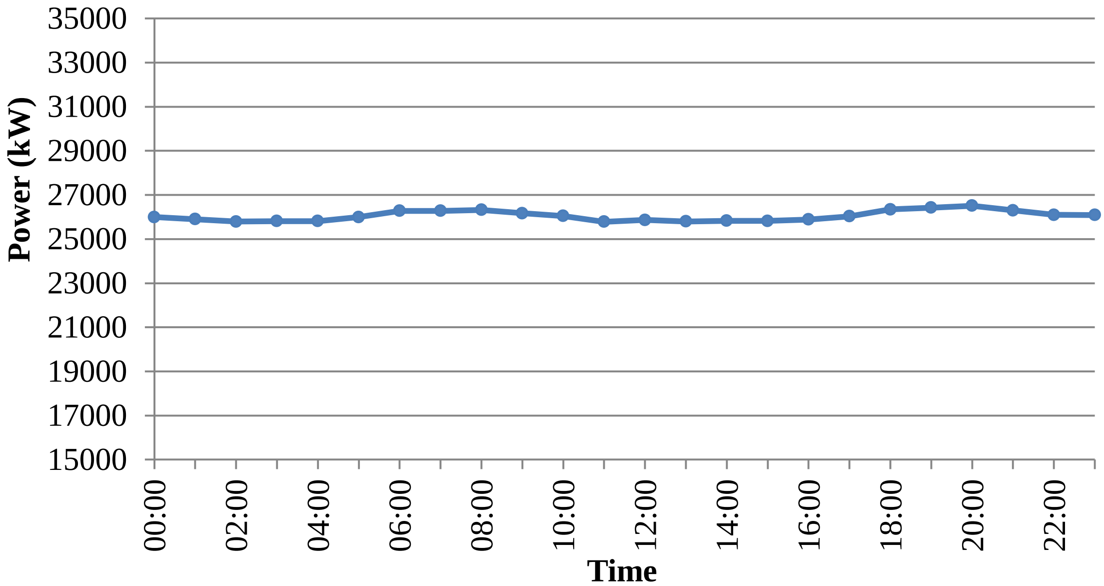

Figure 94: WTW-B average power baseline

Tariff structure

As discussed in Section 1.3.1, different tariff structures influenced the cost savings. WTW-B used the Emfuleni tariff structure.

Integrated layout

The integrated layout of WTW-B is shown in Figure 95.

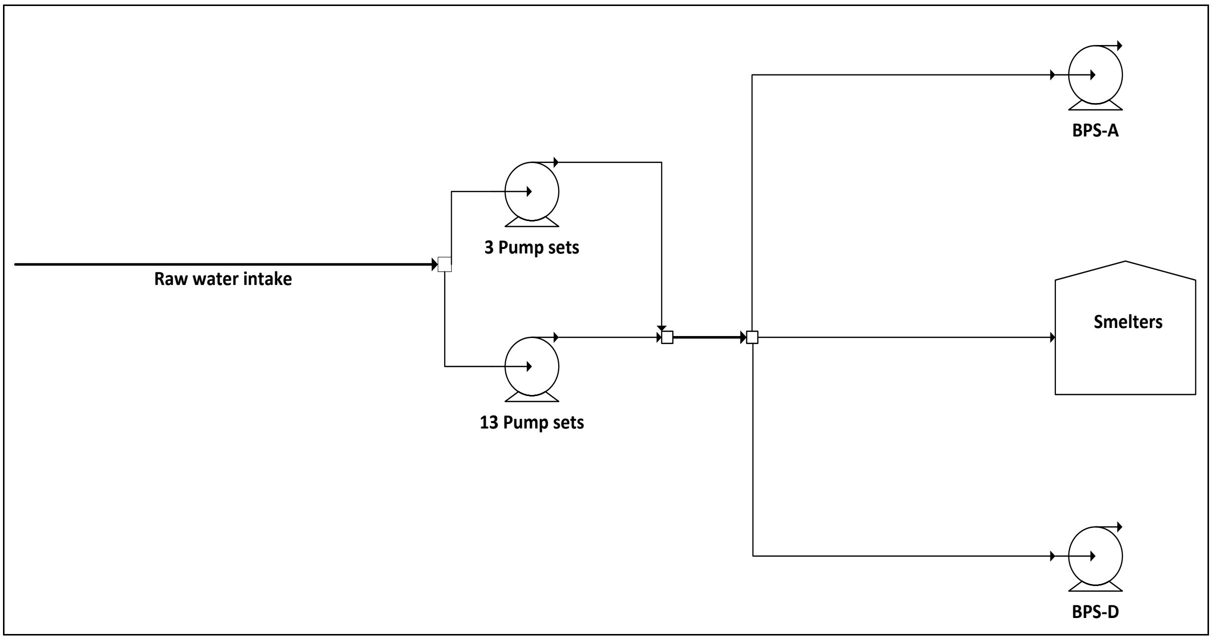

Figure 95: WTW-B water treatment works layout

Demand

As was the case with WTW-A, the demand from WTW-B was primarily linked to the amount of water that the BPSs needed. WTW-B was well established and supplied the surrounding areas using five low-pressure pumps. The primary demand still originated from BPS-A and BPS-B.

1.2 BPS-B

Pumps

BPS-B is the second BPS in WDU-A. This booster station had three engine rooms. Engine Room 1 has eight pump sets, and Engine Room 2 has five pump sets. Both Engine Room 1 and Engine Room 2 supply Res-A1 and Res-B1. Engine Room 3 has four pump sets and is dedicated to Res-A1. Table 24 gives the pump characteristics including the number of pump sets and the individual pumps' installed capacities.

Table 24: BPS-B pump characteristics

Pump set number	Engine room number	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Pumping destination
1	1	100	1 508	1 508	Res-A1/Res-B1
2	1	100	1 508	1 508	Res-A1/Res-B1
3	1	100	1 508	1 508	Res-A1/Res-B1
4	1	100	1 508	1 508	Res-A1/Res-B1
5	1	100	1 508	1 508	Res-A1/Res-B1
6	1	100	1 508	1 508	Res-A1/Res-B1
7	1	100	1 508	1 508	Res-A1/Res-B1
8	1	100	1 508	1 508	Res-A1/Res-B1
9	2	200	2 978	3 896	Res-A1
10	2	200	2 978	3 896	Res-A1
11	2	200	2 978	3 896	Res-A1
12	2	200	2 978	3 896	Res-A1
18	3	200	300	3 900	Res-A1
19	3	200	300	3 900	Res-A1
20	3	200	300	3 900	Res-A1
21	3	200	300	3 900	Res-A1

Water flow in the WDU

Potable water is supplied to BPS-B from WTW-B and WTW-A. Excess water received from the water treatment works will bypass the suction valve and enter the balancing reservoirs. From BPS-B, the water is pumped to Res-A1 and Res-B1. From the distribution reservoirs, water is distributed to the final water user.

Water storage facilities

There are three balancing reservoirs at BPS-B. These balancing reservoirs handle the excess water in the system. It can also act as buffer capacity in the event of water loss from the water treatment works. The size of each individual reservoir is 20 Ml. It adds up to a total balancing reservoir capacity of 60 Ml.

The distribution reservoirs that BPS-B supplies have the following capacities:

- Res-A1: 200 000 m^3
- Res-B1: 323 000 m^3

Typical power consumption

The power consumption for BPS-B can be seen in the baseline shown in Figure 96. It can be seen that the baseline was around 35 000 kW.

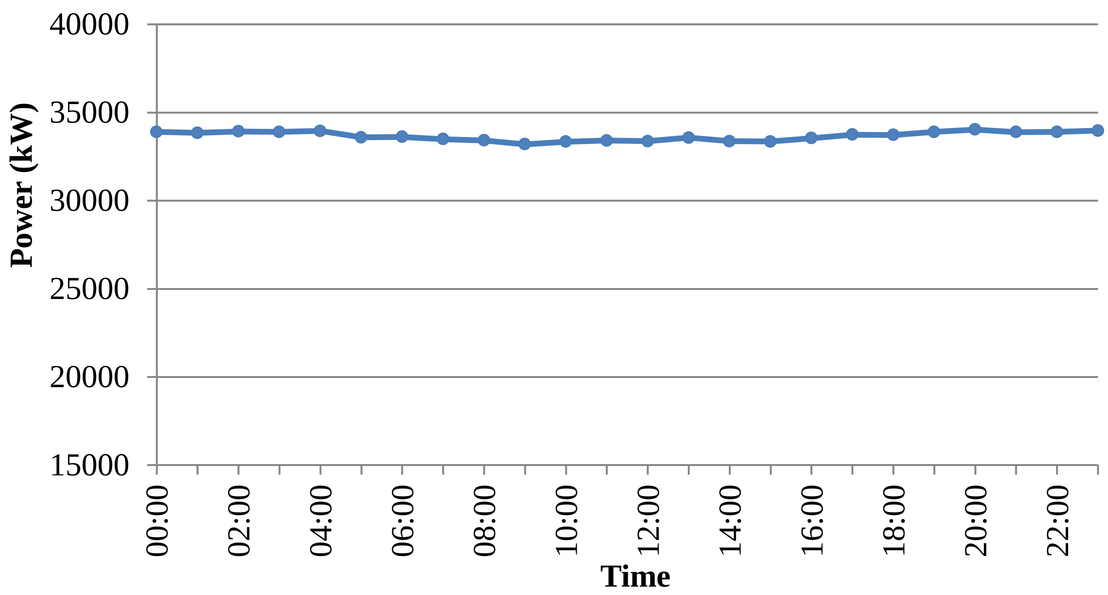

Figure 96: BPS-B average weekday power usage baseline

Tariff structure

BPS-B was billed using the Emfuleni TOU tariff structure. The tariff structure rates can be seen in Section 5.3.3.

System integrated layout

The simplified layout for BPS-B is shown in Figure 97.

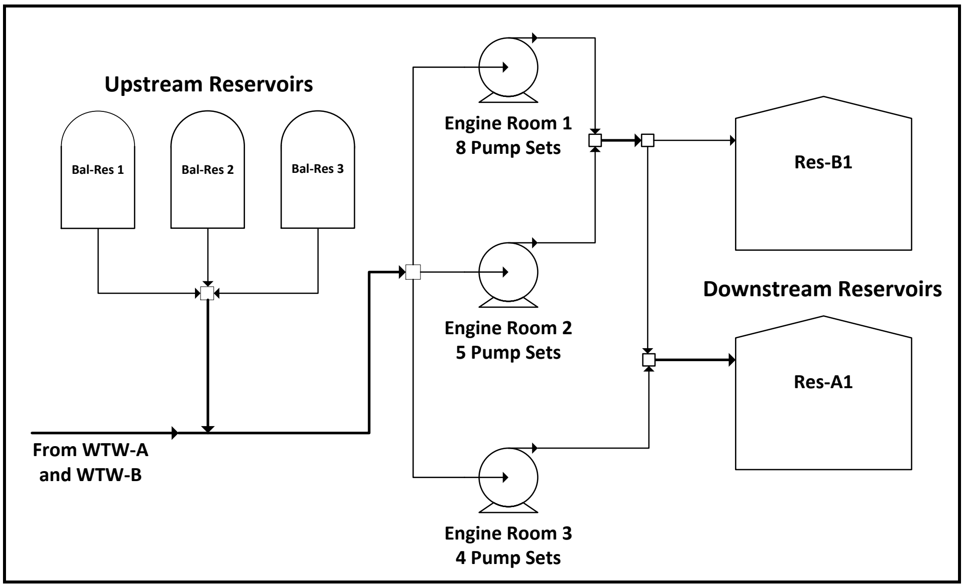

Figure 97: BPS-B integrated layout

Demand

The demand was calculated in the same manner as BPS-A in Section 3.4.1. Table 25 represents the demands on the relevant reservoirs during the four seasons of the year. The demand is given in total flow (ℓ/s).

Table 25: Reservoir demands for BPS-B

		Res-A1	Res-B1
	Average	**2 239.00**	**9 774.39**
Summer	Max	3 738.66	11 954.28
	Min	0.00	8 170.49
	Average	**2 632.14**	**10 155.71**
Autumn	Max	3 943.98	12 141.20
	Min	1 319.68	7 823.26
	Average	**3 080.36**	**9 574.37**
Winter	Max	3 819.21	12 208.91
	Min	2 062.96	8 132.18
	Average	**3 632.49**	**9 990.34**
Spring	Max	4 362.27	10 844.10
	Min	2 824.31	8 734.03

1.3 BPS-C

Pumps

BPS-C is also a booster pumping station in the WDU-A network. The site has three engine rooms. Engine Room 1 has seven pump sets and supplies the Res-C1 and Res-C2 reservoirs. Engine Room 2 has nine pump sets and Engine Room 3 has four pump sets, both dedicated to supplying Res-C1. Table 26 shows the number of the pump sets and the installed capacity.

Table 26: BPS-C pump characteristics

Pump set number	Engine Room number	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Pumping destination
1	1	70	1 450	1 450	Res-C1
2	1	70	1 450	1 450	Res-C1
3	1	70	1 450	1 450	Res-C1
4	1	70	1 450	1 450	Res-C1
5	1	70	1 450	1 450	Res-C1
6	1	70	1 450	1 450	Res-C1
7	1	70	1 450	1 450	Res-C1
8	2	40	2 740	2 740	Res-C1
9	2	40	2 740	2 740	Res-C1
10	2	40	2 740	2 740	Res-C1
11	2	40	2 740	2 740	Res-C1
12	2	40	2 740	2 740	Res-C1
13	2	25	5 27	527	Res-D1
19	2	25	527	527	Res-D1
20	2	25	527	527	Res-D1
21	2	25	527	527	Res-D1
21	2	50	940		Res-D1
1	3	200	2 130	3 880	Res-C1
2	3	200	2 130	3 880	Res-C1
3	3	200	2 130	3 880	Res-C1
4	3	200	2 130	3 880	Res-C1

Water flow in the WDU

BPS-C receives water from WTW-A. Water is pumped from WTW-A directly to BPS-C. Excess water is absorbed by the balancing reservoirs. BPS-C feeds potable water to Res-C1 and Res-C2.

Water storage facilities

As with the BPS-B, there are three balancing reservoirs at BPS-C. They act as buffer capacity and absorb excess water from the water treatment works. These balancing reservoirs also have individual storage capacities of 20 Ml. The total adds up to 60 Ml. Res-C1 and Res-C2 have the following capacities:

- Res-C2: 200 000 m^3
- Res-C1: 980 000 m^3

Typical power consumption

Figure 98 represents the baseline profile for the power usage average of the BPS on a weekday basis. The power baseline averaged just below 40 000 kW.

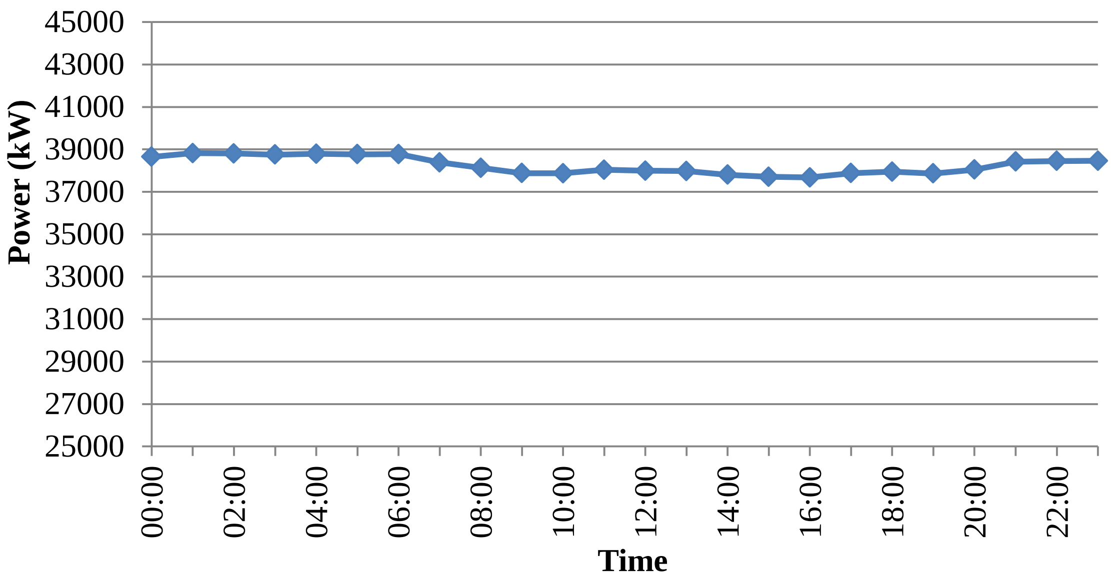

Figure 98: BPS-C average weekday power usage baseline

Tariff structure

BPS-C was on the Megaflex TOU tariff structure of Eskom. The tariff rates were applicable as can be seen in Section 5.3.4.

System integrated layout

Figure 99 shows a simplified layout of the BPS-C system.

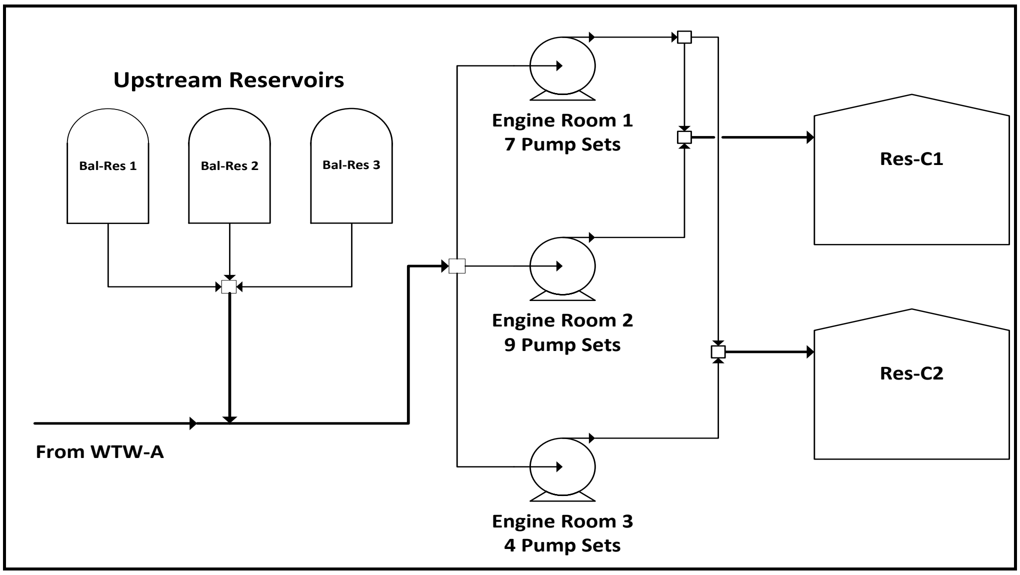

Figure 99: BPS-C integrated layout

Demand

The demand was calculated using the same method as for BPS-A in Section 3.4.2. Table 27 represents the demands on the relevant reservoirs during the four seasons of the year. The demand is given in total flow (ℓ/s).

Table 27: Reservoir demand for BPS-C

		Res-C1	Res-C2
Summer	**Average**	**15 029.12**	
	Max	17 891.20	–
	Min	11 069.44	–
Autumn	**Average**	**16 175.93**	
	Max	19 787.04	–
	Min	9 668.98	–
Winter	**Average**	**16 565.25**	**599.79**
	Max	17 900.46	2 642.82
	Min	14 902.78	106.02
Spring	**Average**	**16 551.67**	**388.57**
	Max	19 729.17	1 666.44
	Min	10 909.72	20.60

1.4 BPS-D

Pumps

BPS-D is the fourth and the last of the BPSs assigned to each of the four WDU subsections. BPS-D has two engine rooms. Engine Room 1 has eight pump sets and is dedicated to Res-D1. Engine Room 2 has three pump sets and pumps to Res-D2. Table 28 represents the pump characteristics, including the installed capacities of the individual pumps.

Table 28: BPS-D pump characteristics

Pump set number	Engine Room number	Pump capacity (Ml/day)	Power – 1st stage (kW)	Power – 2nd stage (kW)	Pumping destination
1	1	100	740	1347	Res-D1
2	1	100	740	1347	Res-D1
3	1	100	1 902	–	Res-D1
4	1	100	1 902		Res-D1
5	1	200	643	3 263	Res-D1
6	1	200	643	3 263	Res-D1
7	1	200	1 950	1 950	Res-D1
12	1	200	1 950	1 950	Res-D1
13	2	40	250	1 450	Res-D2
10	2	40	250	1 450	Res-D2
11	2	40	250	1 450	Res-D2

Water flow in the WDU

BPS-D feeds potable water to Res-D1 and Res-D2. The potable water pumped from Mapleton is received from WTW-A, which is a smaller subsystem than the other three subsystems. Res-D1 is the primary receiver of water pumped from BPS-D.

Water storage facilities

BPS-D has two balancing reservoirs, each with 20 Ml storage capacity. Excess water is absorbed by the balancing reservoirs. The capacities of the two destination reservoirs are:

- Res-D1: 166 000 m^3
- Res-D2: 14 000 m^3

Typical power consumption

Figure 100 represents the BPS-D power baseline for a daily average profile. The power baseline was just below 12 000 kW.

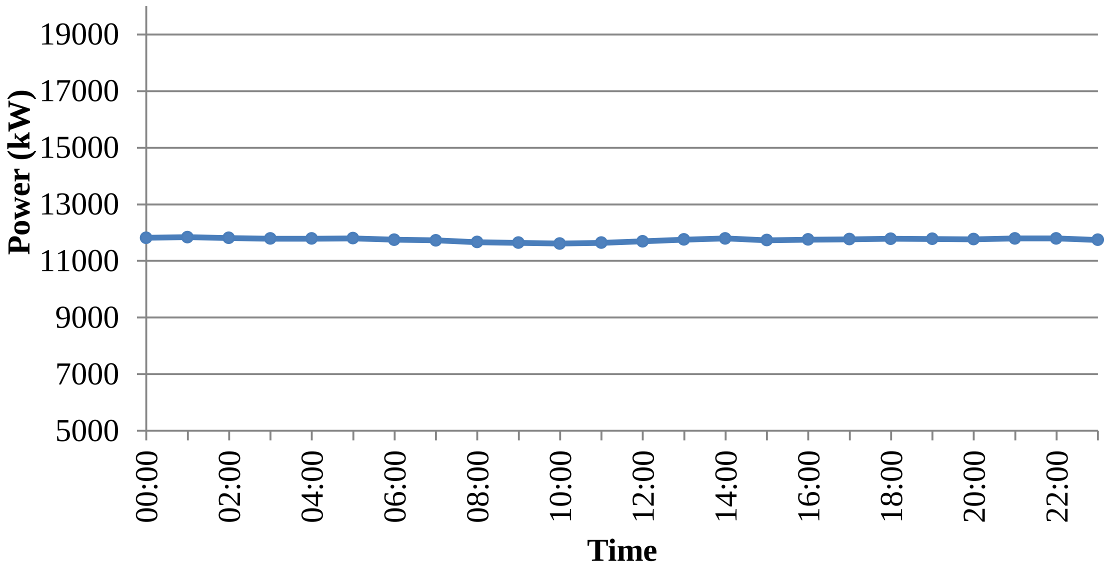

Figure 100: BPS-D average weekday power usage baseline

Tariff structure

BPS-D was billed according to the Eskom TOU tariff. The tariff rates applicable were shown in Section 5.3.5.

System integrated layout

Figure 101 is a simplified layout of the BPS-D system.

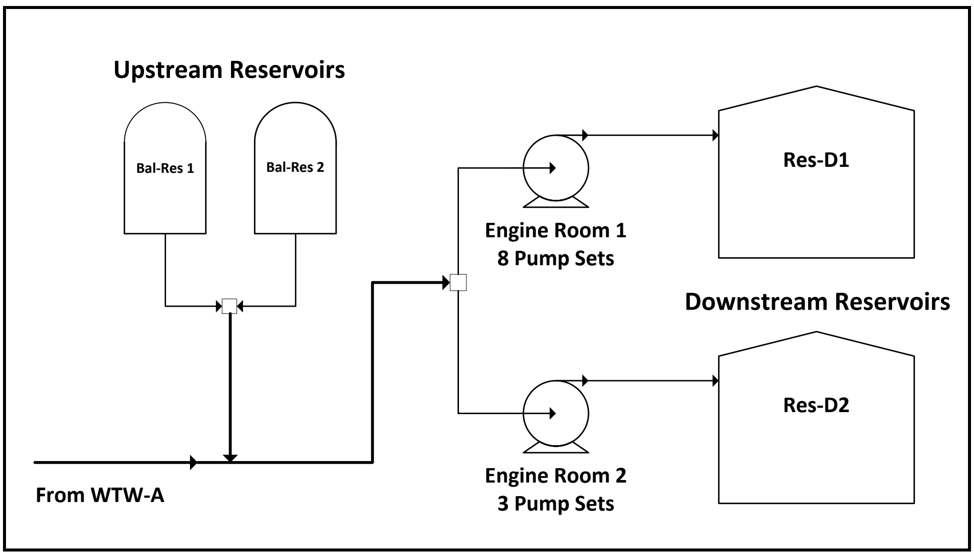

Figure 101: BPS-D integrated layout

Demand

The demand was calculated using the same methods as for BPS-A in Section 3.4.2. Table 29 represents the demands on the relevant reservoirs during the four seasons of the year. The demand is given in total flow (ℓ/s).

Table 29: Reservoir demand for BPS-D

		Res-D1	Res-D2
Summer	**Average**	**7 099.**71	
	Max	8 177.55	–
	Min	3 645.72	–
Autumn	**Average**	**7 285.90**	
	Max	9 009.26	–
	Min	4 230.67	–
Winter	**Average**	**7 008.05**	**307.66**
	Max	8 387.73	733.56
	Min	116.55	45.49
Spring	**Average**	**7 918.99**	**307.23**
	Max	9 207.87	818.98
	Min	4 853.94	37.50