Quantifying the effects of system constraints on the electricity cost of dewatering pumps

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ABSTRACT

Title: Quantifying the effects of system constraints on the electricity cost of dewatering pumps

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Eskom embarked on a capacity expansion programme in 2005. The capacity expansion programme is being funded by above-inflation electricity tariff increases, which put large electricity consumers such as mines under financial pressure. The implementation of demand side management (DSM) initiatives has become an important measure to offset the impact of above-inflation electricity tariff increases in the mining industry.

Mine dewatering pumps consume approximately 15% of the total electricity used at gold mines. The implementation of DSM initiatives on dewatering pumps can result in significant cost savings. Unfortunately, various constraints may negatively affect the cost savings generated by DSM initiatives on mine dewatering pumps. The system constraints include low pump efficiencies, low pump availability, low water storage capacity and high water inflow.

The aim of this research is to quantify the effects of these system constraints on the electricity cost of dewatering pumps. Simulations were done to determine the cumulative cost effect of reducing the impact of the system constraints. The constraints to the electricity costs of the dewatering system were changed individually to quantify effects of each of the constraints. The effect of these changes were also added together to obtain a cumulative cost saving. It was found that cumulative savings of R21.57 million per annum are possible if an improvement strategy to reduce the impact of the system constraints could be implemented.

The possible savings were also compared with the savings achieved when manual load shifting was done on the same mine. This manual load-shifting attempt was done by doing daily load shifting by stopping and starting pumps according to load-shifting possibilities. A brief overview was also given of a mine of which the mine dewatering system was being maintained properly.

This study concluded by summarising the outcomes and making recommendations towards future studies.

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I would firstly like to start by thanking our Creator and Father for being in a position to learn so much, for having the privilege of being alive and honouring Him. He has also carried me through tough times and brought me back from the brink of death to be able to honour Him and praise Him with my life.

“But now this is what the LORD says, the one who created you, Jacob, the one who formed you, Israel: Do not be afraid, because I've redeemed you. I've called you by name; you are mine. ~ Isaiah 43:1”

I would also like to thank my parents, Gawie and Marietjie Stols, for raising me to become who I am today. You are an inspiration to me and an example to live by. I know you have had sleepless nights about me. Thank you for all your love and care, and the time you have dedicated to helping me when I needed it. I can honestly say that I am truly blessed to have people like you as parents. Thank you for your support and interest in my progress on this dissertation. My siblings, Gawie, Petrus and Madelie Stols, I thank you for who you are. Thank you for your love and support during difficult times.

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ABBREVIATIONS

3CPFS	Three-Chamber Pipe Feeder System
BAC	Bulk Air Cooler
BEP	Best Efficiency Point
CFC	Chlorofluorocarbon
DSM	Demand Side Management
NPSH	Net Positive Suction Head
OCGT	Open Cycle Gas Turbine
PLC	Programmable Logic Controller
PRV	Pressure-reducing Valve
REMS	Real-Time Energy Management System
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-Use
WSO	Water Supply Optimisation

UNITS OF MEASURE

C	Cost	R
D	Number of days	NA
g	Gravitational acceleration	m/s^2
GWh	Unit of energy in billions	Gigawatt-hour
H	Head	m
kWh	Unit of energy in thousands	Kilowatt-hour
L	Dam level	%
ℓ	Unit of volume	Litre
m	Unit of length	Metre
Ml	Unit of volume	Megalitre
MVA	Apparent power	Megavolt ampere
MWh	Unit of energy in millions	Megawatt-hour
N	Unit of rotational speed	rev/s
P	Pressure	Pa
ppm	Count of dissolved solids in a solution	Particles per million
P_s	Shaft power	kW
Q	Flow rate	ℓ/s or m^3/s
T	Time	s
V	Volume	m^3
W	Unit of power	Watts
°C	Unit of temperature	Degrees Celsius
ρ	Density	kg/m^3
Ƞ	Unit of efficiency	NA

CHAPTER 1. INTRODUCTION

1.1 Electricity in South Africa

Eskom is the national power utility of South Africa. It supplies approximately 95% of all electricity consumed in South Africa [1]. The difference between supply capacity and demand is known as the reserve margin [2]. Eskom's reserve margin was 24.6% in 2000 but it fell to an all-time low of 5.6% in 2007 [3]. This was well below the international recommended minimum reserve margin of 15% [4]. Eskom's reserve margin for the 1999 to 2011 period is shown in Figure 1.

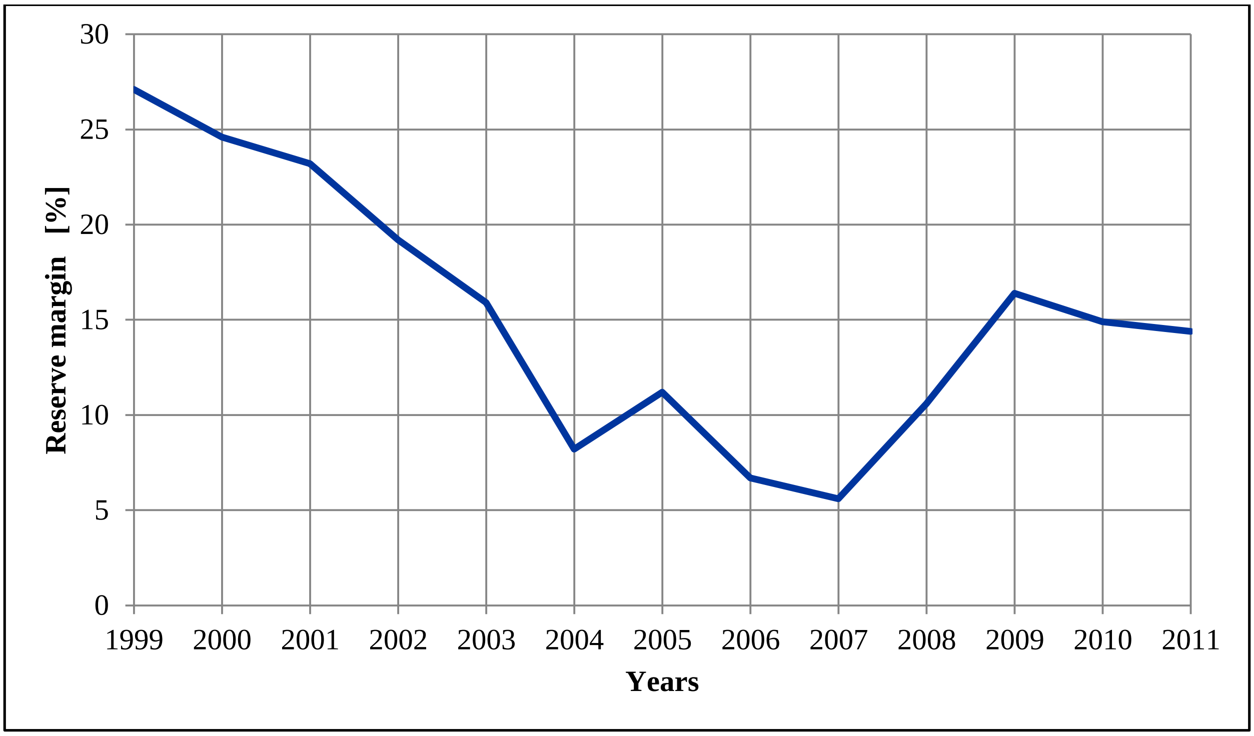


Figure 1: Eskom reserve margin (Adapted from [3])

Peak electricity demand in South Africa decreased by 8.2% from January 2013 to May 2015 [5]. Unfortunately, the electricity supply capacity has also been decreasing, which resulted in a further reserve margin reduction. The reserve margin deteriorated to an average of -2% during peak demand periods in May 2015 [6]. The low reserve margin resulted in rolling blackouts, also known as load shedding, being implemented from January to April 2008. Frequent load shedding has been occurring since November 2014 when a coal silo collapsed at the Majuba power plant [7]. Load shedding is detrimental to the economy of South Africa [8].

Eskom's inadequate reserve margin resulted in a generation capacity expansion programme being implemented in 2005. The recommissioning of mothballed power plants was the immediate objective of the expansion programme. The capacity expansion programme also included constructing new coal-fired power plants, which has a lead-time of seven years or more. The recommissioning of the mothballed plants was completed in a relatively short period, but the construction of new coal-fired power plants has been plagued by various delays [9].

The long lead-time needed for the construction of coal-fired power plants meant a speedier solution was needed. Eskom, therefore, decided to build open cycle gas turbine (OCGT) power plants. These power plants were only intended to be used during peak periods since they can be started and stopped easily. The high running cost of OCGT power plants (when compared with the running cost of coal-fired power plants) makes them too cost-intensive to operate for extended periods [10].

Since 2008, the high cost of the capacity expansion programme has been contributing directly to above-inflation electricity price increases. The total average price increase of electricity from 2008 to 2014 was 255%, which is significantly higher than the inflation increase (measured according to the consumer price index) of 55% [11]. A cumulative comparison between the average Eskom tariff and the inflation increase for the period of 2008 to 2014 is shown in Figure 2.

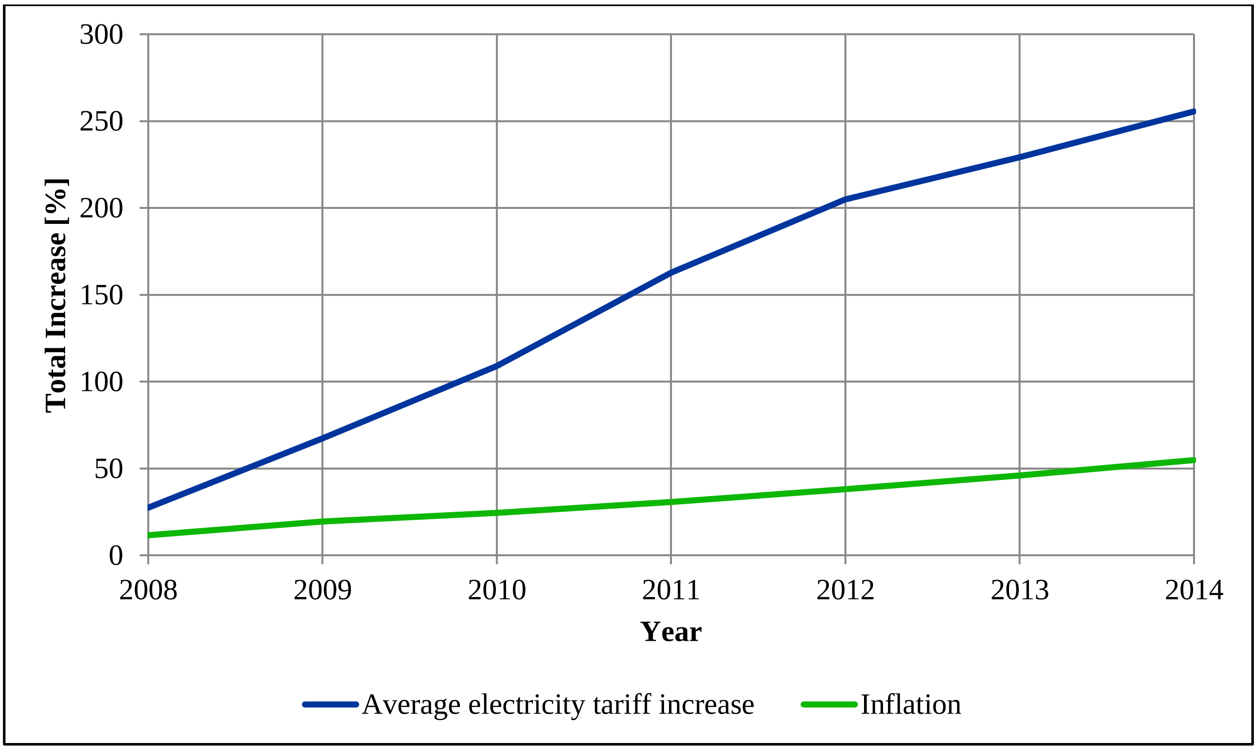


Figure 2: Cumulated annual inflation versus electricity price increase (Adapted from [11] and [12])

1.2 Electricity in the South African mining industry

South Africa's soil is rich in minerals and plays a very important role in the economic development of the country [13]. In 2014, South Africa was the sixth-largest gold producer in the world, with a contribution of 5.3% to gold production worldwide [14]. The total electricity consumption in South Africa was 205 525 GWh in the 2013/2014 financial year [15]. South Africa's electricity consumption can be divided into different industries as shown in Figure 3.

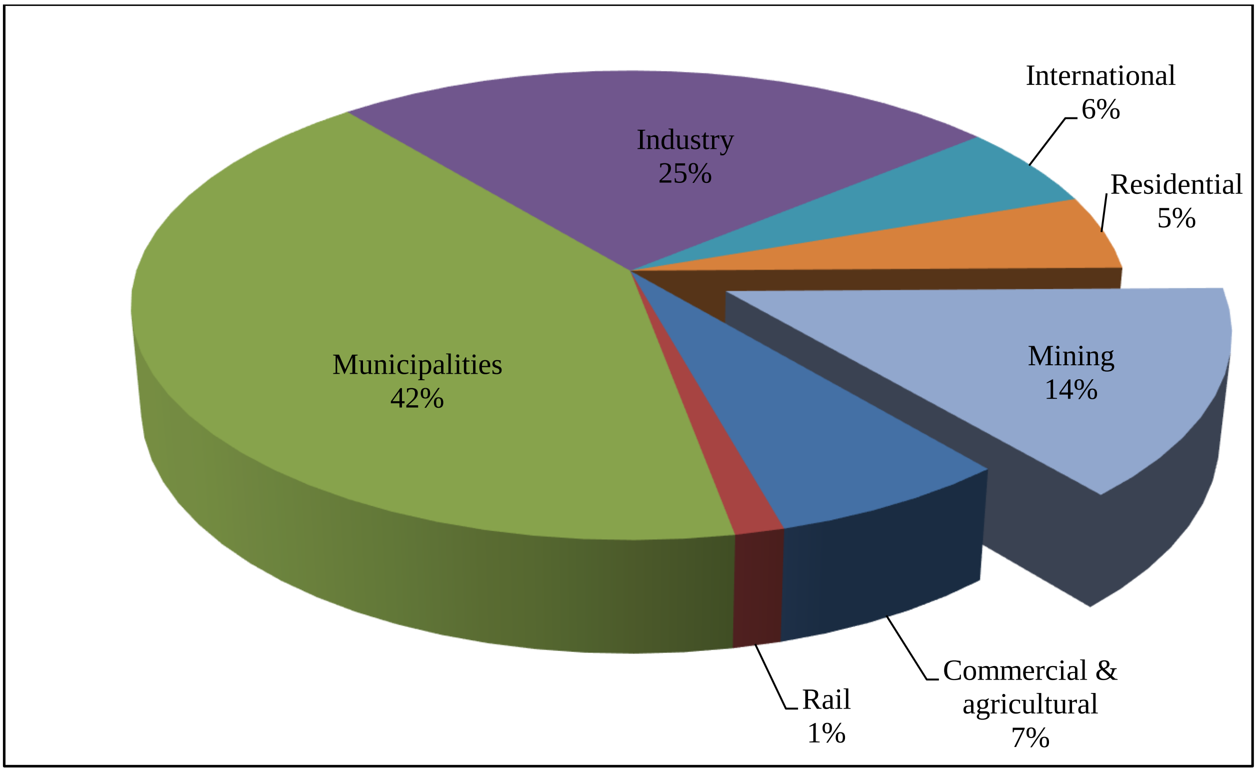


Figure 3: Energy usage by industry in 2014 (Adapted from [15])

The mining industry accounted for 14% of the total electricity consumed in 2014. Eskom's high electricity tariff increases since 2008 contributed to high production cost increases being experienced by the mining sector. On a typical South African gold mine, electricity costs account for approximately 19% of the total production costs [16]. Production costs are further increased due to high wage increases [17]. The gold price has also been steadily decreasing since 2012, which means that the profit margins of gold mines are also decreasing [18]. A practical way to reduce production costs is to reduce electricity costs. This can be achieved by implementing initiatives such as demand side management (DSM).

1.3 Introduction to mine dewatering

South Africa has eight of the ten deepest mines in the world. Mponeng mine, located south-west of Johannesburg, is the deepest mine in the world at a depth of 3 900 m [19]. The problematic aspect of mining at extreme depths is high virgin rock temperatures that result in hot working environments. Working areas are cooled down with cold water and air that are sent underground. Cold water is also used for other mining activities such as drilling and cleaning. The cold water sent underground accumulates at the bottom of the mine and needs to be pumped to surface in order to prevent mine levels from flooding.

Water is pumped to surface by means of a large network of interconnected dams and dewatering pumps with installed capacities often exceeding 1 MW. This network of pumps and dams is known as a dewatering system. Dewatering pumps consume as much as 15% of the total electricity budget of mines [20]. Various DSM interventions can be implemented on mine dewatering systems to reduce electricity costs. The success of these DSM interventions depends on various system constraints. Quantifying the effect of these constraints on the performance of DSM interventions on dewatering systems forms the central theme of this research.

1.4 Demand side management

1.4.1 Introduction

The first DSM projects in South Africa were officially introduced in 1992. Funding of DSM projects by Eskom started in the last quarter of 2002 [21]. The aim of this initiative was to slow the growth of electricity demand when it was realised that demand would surpass generation by 2006 if no action was taken [21]. DSM projects help both Eskom and the consumer to optimise electricity usage and costs, thus reducing pressure on the power grid, especially during peak periods.

1.4.2 Megaflex tariff structure

South Africa’s total demand profile on a typical winter day and a typical summer day is shown in Figure 4. This implies that electricity cost savings are higher during the winter season than during the summer season. Figure 4 also shows that there are two daily peaks in the demand profile. These peaks are clearly distinguishable on the winter day profile – they are from around 05:00 to 07:00 and from around 16:00 to 20:00 every day.

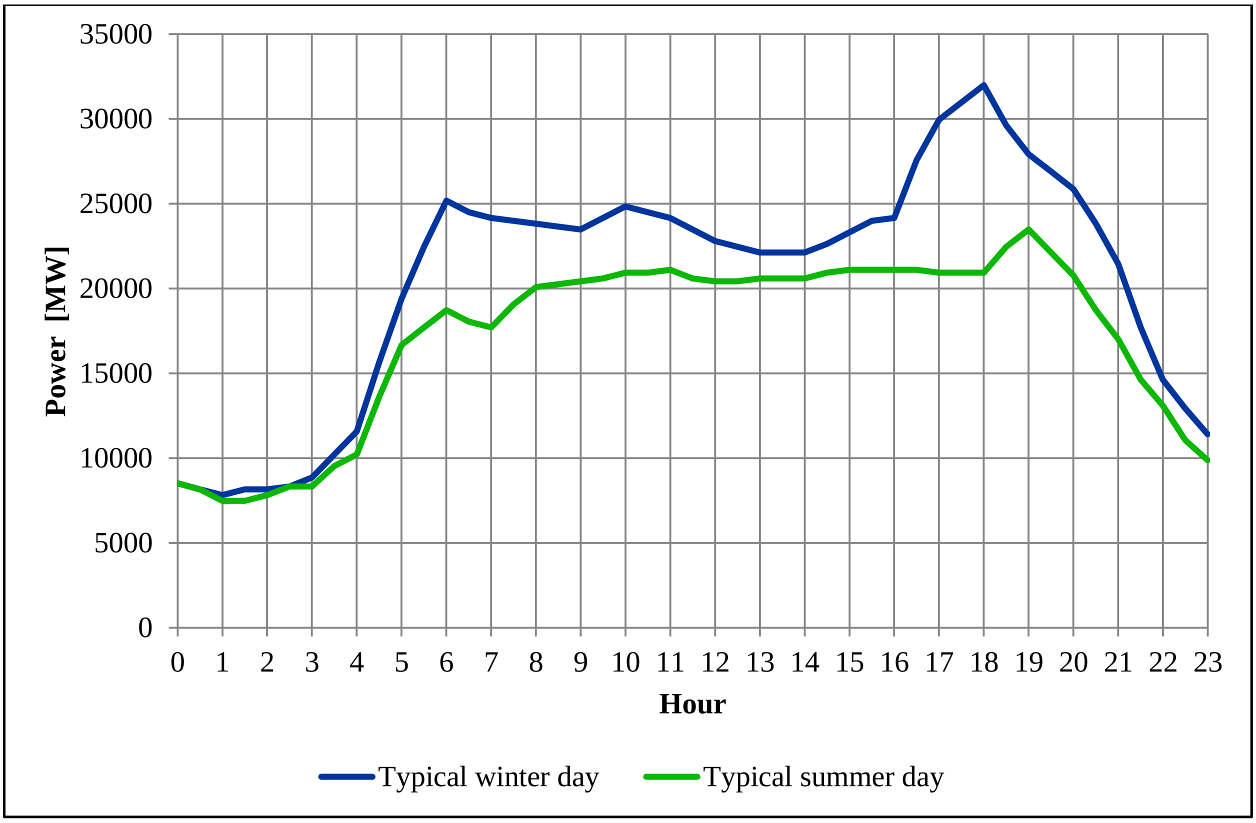


Figure 4: Eskom typical demand profiles (Adapted from [22])

Eskom has to start additional power plants during peak periods to accommodate the increased electricity demand. This can become very expensive as the damage incurred by cycling power plants increases with the duration of time that the power plant was offline. In order to minimise power plant cycling and to keep additional power plants offline for longer, some power plants are often run at just below or just above their designed rating. Both power plant cycling and the running of power plants above their designed rating incur significant costs to Eskom [23].

In order to reduce power plant cycling, Eskom employs TOU tariff structures to encourage large consumers to reduce their electricity usage during peak periods of the day. One of these tariff structures is called Megaflex.

The Megaflex tariff structure is intended for consumers with a notified maximum demand (NMD) of more than 1 MVA. There are three TOU periods for this tariff structure, namely off-peak, standard and peak periods. The periods of the Megaflex tariffs are shown in Figure 5. The figure also shows the daily schedule for the three different TOU pricing periods, i.e. weekdays, Saturdays and Sundays. The numbers at the circular edge of each chart represent the hour of the day, while the different colours represent different pricing periods. The green sections represent off-peak periods, the yellow sections represent the standard periods and the red sections represent the peak periods.

The Megaflex pricing structure is determined by three main factors. They are:

- The direct distance from Johannesburg;
- The supply voltage; and
- The demand season.

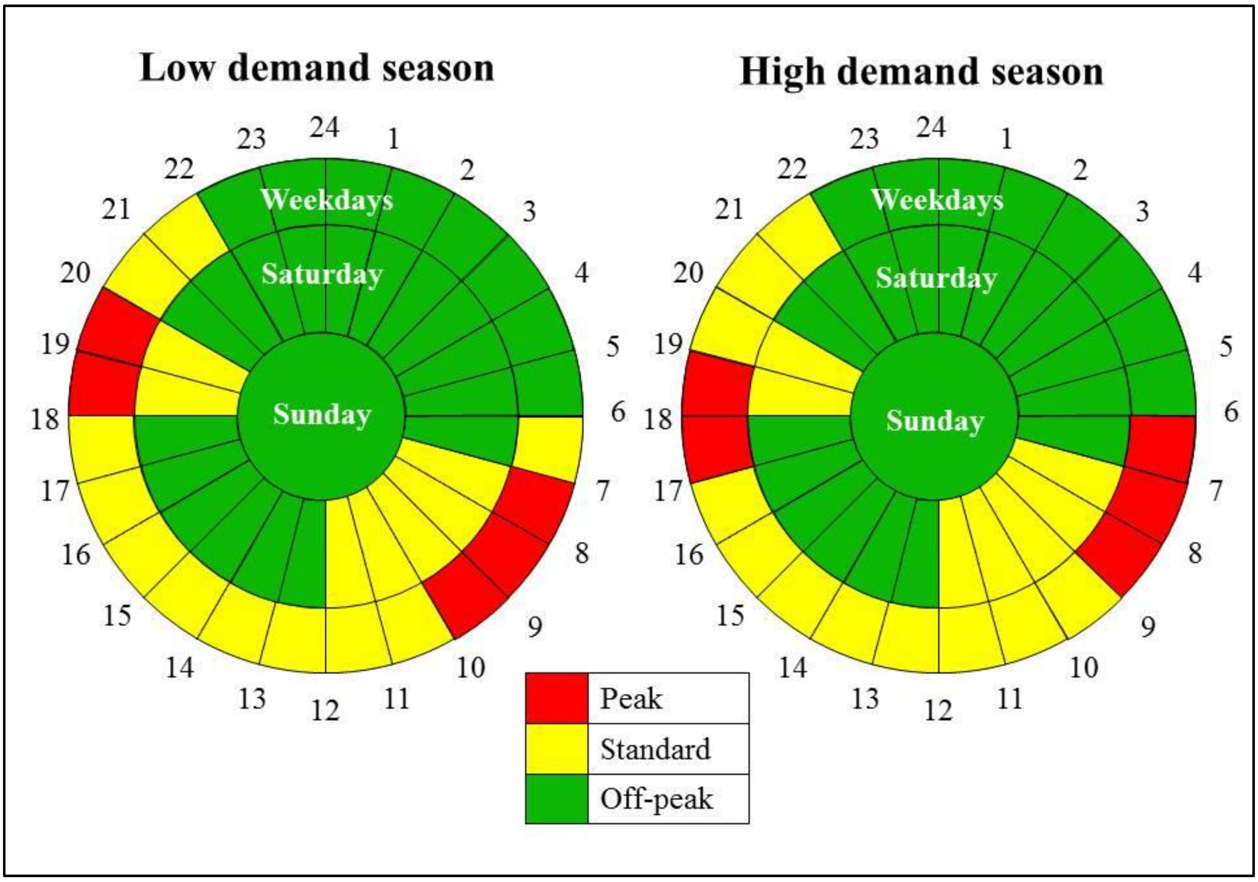


Figure 5: Megaflex TOU tariff periods 2015/2016 (Adapted from [24])

For example, a customer in the following situation will be charged according to Figure 6 for each kilowatt during the 24 hours of the day:

- Located within 300 km of Johannesburg;
- Has a supply voltage of between 500 V and 66 kV; and
- Is billed according to the Megaflex tariff structure.

It is important to note that the implementation of a load shifting initiative on dewatering pumps is not expected to affect the maximum demand of the mine. This is discussed in more detail in Appendix A. The charges for the high demand and low demand seasons are shown in Figure 6.

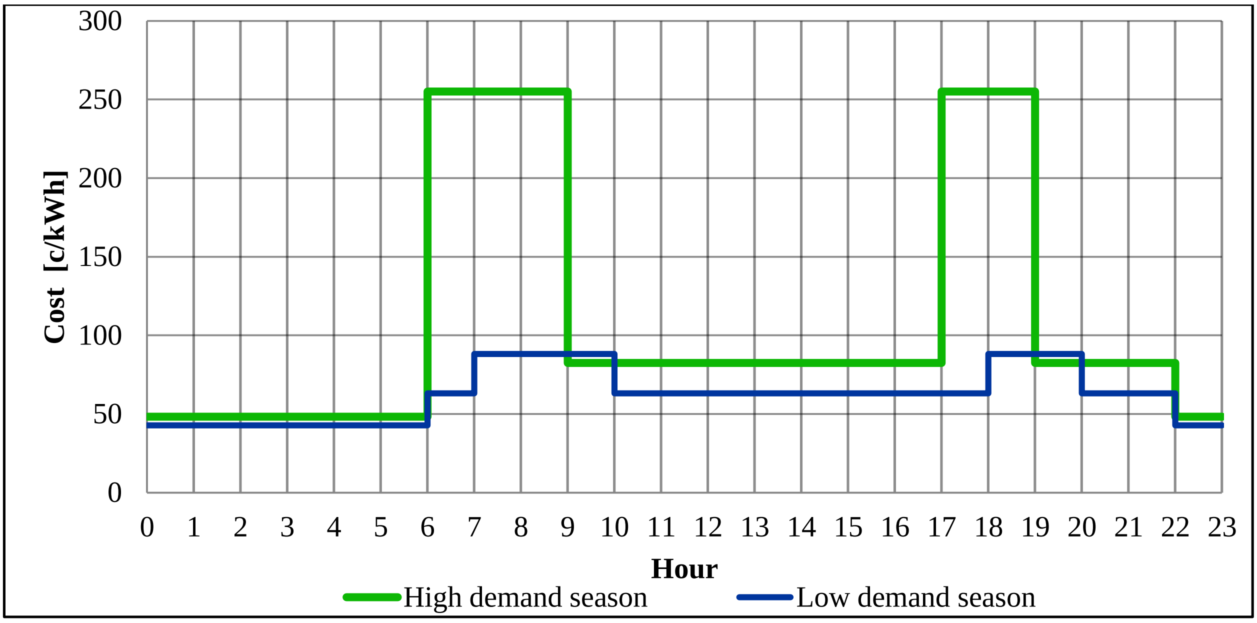


Figure 6: Graphical representation of Megaflex for tariff 2015/16

1.4.3 DSM initiatives

DSM initiatives can be divided into three main categories, which are load shifting, energy efficiency and peak clipping [24]. For Figures 7–9, the following assumptions are made:

- The DSM initiatives have an ideal performance and thus an ideal power profile;
- Megaflex tariff structure is used;
- High demand season is active;
- Red bars indicate peak periods;
- Yellow bars indicate standard periods; and
- Green bars indicate off-peak periods.

1.4.4 Load shifting

Load-shifting initiatives are focused on reducing electricity consumption during peak periods by shifting electricity loads from peak periods to off-peak periods. This reduces demand in peak periods and maximises electricity demand during off-peak periods. The total daily electricity consumption after load shifting remains the same as before load shifting, because the same amount of electricity that was removed from peak periods was added to the off-peak periods. The effect of a load-shifting initiative is illustrated in Figure 7.

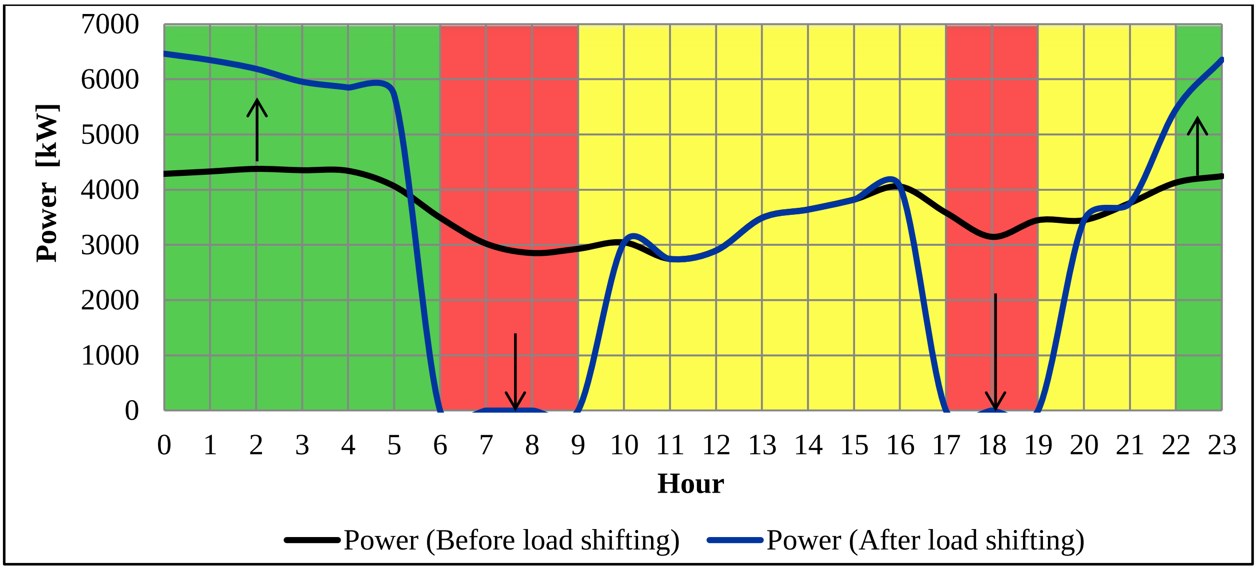


Figure 7: The effect of a load-shifting project (Adapted from [26])

1.4.5 Energy efficiency

The goal of an energy efficiency project is to lower the average daily electricity consumption of the consumer. This reduction in electricity consumption reduces electricity costs. The effect of an energy efficiency initiative is illustrated in Figure 8.

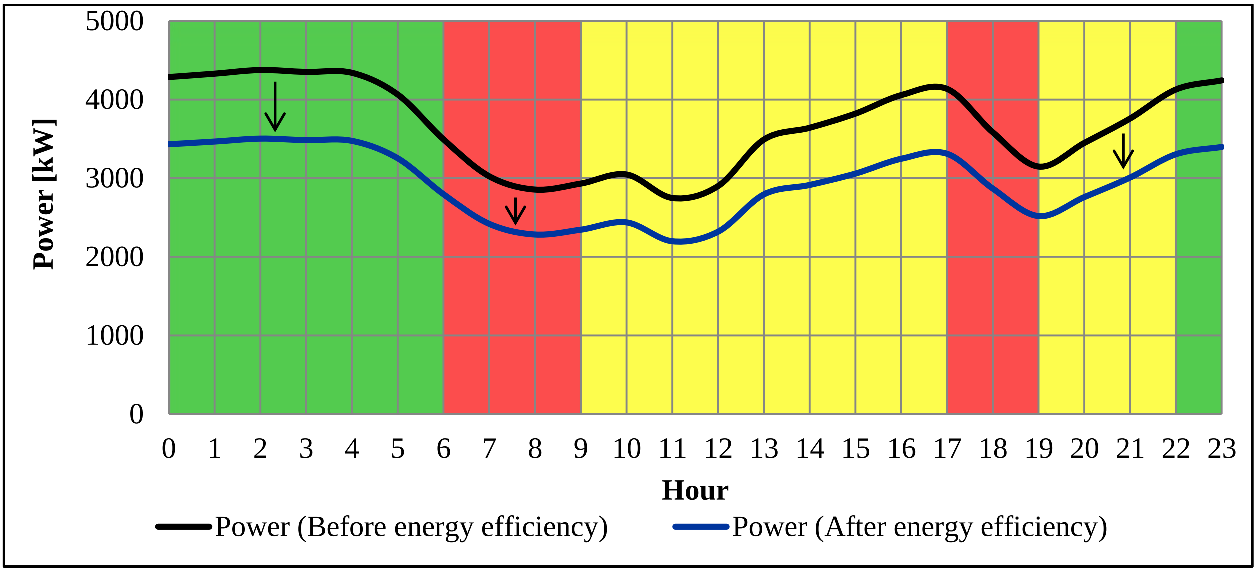


Figure 8: The effect of an energy efficiency project (Adapted from [27])

1.4.6 Peak clipping

Peak-clipping initiatives are aimed at reducing electricity consumption during peak periods only. It differs from load-shifting initiatives in the sense that the loads reduced during peak periods are not shifted to other parts of the day. The effect of a peak-clipping project is illustrated in Figure 9.

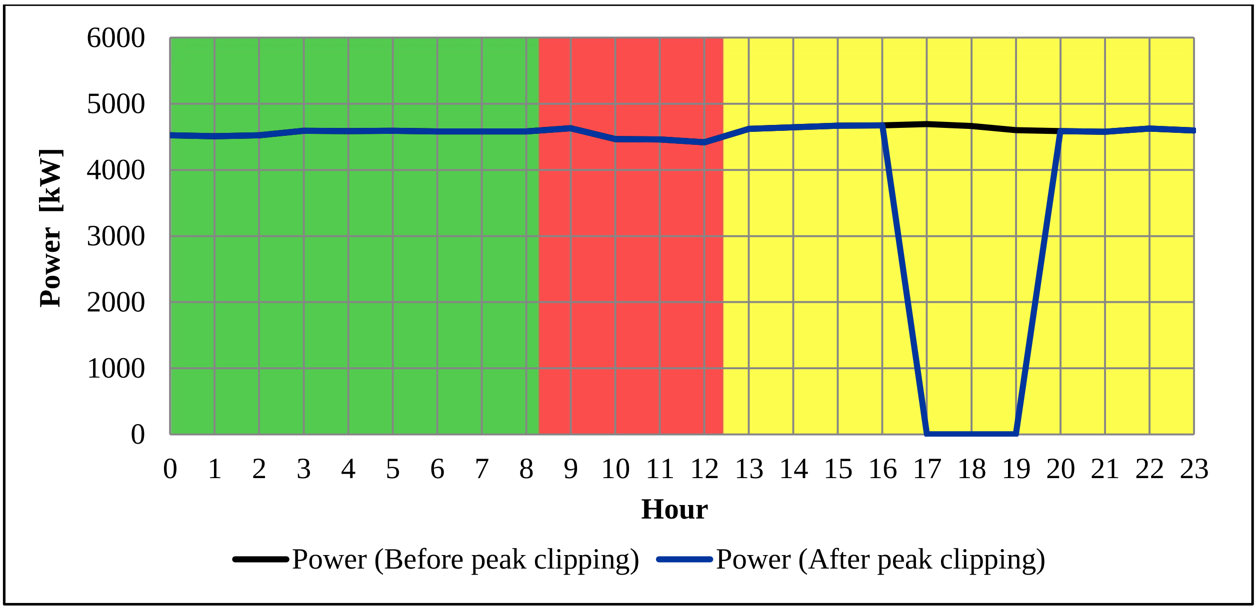


Figure 9: An example of a peak-clipping project (Adapted from [25])

1.5 DSM applications on water reticulation systems

There are two types of DSM applications that can be applied on water reticulation systems:

- Water supply optimisation
- Load shifting

These DSM applications will be discussed in the sections that follow.

1.5.1 Water supply optimisation

Two main factors influence the volume of water that needs to be pumped from the bottom of a shaft to surface. The first is the rate at which underground water (fissure water) flows into the mining levels. The second aspect is the volume of water sent underground for mining purposes.

The amount of water used by a mine can be roughly linked to the production rate of the mine [24]. Reducing the amount of water sent underground, which needs to be pumped to surface again, would reduce the electricity consumption of the dewatering pumps. This should be the first step in reducing a mine’s pumping requirements. Reducing the volume of water sent underground is referred to as a water supply optimisation (WSO) project.

The chilled water that is supplied to individual mining levels can be reduced by installing control valves on the water columns (pipes) supplying each level. The flow to these mining levels can then be controlled individually by using these control valves. Closing a control valve will result in a supply pressure decrease to the related mining level and thus a reduced water flow [26]. It has been found that the daily water consumption of a gold mine can be reduced by between 7% and 30% [27].

1.5.2 Load shifting

Water that has been used by mining and cooling processes are collected in settler dams, which supply clean water to hot water dams. This cleaned water is then pumped vertically from level to level into hot water dams. Hot water dams store water during peak periods when pumps are switched off. To keep pumping costs to a minimum, hot water dams are emptied during off-peak periods to minimise pumping during peak periods and to maximise pumping during off-peak periods. The management of the dewatering pumps according to this control philosophy is called a load-shifting initiative. This system of pumps and dams is known as a mine dewatering system [28].

When considering DSM initiatives on automated dewatering pump systems, a load-shifting initiative is preferred over an energy efficiency initiative for mine dewatering systems. This is because the initial cost of implementing a load-shifting initiative on an automated dewatering system can be less than the cost of implementing an energy efficiency initiative.

1.6 Need for this study

In a study by Cilliers, the electricity costs of a mine dewatering system were considered. The study focused more on the power consumption of the mine dewatering system before and after peak periods. The main aim of this study was to minimise the power consumption of the mine dewatering system during peak times without affecting the load-shifting potential during morning peak and evening peak periods. The results of this study proved that load-shifting initiatives could be implemented and successfully optimised on mine water reticulation systems. Cilliers also recommended that the water storage capacity of the mine dewatering system be increased, higher efficiency dewatering pumps be used and the water into the settler dams be reduced [29].

A study by Botha was done on the water supply to underground mining levels. Different techniques were identified to increase the efficiency of the water usage on underground mining levels. The study focused on reducing water wastage on mining levels. The resulting water reduction was quantified in terms of an annual water saving and water volume. The resulting water savings achieved in this study proved that the reduction in water sent underground can be significantly lowered, and that an energy efficiency initiative could be implemented on WSO projects to achieve savings [27].

A study conducted by Vosloo in 2008 was aimed at optimising the costs of entire water reticulation systems of deep mines. In this study, Vosloo investigated different systems that make up water reticulation systems. He showed that the different systems are interdependent and that constraints in the system will influence performance [30].

There is thus a need to quantify the effects of these constraints on the components' performance and consequently the financial impact on the electricity costs of a mine dewatering system.

There has been an increase of 255% in the price of electricity over the past six years [11]. The implementation of DSM initiatives has become an important measure for mines to offset the cost impact of high tariff increases.

Feasibility is the most important factor when investigating potential DSM initiatives. When implementing DSM initiatives it should be done without compromising mine production or the health and safety of mine workers [24]. The dewatering system should be one of the first systems to be investigated for possible DSM implementations, since pumps are some of the largest electricity consumers on gold mines [31].

It is, therefore, important for gold mines to implement these initiatives where possible to keep electricity costs low and make the mines more economical to operate. Implementing DSM initiatives on a dewatering system can greatly decrease electricity consumption and costs.

Unfortunately, some system constraints influence the feasibility and performance of such DSM initiatives. They are:

- Low pump efficiencies;
- Pump availability;
- Water storage capacity; and
- Fissure water.

As mentioned earlier, load-shifting initiatives are preferred when considering an automated dewatering system. The constraints involved in load shifting need to be identified and quantified. The best way to quantify the possible savings in a safe and affordable way is through simulations. A simulation model will be used to simulate the effects of reducing or eliminating the above-mentioned constraints. The changes to the simulation model will be added one by one to show the impact of each change as well a cumulative impact.

1.7 Dissertation overview

Chapter 2

An introduction to mine cooling will be given along with an overview of the main water uses on a gold mine. The individual components of a mine dewatering system are presented in this chapter. Integrating the components that form a complete system is explained.

Chapter 3

System constraints and common problems of a dewatering system are presented in this chapter. The method of evaluating different system components' performance is explained. The model that is used to simulate the effect of specific constraints and problems is presented.

Chapter 4

Results of two case studies are presented in this chapter. The system constraints identified in the previous chapter is tested by simulating the different scenarios for reducing the impacts of these constraints. The different solutions will then be ranked according to the cost saving that can be achieved with each.

Chapter 5

Chapter 5 concludes the study. Various suggestions for future work are presented.

CHAPTER 2. OPERATIONS AND CONSTRAINTS OF MINE DEWATERING SYSTEMS

2.1 Introduction

Mine dewatering systems consist of different components. In this chapter, the operation of each component in the dewatering system as well as the overall system operation are discussed. This chapter also includes an overview of water uses on a gold mine.

2.2 Water usage in the mining industry

The water requirements for mining processes are specific to each mine. The main processes in deep-level mines that use water are:

- Cooling;
- Drilling;
- Cleaning; and
- Energy recovery.

2.2.1 Introduction to mine cooling

Virgin rock temperatures can increase by up to 10 °C/km beneath the surface and reach a maximum of around 60 °C [30], [32]. Other sources of heat in a gold mine include auto compression, mining equipment and groundwater. Auto compression is a process where heat is added to air as it moves down the mining shaft by converting potential energy to thermal energy. The air temperature can increase by 4–6 °C per kilometre below surface due to the effect of auto compression alone [32].

All of these heat sources make it difficult to maintain a working environment below the specified maximum wet-bulb temperature of 27.5 °C for underground operations [30]. Figure 10 shows how virgin rock temperatures decrease as the distance from the centre of the earth increases [33], [34].

Constant exposure to high temperatures can have the following effects on workers [35]:

- Confusion;
- Fatigue;
- Dizziness; and
- Cramps/muscle spasms.

This condition is more commonly known as heat exhaustion and can cause permanent damage to organs [35]. Constant high temperatures in the workplace can also diminish worker morale and reduce productivity. Mine cooling is thus very important to provide a sustainable working environment. Mine cooling is done by both cooled air and water that is sent from surface. In the case of some deep mines, this water and air has to be recooled by underground bulk air coolers (BACs) and fridge plants.

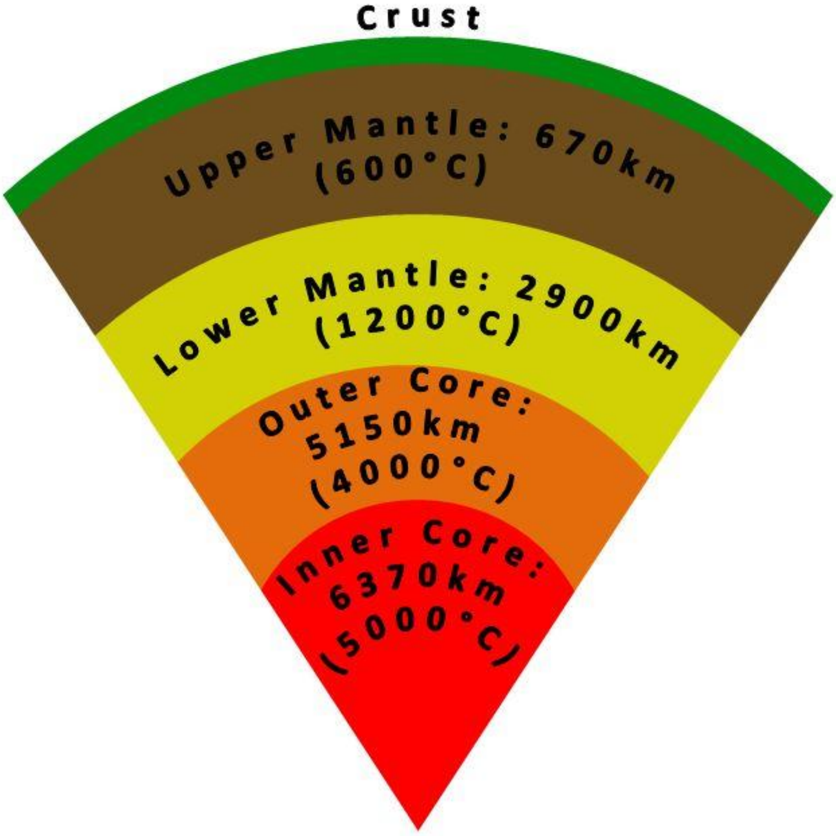


Figure 10: Underground temperatures (Adapted from [33], [34])

2.2.2 Mine cooling components

Fridge plants utilise the standard vapour-compression cycle to cool hot process water used for various mining purposes. The standard vapour-compression cycle is one of the most commonly used processes for cooling purposes worldwide [36]. Figure 11 illustrates the vapour-compression cycle.

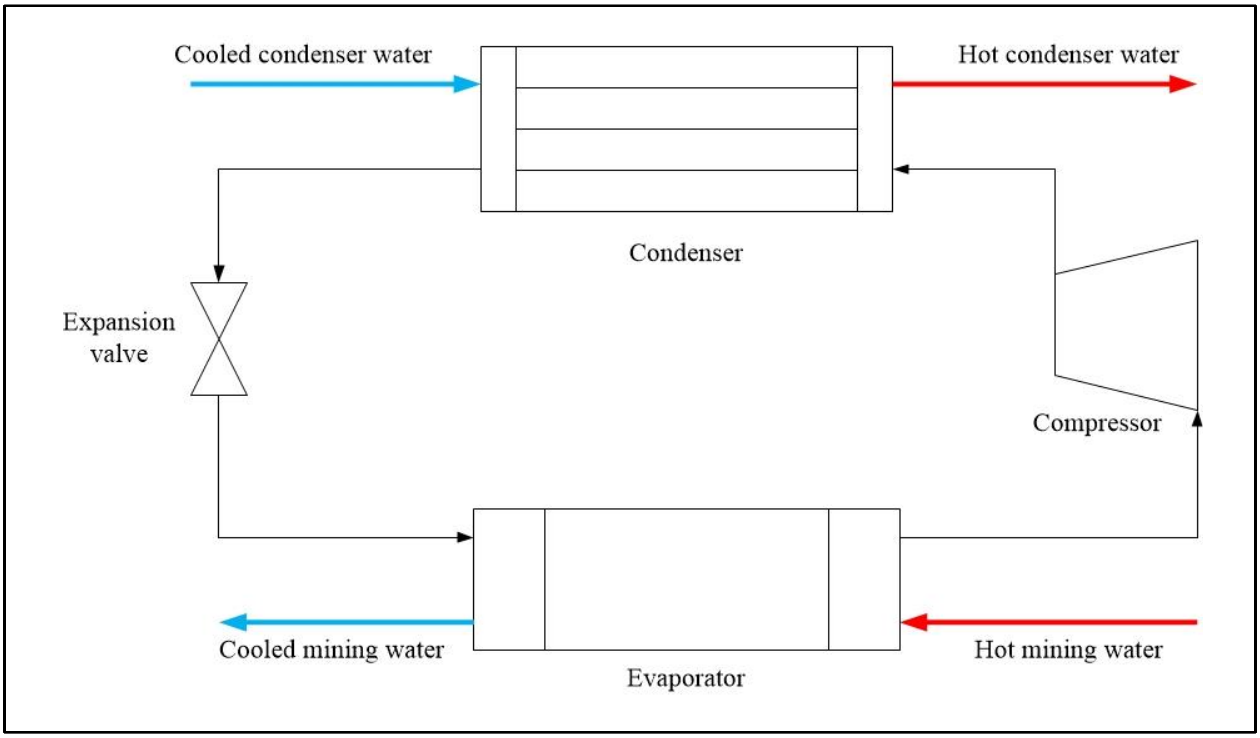


Figure 11: Typical vapour-compression cycle (Adapted from [37])

The four steps of the vapour-compression cycle can be summarised as follows [37]:

1. Cold liquid refrigerant is depressurised over the expansion valve to partly evaporate and cool it down.
2. The refrigerant enters the evaporator where it absorbs the thermal energy from the process water to cool it down. This energy addition to the refrigerant evaporates it completely.
3. The compressor compresses the refrigerant into a liquid state, but this compression adds more thermal energy to the refrigerant.
4. The refrigerant enters the condenser where it dissipates thermal energy into the condenser water to cool down – this heats the condenser water. The refrigerant continues to the expansion valve to restart the whole cycle.

It is important to know that chlorofluorocarbon (CFC) refrigerants are no longer used in accordance with the Montreal Protocol on Substances that Deplete the Ozone Layer. Alternative refrigerants such as ammonia cannot be used for underground refrigeration due to the potential hazard to workers' health [38]. This means that ammonia can only be used on surface fridge plants and that refrigerants such as R-134a are preferred for underground fridge plants [39].

The condenser water is constantly circulated between the cooling towers and the fridge plants. This is known as the condenser circuit [39]. Figure 12 shows the layout of a typical condenser circuit.

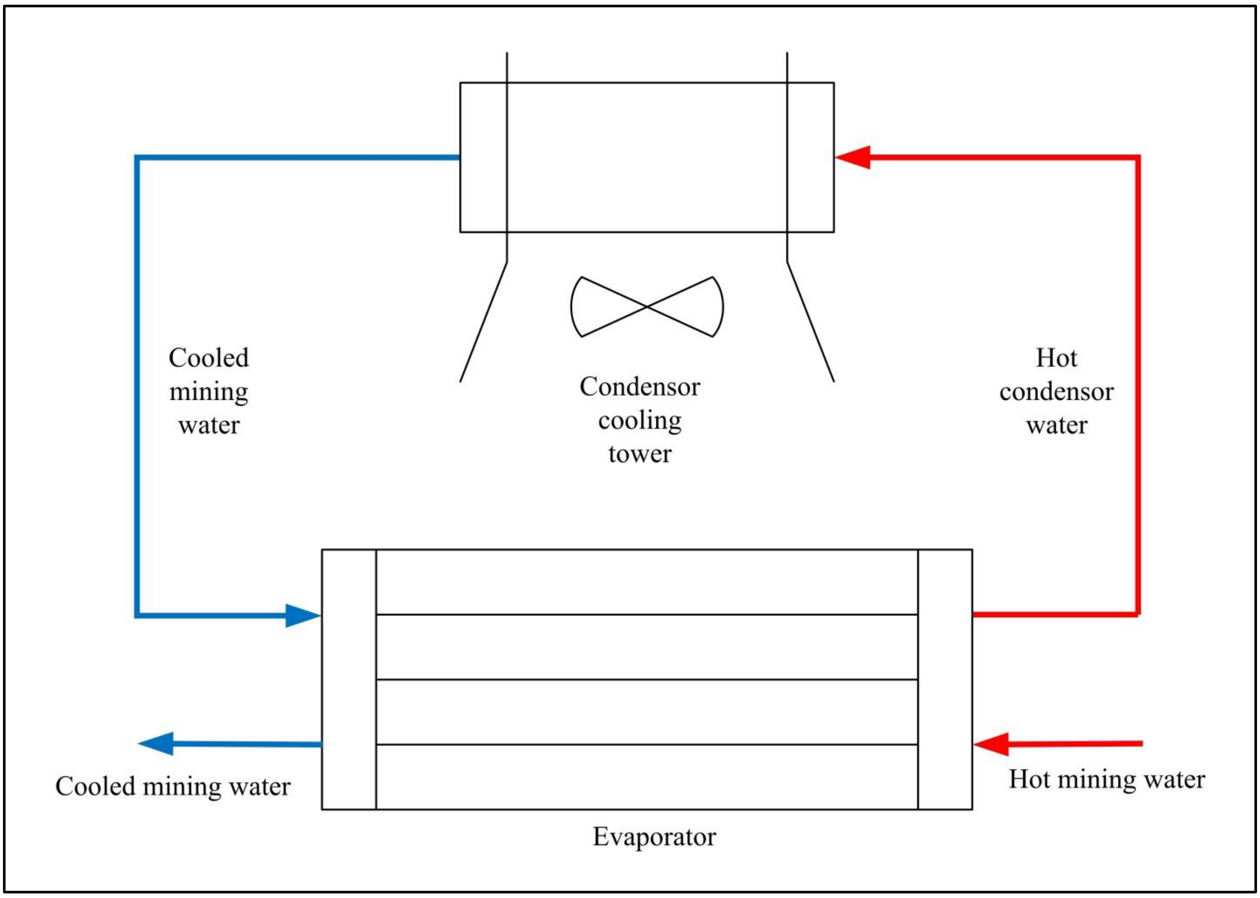


Figure 12: Simplified layout of a typical condenser circuit (Adapted from [40])

Cooling towers are used to absorb thermal energy from the water, which was added by the fridge plants. The amount of thermal energy dissipated into the atmosphere is greatly dependent on the atmospheric wet-bulb temperature [41]. Warm water is sprayed into the top of the cooling tower, from where it falls into a reservoir at the bottom. Air is drawn from the bottom of the cooling tower and blown by a fan from the top of the cooling tower into the atmosphere. The temperature of the water decreases as it falls to the bottom of the cooling tower because of evaporation, while the air temperature increases as it rises to the top [42]. The operation of a cooling tower is illustrated in Figure 13.

Basic mine ventilation, which entails circulating uncooled air, can be used for cooling of mines up to a depth of 600–800 m. This depth depends on mining methodology and design temperatures and is known as the depth horizon [43]. BACs provide the cooling air that is used for deeper mineshaft ventilation.

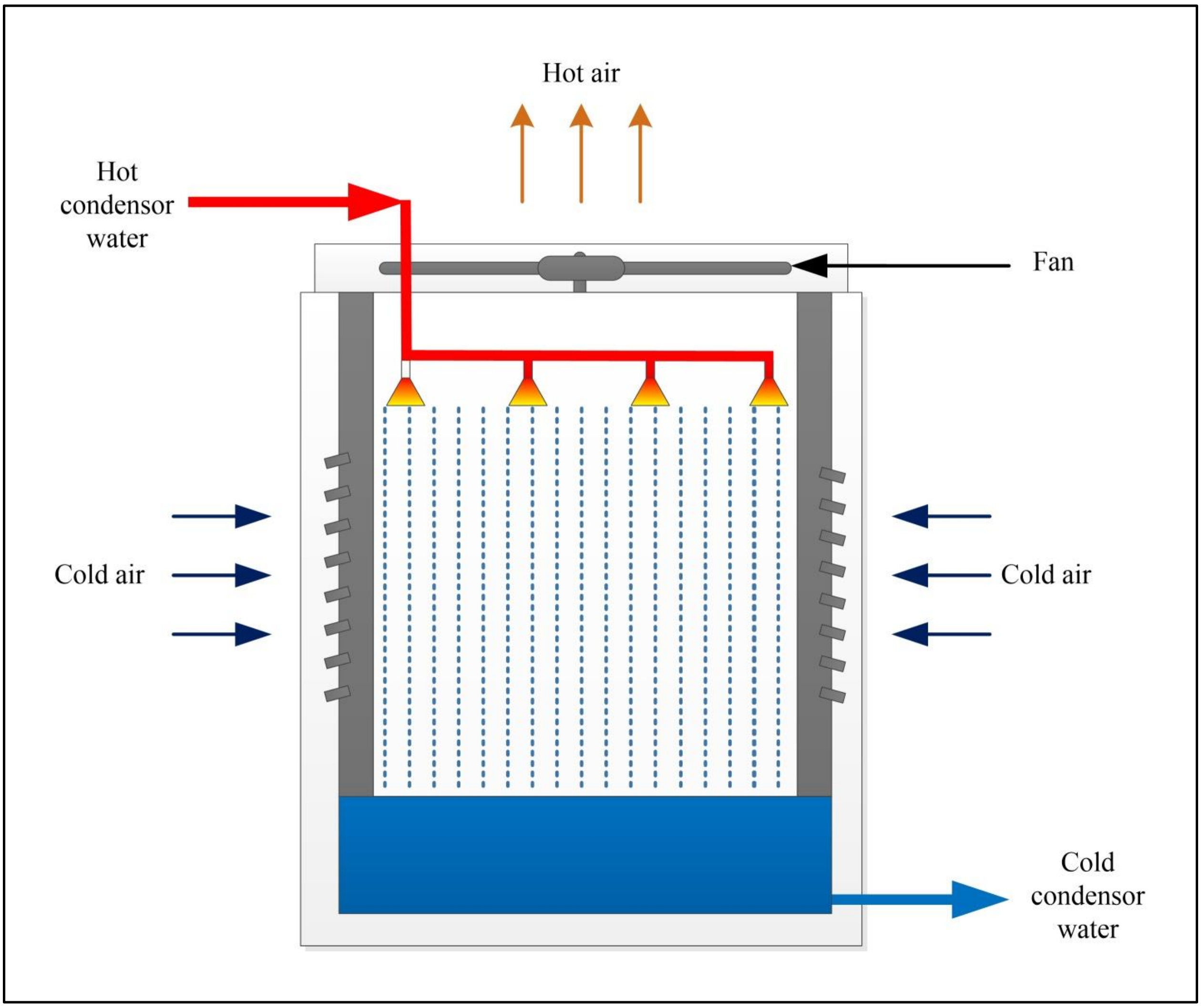


Figure 13: Typical cooling tower (Adapted from [40])

The BACs used in the mining industry use the same principle as the cooling towers. In the case of BACs, chilled water replaces the hot condenser water and the resulting cooled air is used instead of the condenser water. Chilled water droplets cool the hot air moving through the BAC, while evaporation of these droplets cools the air even further. BACs can be located on surface or underground, depending on the depth of the mine [44]. It is preferred to maximise the use of surface BACs as installing and operating underground BACs are complex and expensive [43].

Cooling cars, also known as spot coolers, can be used to provide cooling where BACs are unable to provide sufficient cooling, for example at stopes. Stopes are the places where mining – such as blasting, drilling and sweeping – is done. Cooling cars use chilled water to provide cooling. Cooling cars use water-air heat exchangers to cool the air at the stopes. Water usually reaches the cooling cars at 18–20 °C, which is still cold enough for cooling purposes [45]. Figure 14 shows an example of a cooling car.

Figure 14: A cooling car [29]

2.2.3 Drilling

A typical gold mine can advance faces at rates of up to 26 metres per month [46]. Most South African gold mines use pneumatic drills at rock faces as they are more durable in the working environment and use more readily available supply points. The pneumatic drills are also more reliable than their hydraulic counterparts and have a smaller thermal load on the underground working environment [47]. The drills are used to bore holes where explosives are planted for blasting [38]. The drill bits generate heat and dust. Chilled water is used to cool drill bits to prolong their lifespan. The chilled water is also used for dust suppression so that the drill operator does not inhale dust, which can have serious health implications [38]. Figure 15 shows a pneumatic drill being used to bore holes for blasting.

Figure 15: A pneumatic drill in use [48]

2.2.4 Cleaning

The cleaning shift follows the blasting shift. During this shift, the blasted rock is removed from stopes using water jets and scrapers connected to winches [20], [27]. Water jets aid larger equipment in the sweeping process by removing smaller debris created by blasting [49].

2.2.5 Energy recovery

In addition to the previously mentioned water uses, water is also used by the supply system for energy recovery purposes. The water is usually gravity-fed to underground mining levels. This causes a pressure increase directly proportional to the vertical length of the column. The pressure in these vertical columns can be calculated using Equation 1 [50].

Equation 1: Calculation for static pressure

$$\boldsymbol{P = \rho g H}$$

With:

P – Pressure in water column	[Pa]
ρ – Density of the water	[kg/m^3]
g – Acceleration of gravity	[m/s^2]
H – Height of water above calculation point	[m]

By using Equation 1 to calculate pressure, it is shown that the pressure in South African gold mines can reach up to 30 MPa at a 3 km depth if there are no pressure control measures in place. Pressure can be reduced by using a cascading dam system, water turbines or pressure-reducing valves (PRVs). A cascading dam system refers to a system of chilled water dams on multiple mining levels. The dams reduce the total water head in a water column and thus the static pressure [51].

PRVs are used to keep the pressure in columns under control according to a predetermined pressure set point [52]. The PRVs transform the potential energy of the water into thermal energy, which causes the water temperature to increase [24]. PRVs are used to reduce supply pressure and flow rate to working areas and can even be installed in series if one PRV is unable to provide a sufficient pressure reduction [53]. Turbines can also be used to dissipate high pressures in water columns [54].

The biggest advantage of using turbines to reduce pressure in water supply columns is that the recovered energy can be used to drive either generators or pumps while reducing the underground thermal load. When using turbines, a bypass valve should be installed so that the turbine can be taken offline without disrupting the water supply. A turbine, such as a Pelton wheel, should be situated near the cold-water column. Pelton wheels are ideal for mining applications because they can handle wide ranges of flow with relative high efficiency. A Pelton wheel discharges into the atmosphere and needs to be placed above the chill dam as shown in Figure 16 [55].

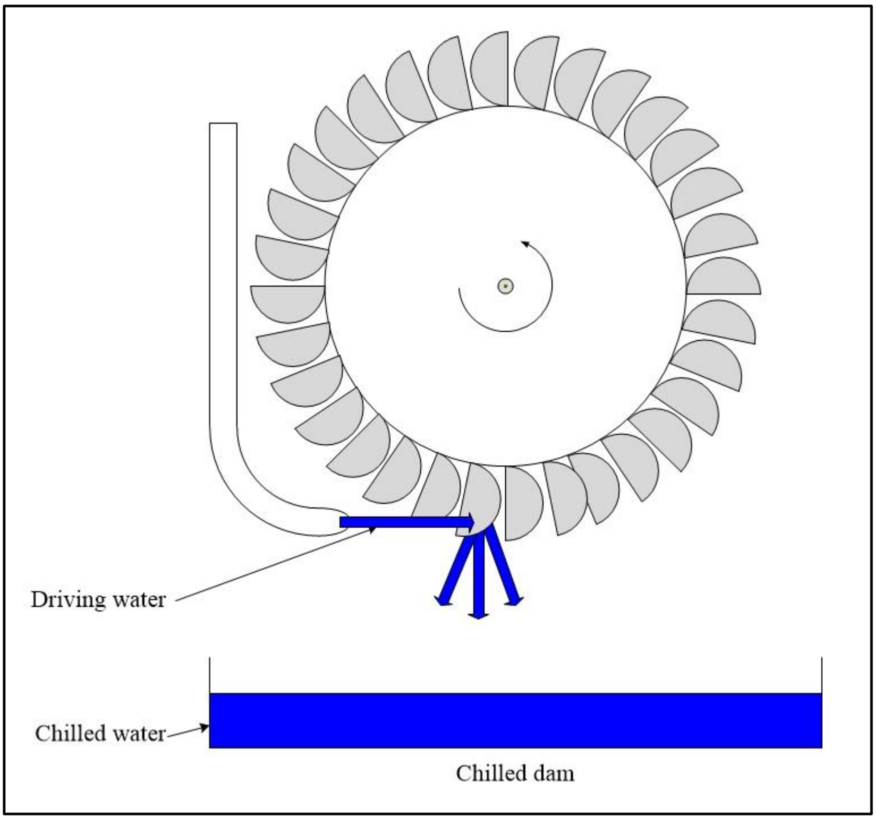


Figure 16: A single-jet Pelton wheel (Adapted from [53])

Using turbines for turbine-pump applications can be more complicated than using turbine-generator setups. When using a turbine-pump setup, chilled water is used to drive the turbine, the turbine then drives the pump, which pumps the hot water in the dewatering system towards the surface. The turbine’s efficiency causes some of the energy being transferred to the pumps to dissipate, while the pump’s efficiency causes a further energy loss when transferring this energy into the water. A turbine-pump set up can thus only be set up to pump either the same flow rate to a lower head, or to pump to surface at a lower flow rate than the turbine supply. It is also important to synchronise the water-supply flow rate and hot water for such an application [55]. This is important because the turbine cannot be used to pump hot water to surface if there is not sufficient hot water. In the same way, water cannot be sent underground through the turbine to pump water to the surface if the chilled water storage capacity is insufficient.

Multi-stage pumps can be reversed and used as turbine-generator sets, but this configuration has some limitations. The pump can only provide good performance when it is used at or near its designed flow rate. The efficiency of the pump can vary greatly with fluctuating flow rate. In this application, the flow should be throttled to keep it within the pump's design range. The bypass valve for the water supply will be in permanent use in order to handle the excess water [55].

A three-chamber pipe feeder system (3CPFS) is an energy recovery system more commonly used on South African gold mines. The 3CPFS is laid out in the form of a U-tube and works on the principle of hot water being displaced upwards by the pressure created by the downwards moving cold water. The U-shape is made up of the chilled water going down on one side, the 3CPFS at the bottom and the hot water going out on the other side. The basic shape of a 3CPFS is shown in Figure 17.

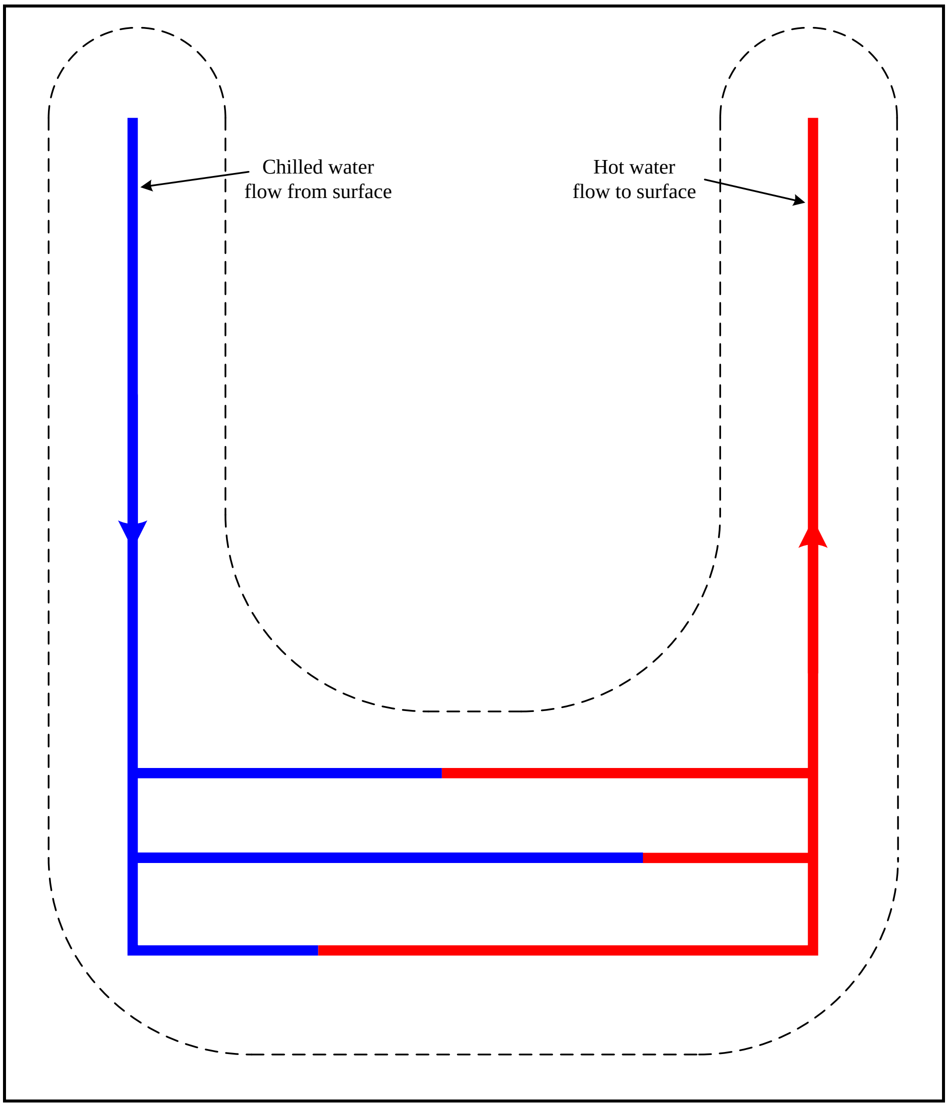


Figure 17: Basic 3CPFS U-tube shape

2.3 System components

Different components in a water reticulation system have their own constraints that can influence the efficiency and operating cost of a mine dewatering system. More information about each component is provided in the following sections.

2.3.1 Settler dams

Settler dams are used to extract unwanted particles from liquids by using the different densities of the involved substances. Water that has been used for cooling or other processes is channelled into settler dams at the bottom mining levels.

Raw water from mining levels must have a pH value of about 8.5. A lime solution is added 20 m upstream of the settler dam to increase the pH from ±6.8 to help reduce corrosion (caused by dissolved chlorides) and increase flocculent efficiency. Flocculent is a substance added to water, usually at ±10 m upstream of the settler dam, which helps suspended particles to bond and increases the rate at which suspended particles descend to the bottom. This process of descending particles is known as settling or sedimentation. The flocculent dosage required depends on the flocculent and composition of the water that needs to be treated [56]. The main operational process of settler dams is illustrated in Figure 18.

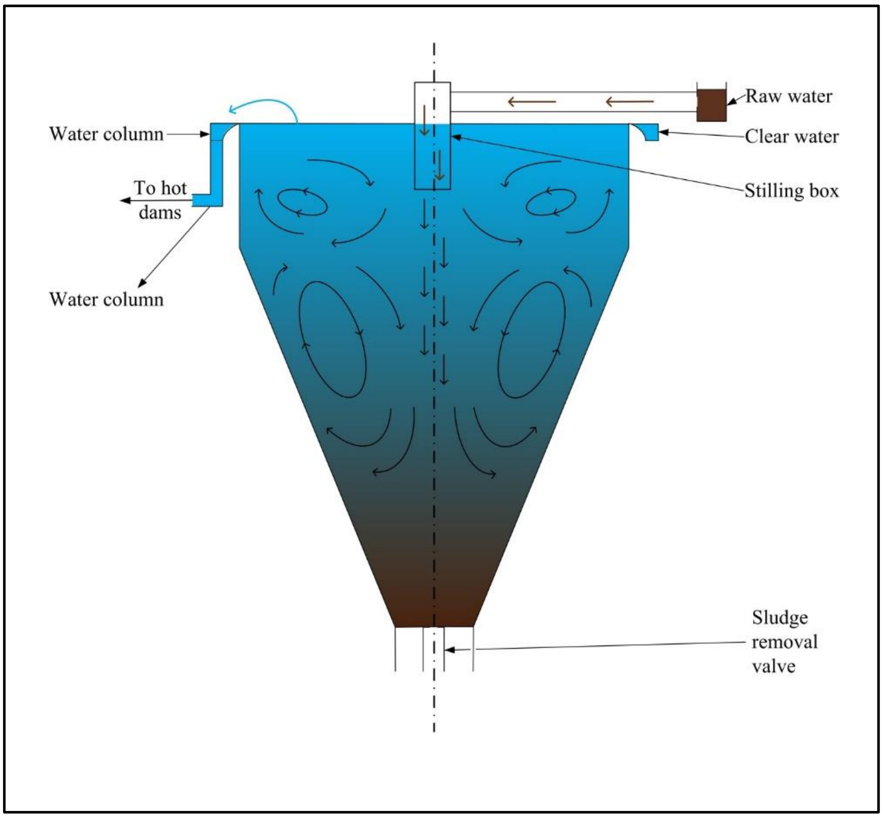


Figure 18: Conical settler (Adapted from [56])

The flow rate into each settler is controlled by a gate that slides over an inverted V-notch. This ensures that the first settlers in a multi-settler system are not overloaded when the flow in the inlet channels increases. The water is then channelled to a stilling box in the centre of the settler dam. The water exits the stilling box in a downward direction. Clear water exits the settler by flowing over the outer edge of the settler dam into hot water dams. The dissolved solids settle downwards against the water current, which is known as countercurrent settling [56].

Flocculent forms a thick solution when mixed with water in order to help particles bind with each other and settle faster. Adding flocculent can increase the performance of a settler by as much as 450%.

A study conducted on a settler designed to handle 1 636 Ml/d could sufficiently handle rates of up to 8 Ml/d if the settled mud was removed on a regular basis. It is also important to note that the process of removing mud from settlers is not automated. It is a manual process that needs to be done on a regular basis [56].

2.3.2 Hot water dams

Hot water dams are used to collect water after it has been processed by the settler dams before extraction to the surface. Hot water dams usually form part of a dewatering pumping station. Depending on available space and design of different mining levels, either horizontal dams or vertical dams are used.

Each pumping station has at least two individual dams to provide capacity for cleaning. This ensures that one dam can still be used for dewatering while the other dam is being cleaned. Due to some mud not being removed by settler dams, it ends up settling in the hot water dams, which causes a build-up of mud. Mud that settles in hot water dams contains gold amongst other elements, thus the mud needs to be processed. The mud build-up decreases the total dam capacity and poses a risk of damaging dewatering pumps. This will be discussed in the next section.

Another parameter that can decrease pump performance is the net positive suction head (NPSH). This is the minimum required head at the inlet of the pump. If the NPSH is insufficient, water vapour will form on the impeller and cause cavitation that will also decrease the pump efficiency [50].

Mud build-up in dams forces mine personnel to raise the minimum allowed dam levels in order to protect the dewatering pumps from pumping mud and to prevent an insufficient NPSH. The risk to the pumps increases as the dams become emptier due to the reduced intake pressure. If a pump has an insufficient intake pressure, it can damage the pump impeller [37]. This will also be discussed further in the next section. Horizontal dams, which cover large areas but are relatively shallow, have a higher minimum water level in order to provide a sufficient intake pressure to the pumps. Vertical dams are the opposite of horizontal dams and can become much emptier than horizontal dams before mud starts posing a threat to the dewatering pumps.

None of these dams has a specific shape. The shape depends on the available space on each mining level. Dams need to be cleaned on a regular basis depending on settler efficiency to keep their water storage capacities at a maximum. The mud that is removed from the dams is moved to the mud pumps via the water channels present on each mining level. The mud pumps are designed to pump thick slurries and are used to pump mud to the surface. This mud is then sent to the gold plant for further processing.

2.3.3 Pumps

Pumps are designed for specific applications and operating conditions. Dimensionless-specific speed is an important factor that needs to be considered when specifying pumps for different applications. Dimensionless-specific speed is a function of the required head, driven speed and volume flow of a pump [50]. The calculation of dimensionless-specific speed is shown in Equation 2 [50].

Equation 2: Calculation for specific dimensionless speed

$$N_s = \frac{NQ^{1/2}}{(gH)^{3/4}}$$

With:

N_s – Dimensionless-specific speed	[rev]
N – Driven speed	[rev/s]
Q – Volume flow	[m^3/s]
g – Acceleration of gravity	[m/s^2]
H – Required head	[m]

The majority of South African gold mines use centrifugal pumps, also known as radial flow pumps. Equation 2 means that an axial flow pump, which has a high dimensionless-specific speed with a lower head, will be able to deliver a higher volume flow. Figure 19 shows the ranking of radial flow pumps according to dimensionless-specific speed.

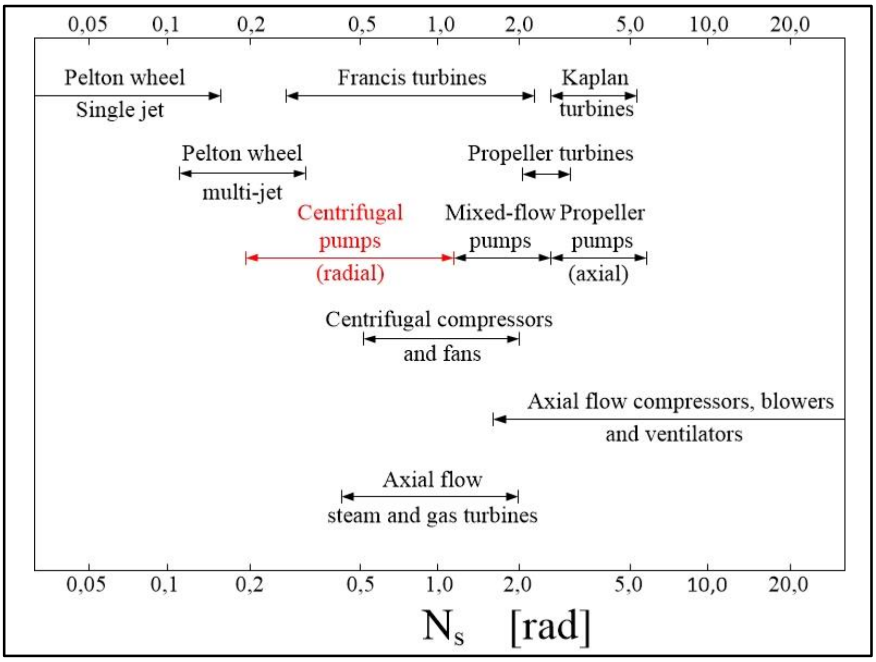


Figure 19: Dimensionless-specific speed of different pumps (Adapted from [50])

Although the cost of a new pump might be high, it represents a small portion of the lifetime operating costs of a pump. Electricity usage usually contributes the biggest part of this cost as illustrated by Figure 20. This is why it is so important to keep the pumps running as efficiently as possible, for as long as possible.

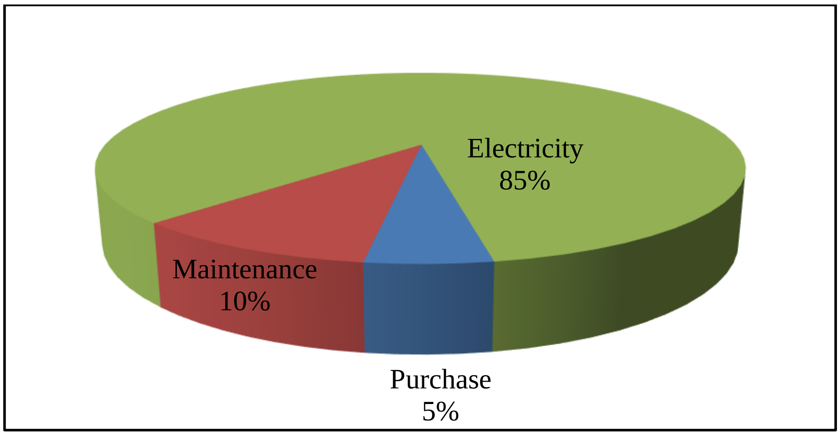


Figure 20: Pump lifecycle costs (Adapted from [57])

The efficiency of a new pump deteriorates over its lifetime. The initial deterioration is usually larger than the deterioration of a pump that has been refurbished because a used pump cannot be restored to its initial efficiency, but only to an efficiency slightly below that point [58]. It is also important to remember this when specifying and maintaining pumps. Equation 3 can be used to calculate the overall efficiency of a pump [50].

Equation 3: Calculation for pump efficiency

$$\eta_o = \frac{\rho g Q H}{P_s}$$

With:

η_o – Overall efficiency	[%]
ρ – Fluid density	[kg/m^3]
g – Acceleration of gravity	[m/s^2]
Q – Volume flow	[m^3/s]
H – Pump head	[m]
P_s – Shaft power (power driving the pump)	[kW]

The efficiency losses for new and unmaintained pumps are illustrated in Figure 21. A new pump can lose as much as 5% of its efficiency within this first five years of operation. Without maintenance a pump can lose approximately 10%-15% of its efficiency within the first 10 years of operation and fail completely after about 20 years [57]. Poor water quality on mines can increase efficiency losses even more [59].

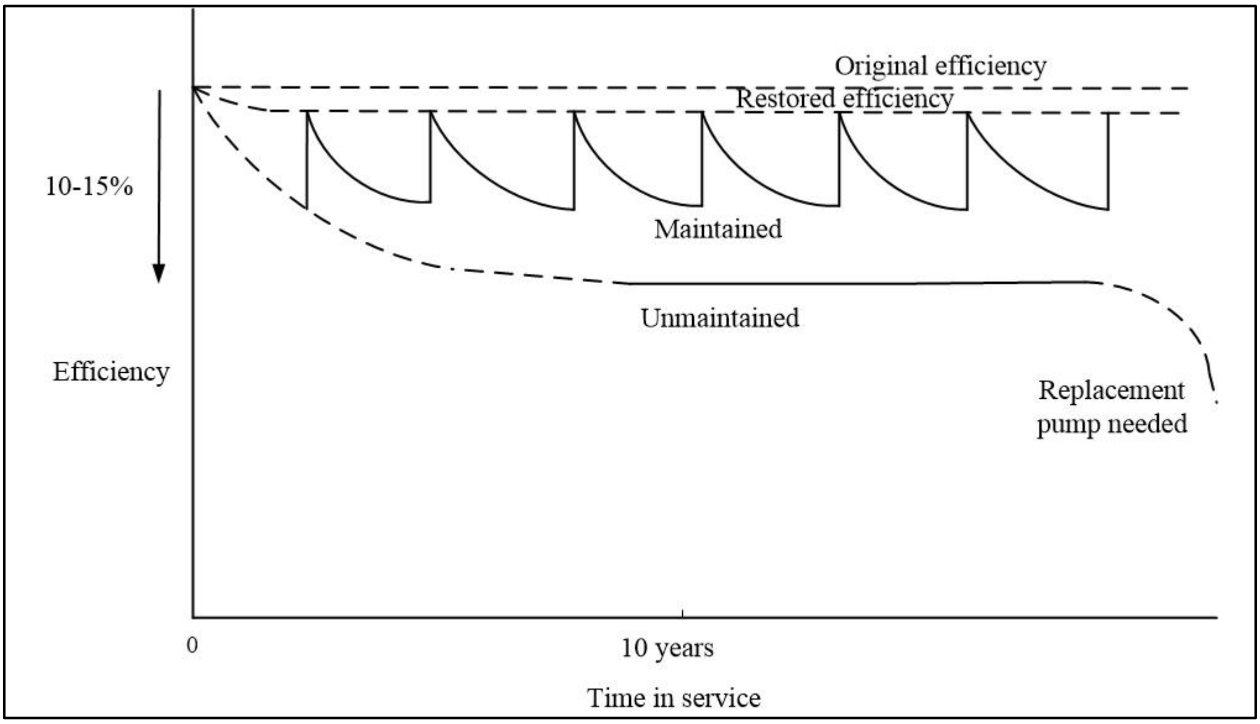


Figure 21: Pump efficiency over time (Adapted from [51])

A new pump can lose as much as 5% of its efficiency within this first five years of operation. Without maintenance, a pump can lose approximately 10–15% of its efficiency within the first 10 years of operation and fail completely after about 20 years [57]. Poor water quality on mines can increase efficiency losses even more [59].

It is important to keep the initial loss off efficiency in mind when specifying a new pump. Every pump has a unique best efficiency point (BEP). This point will be at a fixed speed, flow rate and head. Pumps that are not running at their BEP will also tend to wear out quicker, thus needing more regular maintenance [57]. Factors affected by pump wear are illustrated in Figure 22. It shows that the efficiency of a pump will decrease, the power consumption will increase and the delivery head of a pump will decrease as the flow decreases below the BEP.

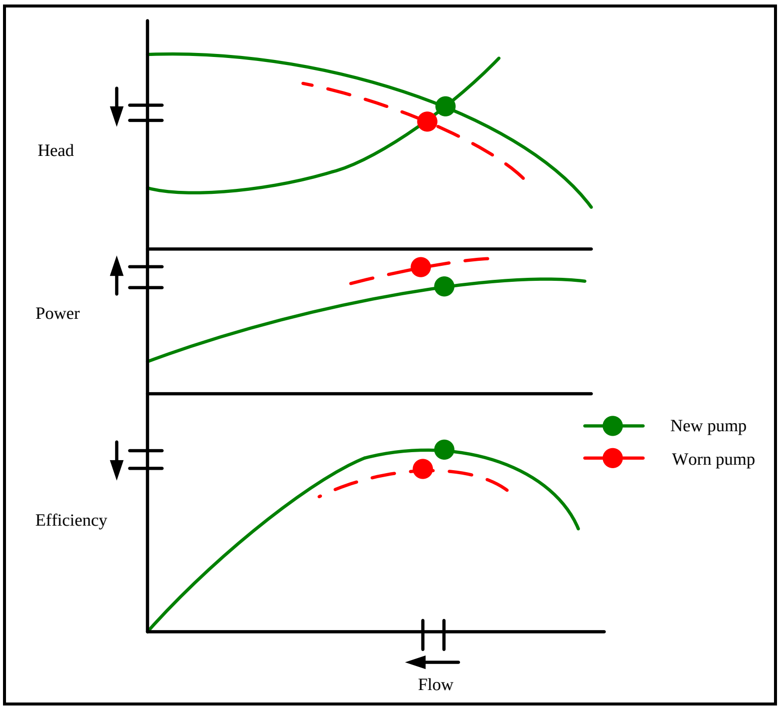


Figure 22: Pump BEP (Adapted from [57])

When a pump is used, the impeller is exposed to corrosion, which can seriously decrease its efficiency. Mine dewatering pumps are always pumping diluted slurries, which can greatly increase corrosion. The particles suspended in the slurry can affect the rate of corrosion depending on their [60]:

- Size and distribution;
- Density;
- Shape; and
- Concentration in the slurry.

A slurry with a 1 000 ppm suspended-solid count can be up to ten times more abrasive than a slurry with a suspended-solid count of 250 ppm [61]. The rate of wear is also increased greatly by suspended particles larger than 25 microns in the slurry [59].

Pumps can be connected to the inlet and outlet columns either in serial or in parallel. The way that pumps are connected is usually determined by the required flow characteristics. Pumps that are connected in parallel deliver a higher volume flow but a lower pump head. The opposite is true for pumps connected in series – they deliver a lower volume flow but a higher pump head. This is why connecting pumps in parallel is the preferred configuration for deep mine dewatering systems. Figure 23 shows a comparison of the head and flow between pumps in parallel and pumps in series.

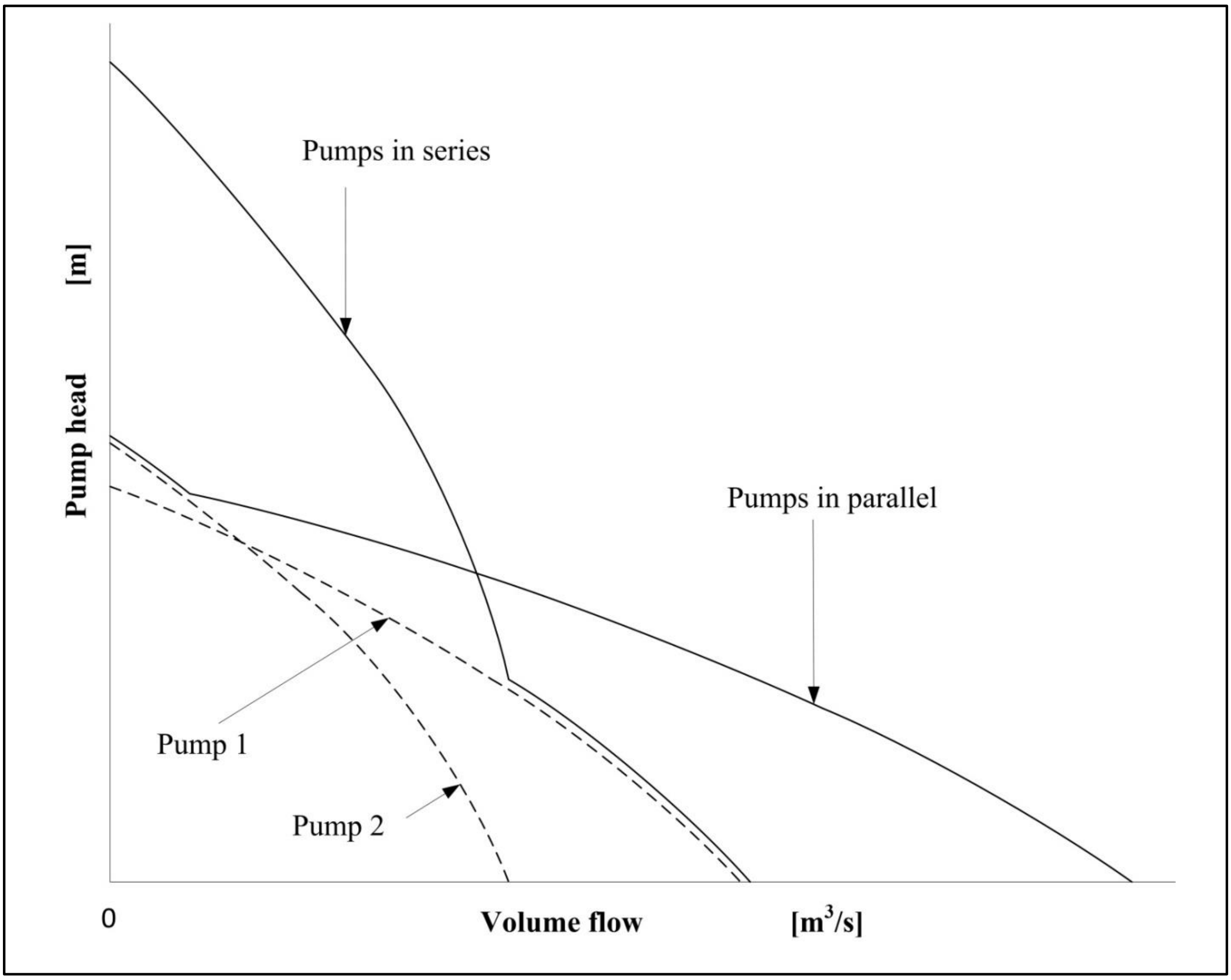


Figure 23: Pumps in parallel versus pumps in series (Adapted from [50])

2.3.4 Valves

Valves are used for regulating the flow rate and pressure of water. The two most common valve types in use are globe valves and butterfly valves. Butterfly valves use a flat disc that rotates within the valve body to increase or decrease pressure and flow. This configuration is more suited for off/on control rather than throttling. Butterfly valves are used to isolate mining levels if water is not needed. Globe valves have round valve bodies and control the flow by vertically moving plugs, which make them more suited for throttling water flow. This makes globe valves ideal for regulating water flow to individual mining levels [62]. Figure 24 shows a typical butterfly valve on the left and globe valve on the right.

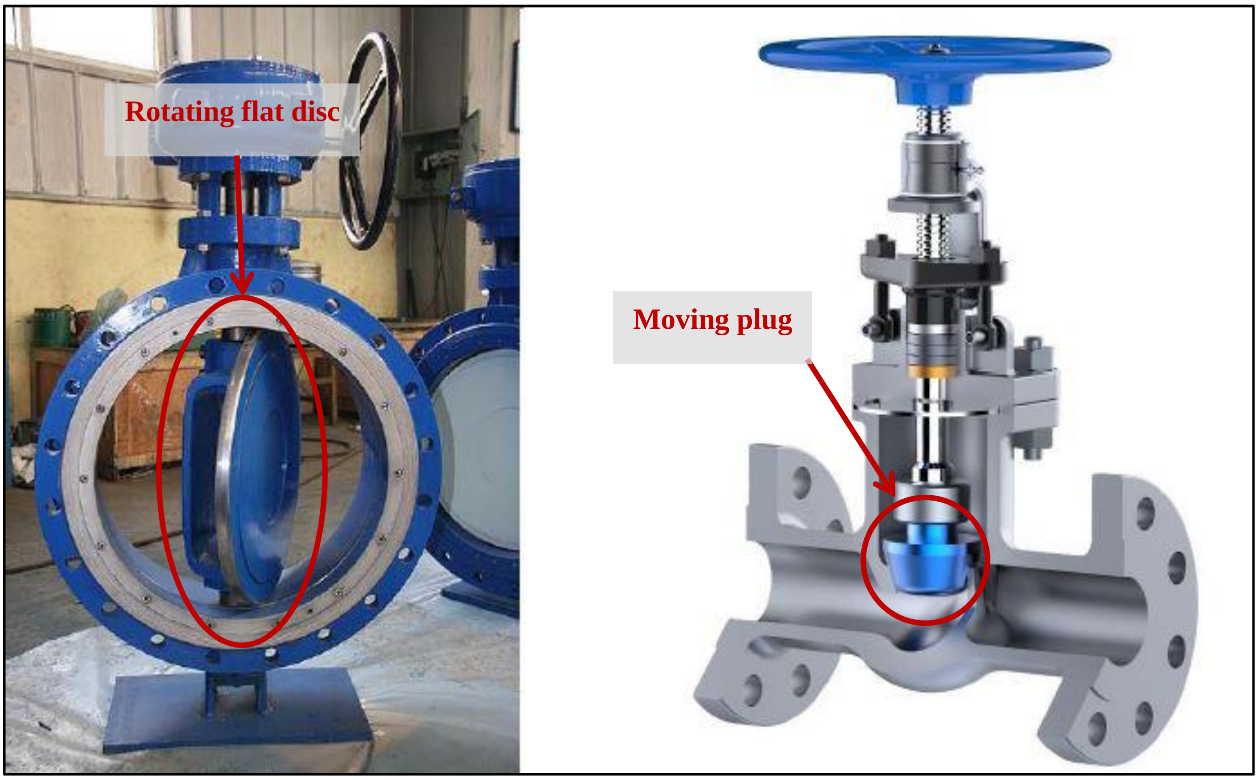


Figure 24: Butterfly valve and globe valve [63], [64]

2.4 Operational system overview

A water reticulation system consists of different interconnected components. The overall performance of such a system can thus be greatly influenced by any part of the system that is not functioning properly for any number of reasons. In order to simplify the water reticulation system, it can be separated into two separate systems – a hot water system and a chilled water system. Figure 25 shows a simplified layout of a mine water reticulation system, with the chilled water system indicated in blue and the hot water system indicated in red.

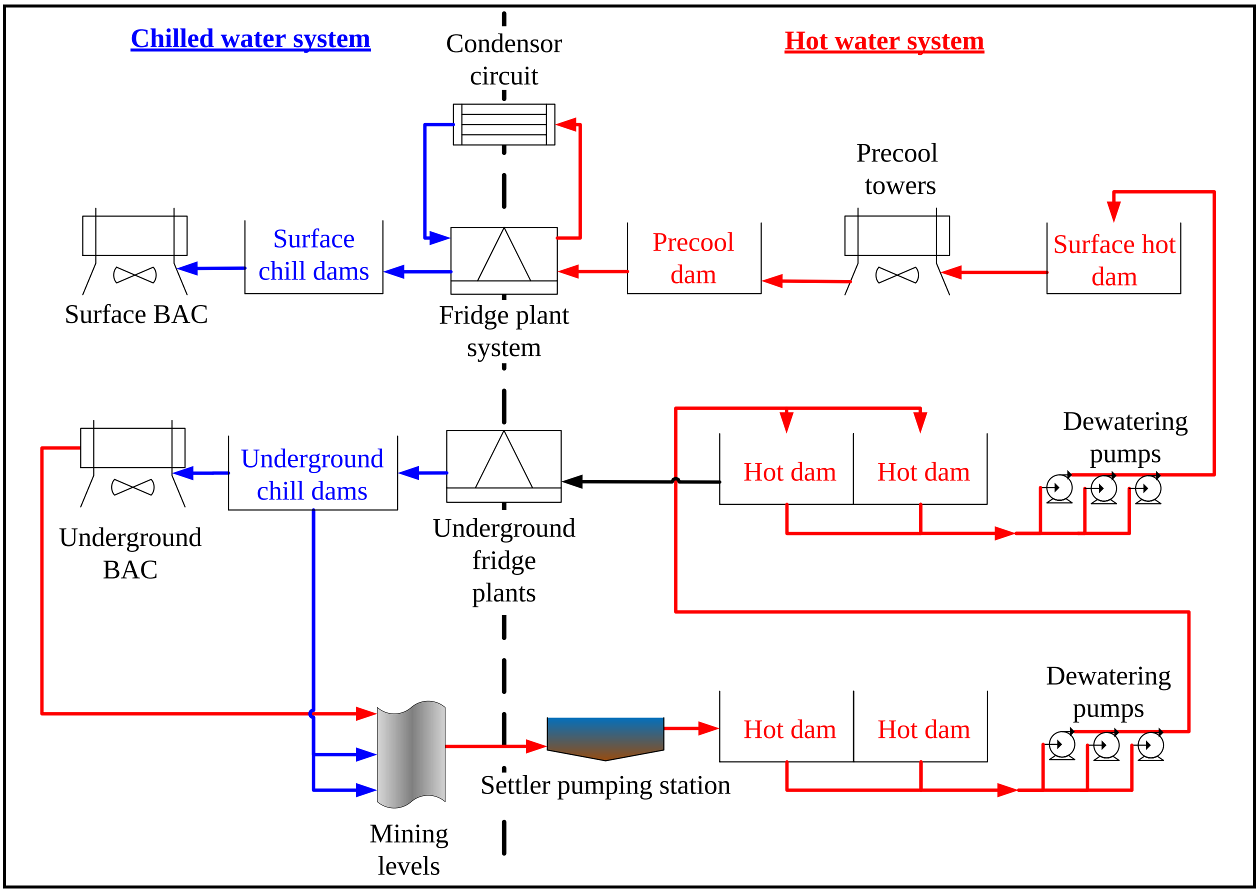


Figure 25: Simplified mine water reticulation system (Adapted from [30])

2.4.1 Chilled water

Chilled water is sent underground via a series of chilled water dams to reduce its pressure. As mentioned earlier, turbines can also be used to dissipate this pressure before the chilled water enters the dams. The chilled water is then used by underground BACs in the case of deep-level mines to recool ventilation air.

The outlet water from the BACs and chilled water from the fridge plants are also used for other mining processes, which includes drilling, sweeping and further cooling with cooling cars.

2.4.2 Hot water

The used mining water flows into settler dams. Fissure water that enters the mineshaft is also collected in settler dams. This used water is known as hot water in the mining industry. The pH of the water flowing into the settler dams is adjusted to prevent corrosion of equipment and to increase flocculent effectiveness. When the pH is sufficiently adjusted, a flocculent is added. Settler dams are usually located near or on the bottom mining levels. The processed water is now cleaner and can be pumped to the surface for recooling.

This cleaner water is transferred from the settler dams into hot water dams or clear water dams. The hot water dams are used as a water storage mechanism when the inflow is more than what the pumps can handle. The storage is also used to help distribute the workload between the pumps and to decrease the need for pump cycling. Pump cycling is the occurrence where pumps have to be started and stopped regularly because the hot water dams fill up and empty too quickly. The dewatering pumps that are fed by the hot water dams have large installed capacities that are not designed to be stopped and started frequently. The dewatering pumps are connected in parallel. They pump water from the hot water dams, at the same pumping station, to the hot water dams at the next pumping station closer to the surface.

This transfer of water from one pumping station to the next, continues until the hot water reaches the surface. Some mines recirculate the hot water underground by pumping it to a fridge plant. This fridge plant chills the water again and it is reused for mining processes. This reduces the amount of water needed from surface and the electricity that would have been used to pump the hot water to the surface. If hot water is not extracted sufficiently, some mining levels can start flooding causing damage to equipment. It will also create an unsafe working environment for mineworkers.

Hot water that reaches the surface is sent through the precooling towers and fridge plants to end up in the chill dams and restart the cycle. It happens from time to time that there is too much water in the system because of fissure water being added from underground sources. When this happens, the excess water has to be discarded. Water is usually drained from the system once it reaches the surface level. If it happens that the amount of water in the reticulation system is not sufficient, water is added to the surface hot water dam from a nearby reservoir or supply line.

2.5 Conclusion

In this chapter, the usage of water in the mining industry was discussed. It was also shown how important the supply and removal of water to underground mining levels are. An overview of the entire water reticulation system of a typical mine was shown and discussed. The problems that could reduce the dewatering pumps’ efficiency were discussed together with the importance of repairing them.

CHAPTER 3. SIMULATION DEVELOPMENT AND VERIFICATION

3.1 Introduction

The performance of a mine dewatering system can be improved in different ways. In practice, testing each improvement theory can be expensive and time-consuming. It is, therefore, more cost effective and less time-consuming to simulate the dewatering system and to test the effects of these improvements on system performance. The simulations for this dissertation were done using only one simulation package. The results of the simulation package are validated at the end of this chapter.

Alternative simulation packages could be used to deliver similar results, provided that their results could be validated. For purposes of this dissertation, it was not deemed necessary to provide information about alternative simulation packages.

The simulation package used in this study is called REMS (Real-Time Energy Management System). REMS can also be used as a real-time control system. The main difference between Control System mode and Simulation mode is the source of the input data. In Control System mode, real-time system data is received from the supervisory control and data acquisition (SCADA) system. In Simulation mode, the input data is calculated or manipulated to determine the system statuses for a particular situation.

The statuses of components refer to aspects such as power consumption, flow rates, on/off statuses, dam levels and dam capacities. These statuses can be seen as simulation outputs. The inputs used for the simulation were programmed into the Simulation model as 24 different values, with a different value for each hour of the day. These inputs were the following:

- Water inflow into the hot water dam at the bottom of the dewatering system;
- Maximum number of pumps allowed to run simultaneously;
- Pump delivery flow rates;
- Pump running capacities;
- Number of available pumps;
- Available hot water dam capacity; and
- Water flow rate from the mine dewatering system.

The values for these inputs were obtained by calculating the average value for each hour of the day using real-time data. Unless stated otherwise, the flow rates and running capacities of the pumps were set to be constant for the entire simulation.

The simulation takes this input data and ‘predicts’ the changes in the system statuses according to the given inputs. These changes in the system statuses are logged into different files corresponding with the specific components and are stored on the computer hard drive. The values are logged every two minutes, but this interval can be changed.

3.2 Overview of case study

Mine A is a gold mine. The design of this mine will be used to develop the simulation model. Mine A has a dewatering system that spans five mining levels and has an installed capacity of 33 MW. The dewatering system starts at 115L and goes up to the surface as shown in Figure 26.

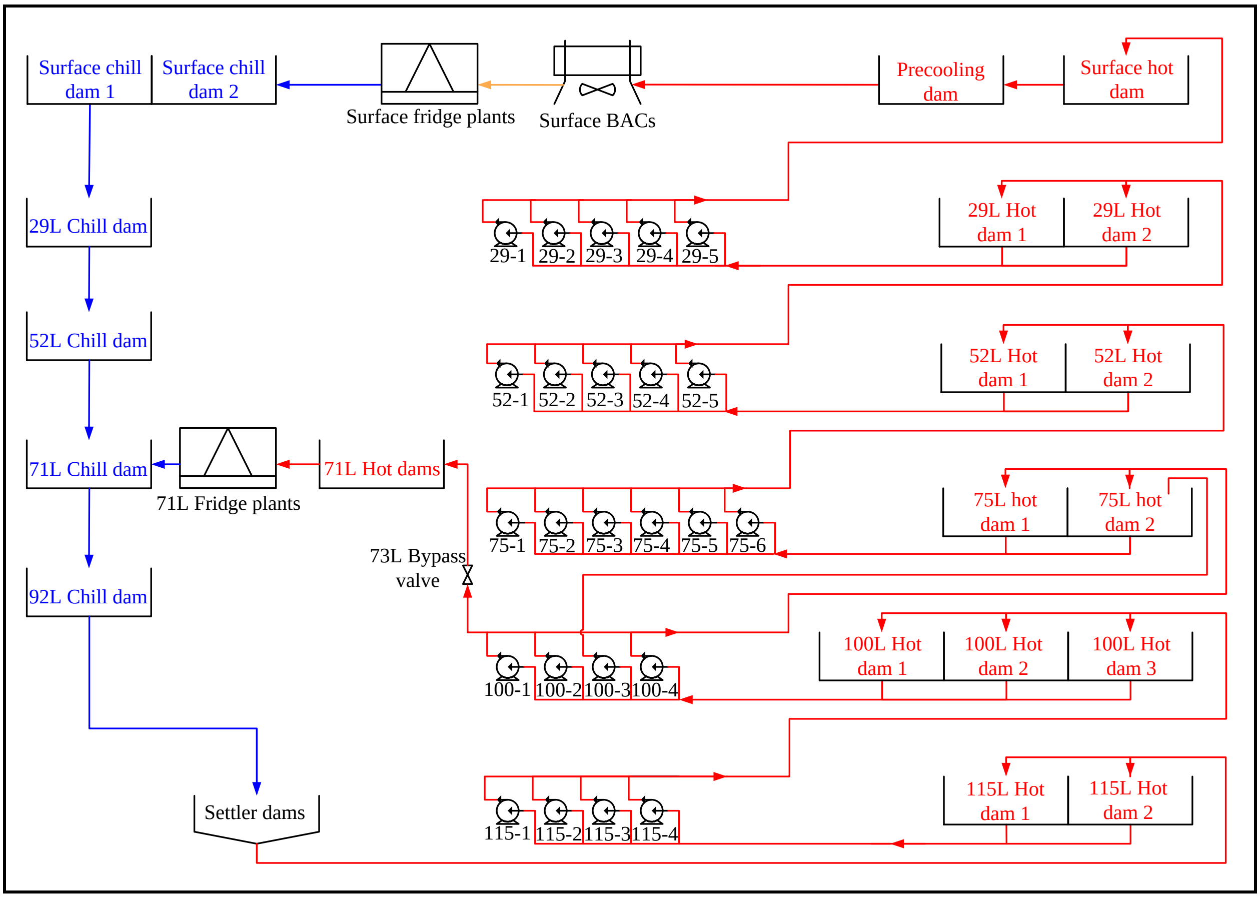


Figure 26: Layout of Mine A’s water reticulation system

The following assumptions are made in this simulation:

- The delivery flow rates and efficiencies of the pumps correspond with the actual values of the simulated period.
- The pumps’ efficiencies and flow rates will stay constant over time, unless stated otherwise.
- There are no breakdowns or other unforeseeable technical issues.
- The dams’ levels at each pumping station are always equal.

3.2.1 115L pumping station

The pumps on 115L have a rated power of 2 000 kW each. Only two of the four pumps are permanently available for use. These pumps use two columns to pump water to the 100L pumping station. The pumps are being controlled manually at this stage, but for simulation purposes, the pumps were set to control the hot water dam levels automatically between 50% and 85%.

There are two hot water dams at the 115L pumping station. The water levels of these dams are being kept relatively equal by a balancing valve, but this is not always the case as the valve tends to be blocked. The dams on this level are vertical dams, which means that the intake pressure on the pumps are relatively high even when the dam levels are low. The minimum dam level is used to prevent pumps from pumping mud, which settles at the bottom of the hot water dams. It is important to keep in mind that the higher the dam levels, the higher the flood risk. This is because the higher the dam levels, the less time is available to rectify problems if something would prevent the dewatering pumps from starting.

3.2.2 100L pumping station

The pumps on 100L are set to have a rated power of 1 600 kW with only two of the four pumps permanently available on this level. The pumps are being controlled manually at this stage, but for the simulation they were set to control the hot water dam levels automatically between 50% and 85%.

The layout of this system differs from the previous level because it has to provide water to two other levels. One of the pumps on 100L is only able to deliver water to the hot water dam on 75L, from where the other three pumps are able to deliver water to deliver water to either 75L or 71L. This is controlled by a valve on 73L. The water can be pumped to either 71L hot water dam when the valve is closed or to 75L hot water dam when the valve is open.

There are three hot water dams at the 100L pumping station. Only two of these dams are being used to store water from 115L. The third dam on this level is kept empty in case of emergency. A typical emergency will arise when there are not enough pumps available to prevent the dam levels from breaching their maximum limits. These dams are vertical dams like the dams on 115L.

3.2.3 75L pumping station

The pumps at 75L pumping station have a rated power of 1 115 kW each. It was also assumed that only four of the six pumps on 75L were available, but a maximum of three were allowed to run simultaneously. This limits the rate at which water can be pumped from the hot water dams on this level to the hot water dams on 52L.

There are two hot water dams on 75L. One of these dams is usually kept empty for cleaning and emergency situations. This means that the capacity on this level is about half of the designed capacity. These hot water dams are horizontal dams. The minimum and maximum dam levels for this hot water dams were thus set at 79% and 95% respectively.

3.2.4 71L cooling station

The average flow into the 71L hot water dam was calculated by averaging the rate of the water that was pumped into it. The flow into the 71L hot water dam is controlled by a valve on 73L, as mentioned earlier.

The 71L hot water dam is one of the key points in Mine A’s water reticulation system. The hot water dam levels at the 71L cooling station are kept close to their maximum levels in order to ensure that there is always water available to supply the fridge plants on 71L. The minimum and maximum dam levels were thus set to be 89% and 100% respectively. The 11% range between the minimum and maximum dam levels of this dam greatly decreases the potential for load shifting.

The fact that the pumps on 100L, which supply the 71L hot water dam with water, are not always pumping water to this dam has to be taken into consideration as well. This also increases the importance of the reliability of the 100L pumps.

The 71L hot water dam provides the fridge plants on the same mining level with water that is chilled and then sent to the 71L BAC. This chilled water, along with the chilled water from surface, then flows into the 71L chill dam. This water eventually ends up in the settler dams on 115L again. If the fridge plant on 71L stops for any reason, it can bring production on lower levels to a complete halt due to the high underground temperatures. It is thus crucial that the hot water dam on this level never runs empty.

3.2.5 29L and 52L pumping stations

The rated power for each pump on these levels was set to be equal. Only four pumps were available on each of the mining levels – a maximum of only three pumps on each mining level were allowed to run simultaneously. These pumps have a rated power of 1 200 kW.

There are two hot water dams on each of these levels. Both dams on 52L are in permanent use and connected by a common node, which is known as a control dam. These dams are also horizontal dams. The pumps on 52L are being used to pump water from the 52L hot water dams to the 29L hot water dams.

There are also two hot water dams on 29L, but one is kept empty for cleaning and emergencies. This means that this pumping station can also only use half of its storage capacity. The water from this hot water dam is pumped to the surface, where it is processed for recirculation.

The minimum and maximum levels for the hot water dams on both mining levels were assumed to be 79% and 95% respectively, although the programmable logic controllers (PLCs) were coded to trip the 29L pumps if the 29L hot water dam level decreased below 81%. The reason for the minimum and maximum dam levels being closer to each other is the horizontal shape and mud build-up in the dams. The low storage capacity of hot water dams causes them to fill up and empty quicker, which means that the pumps will be starting and stopping more regularly.

3.2.6 Surface level

The surface hot water dams receive additional water from an external source if more water is needed in the water reticulation system. Excess water is also removed from the system at this point.

Water from the surface hot water dam is pumped to the precooling dams from where it is pumped to the precooling towers. The water from the precooling towers is then chilled by fridge plants and stored in the surface chill dams. This chilled water is then sent underground again to form a circulatory loop in the water reticulation system. The hot water dam on the surface was set to have a constant level for the entire simulation.

3.2.7 General

The simulation model produced data at two-minute intervals for the system statuses as if the simulation was running in real-time and not as a simulation. This data was then processed to get a better overview of what happened in the system during the simulation. The data from the simulation for one month was compared to the existing baseline of the project in order to verify the results. Cumulative savings were calculated by adding changes to the previous simulation model.

A baseline is a profile that represents the power consumption of a project for a 24-hour period. This profile was obtained by calculating the average hourly power usage from the most recent power consumption data for the relevant project. This baseline was then scaled according to the type of DSM initiative that was implemented.

3.3 Simulation components

Different components were used in the simulation process that represented the actual components of the system. Figure 27 shows the different components and layout of the platform that was used for the simulation of the mine dewatering system.

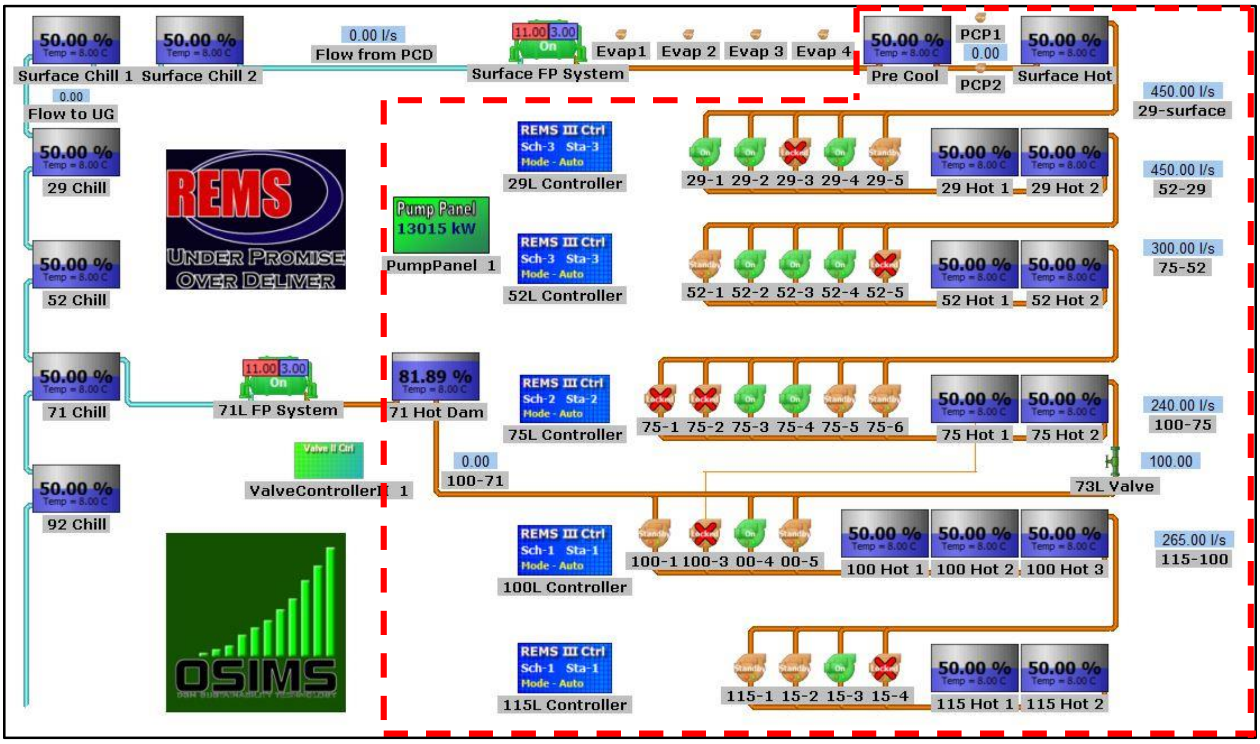
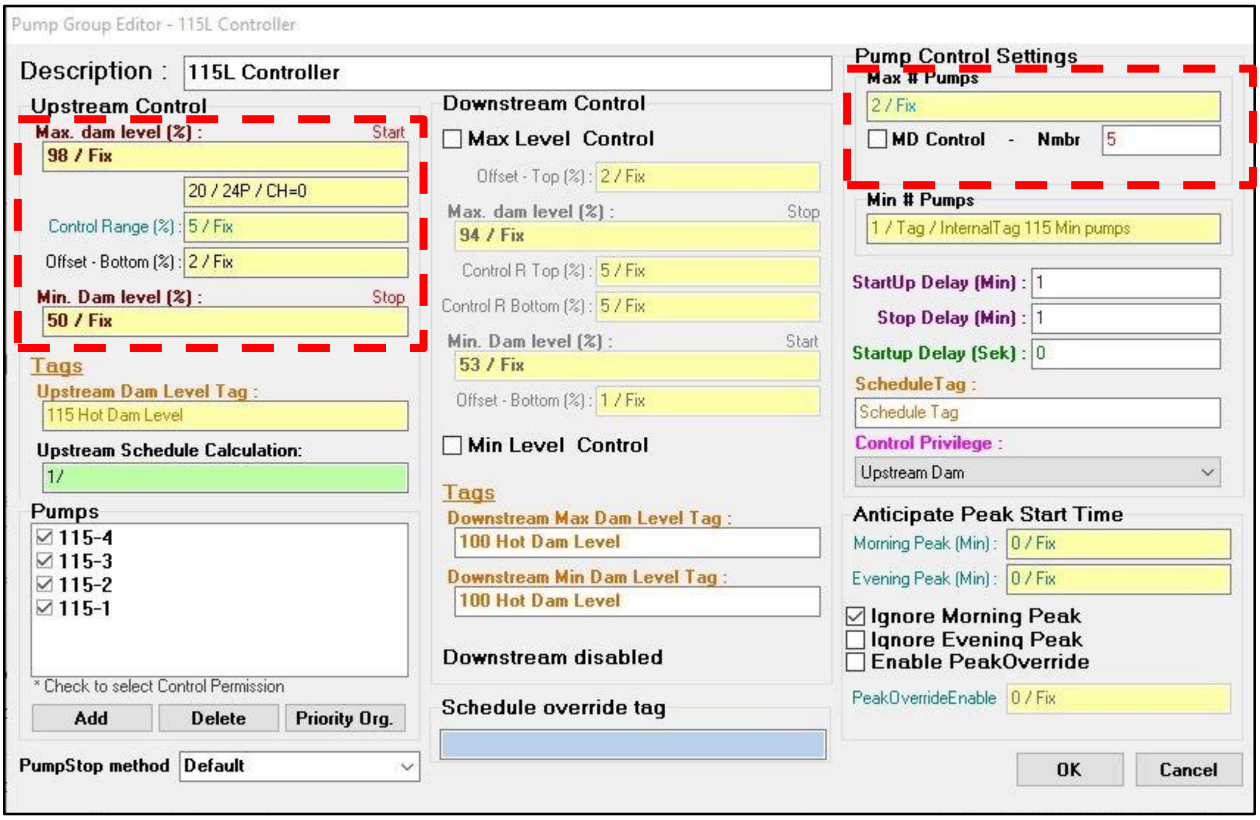


Figure 27: Simulation platform

Figure 27 shows a representation of a mine water reticulation system. The part inside the red dotted box represents the dewatering system. For simulation purposes, only this part of the platform was simulated to obtain the required data.

3.3.1 Pump controller

A pump controller is the component in REMS that is responsible for starting and stopping specific dewatering pumps according to the level of a specified dam. The pump controller can be set to control the dams according to the level of a dam that is upstream or downstream from the pumps. The pump controller will be set to upstream dam control in this case. There are six inputs responsible for the control of each dam level. Figure 28 shows the configuration window for the pump controller. The marked fields are the inputs, which will be described in the following paragraphs.


Pump Group Editor - 115L Controller

Description : 115L Controller

Upstream Control
Max. dam level (%) : Start 98 / Fix
20 / 24P / CH=0
Control Range (%) : 5 / Fix
Offset - Bottom (%) : 2 / Fix
Min. Dam level (%) : Stop 50 / Fix
Tags
Upstream Dam Level Tag : 115 Hot Dam Level
Upstream Schedule Calculation: 1/
Pumps
☑ 115-4
☑ 115-3
☑ 115-2
☑ 115-1
* Check to select Control Permission
PumpStop method: Default

Downstream Control
☐ Max Level Control
Offset - Top (%) : 2 / Fix
Max. dam level (%) : Stop 94 / Fix
Control R Top (%) : 5 / Fix
Control R Bottom (%) : 5 / Fix
Min. Dam level (%) : Start 53 / Fix
Offset - Bottom (%) : 1 / Fix
☐ Min Level Control
Tags
Downstream Max Dam Level Tag : 100 Hot Dam Level
Downstream Min Dam Level Tag : 100 Hot Dam Level
Downstream disabled
Schedule override tag

Pump Control Settings
Max # Pumps: 2 / Fix
☐ MD Control - Nmbr 5
Min # Pumps: 1 / Tag / InternalTag 115 Min pumps
StartUp Delay (Min) : 1
Stop Delay (Min) : 1
Startup Delay (Sek) : 0
ScheduleTag : Schedule Tag
Control Privilege : Upstream Dam
Anticipate Peak Start Time
Morning Peak (Min) : 0 / Fix
Evening Peak (Min) : 0 / Fix
☑ Ignore Morning Peak
☐ Ignore Evening Peak
☐ Enable PeakOverride
PeakOverrideEnable 0 / Fix

Figure 28: Pump controller configuration window

The first input is the “Minimum dam level”, which is specified in terms of percentage. The number of running pumps will decrease if the upstream dam level decreases below this value. The “Maximum dam level” is the level at which the pump controller will begin starting pumps during peak periods. The “Max # pumps” input is used to specify the maximum number of pumps that are allowed to run simultaneously.

The “Top offset” and “Control range” inputs are used to calculate where additional pumps will be started. The first pump will be started at the sum of “Minimum dam level” and “Control Range”. The other pumps will be started at the sum of “Minimum dam level”, “Control Range” and multiplications of “Top offset”. This will continue until all of the available pumps are running or the “Max # pumps” is reached. It is important that the control range is not too small because it can cause pumps to start and stop unnecessarily. Unnecessary stopping/starting of pumps causes increased wear and may result in premature failure.

The next input is the “Bottom offset” for the dam involved. This is also specified as a percentage. The first running pump will be stopped at the “Minimum dam level”, while the second running pump will be stopped at the difference between the “Minimum dam level” and the “Bottom offset”. The remaining pumps will be stopped at the difference between the “Minimum dam level” and multiplications of the “Bottom offset”. This will continue until no more pumps are running.

Starting pumps

Equation 4 is used to calculate the dam level at which the first pump will start outside of peak periods.

Equation 4: First pump starting level

$$L_1 = L_{Min} + L_{CR}$$

With:

L_1	=	Dam level at which the pump controller will start the first pump	[%]
L_{Min}	=	Minimum dam level specified in the pump controller	[%]
L_{CR}	=	Control range specified in the pump controller	[%]

After the first pump has been started, the controller will keep starting more pumps at specific intervals until the outflow of the dam is greater or equal to the inflow. The dam level at which the rest of the pumps will be started can be calculated using Equation 5.

Equation 5: Starting pump number 2 and upwards

$$L_i = (L_{Min} + L_{CR}) + ((\mathrm{i} - 1) \times L_{TO})$$

With:

i = The number of the pump that will start next (ranging from pump 2 to the number of the last pump in the pump set) [%]

L_i = Dam level at which pump number i will start [%]

L_{Min} = Minimum dam level specified in the pump controller [%]

L_{CR} = Control range specified in the pump controller [%]

L_{TO} = Interval of change in dam level at which pump number 2 and upwards will start [%]

The starting of pumps is calculated differently during peak periods. These calculations differ to be able to start pumps only if absolutely necessary. The dam level at which the first pump will be started in peak periods can be calculated by using Equation 6.

Equation 6: Starting level of first pump during peak periods

$$L_1 = L_{Max} + L_{CR}$$

With:

L_1 = Dam level at which the pump controller will start the first pump [%]

L_{Max} = Maximum dam level specified in the pump controller [%]

L_{CR} = Control range specified in the pump controller [%]

The dam levels at which the rest of the pumps will be started can be calculated using Equation 7.

Equation 7: Starting pump number 2 and upwards during peak periods

$$L_i = (L_{Max} + L_{CR}) + ((\mathrm{i} - 1) \times L_{TO})$$

With:

i	=	The number of the pump starting next (ranging from pump 2 to the number of the last pump in the pump set)	[%]
L_i	=	Dam level at which pump number i will start	[%]
L_{Max}	=	Maximum dam level specified in the pump controller	[%]
L_{CR}	=	Control range specified in the pump controller	[%]
L_{TO}	=	Interval of change in dam level at which pump number 2 and upwards will start	[%]

When setting up a simulation or creating a control philosophy, it is important to ensure that the last pump starts below the allowed maximum dam level to ensure that the maximum dam level is never exceeded.

Stopping pumps

The pump controller stops the pumps very similar to the reverse order of starting them. The dam levels at which the pumps will be stopped can be calculated using Equation 8.

Equation 8: Stopping pumps

$$L_i = L_{Min} - ((\mathrm{i} - 1) \times L_{BO})$$

With:

i = The number of the pump stopping next (ranging from pump 1 to the number of the last pump in the pump set) [%]

L_i = Dam level at which pump number i will stop [%]

L_{Min} = Minimum dam level specified in the pump controller [%]

L_{BO} = Bottom offset as specified in the pump controller [%]

During peak periods, the dam levels at which pumps will be stopped are calculated differently than for non-peak periods. The dam level at which the first pump will be stopped, can be calculated according to Equation 9.

Equation 9: Stopping pumps during peak periods

$$L_i = L_{Min} - (\mathrm{i} \times L_{BO})$$

With:

i = The number of the pump stopping next (ranging from pump 1 to the number of the last pump in the pump set) [%]

L_i = Dam level at which pump number i will stop [%]

L_{Min} = Minimum dam level specified in the pump controller [%]

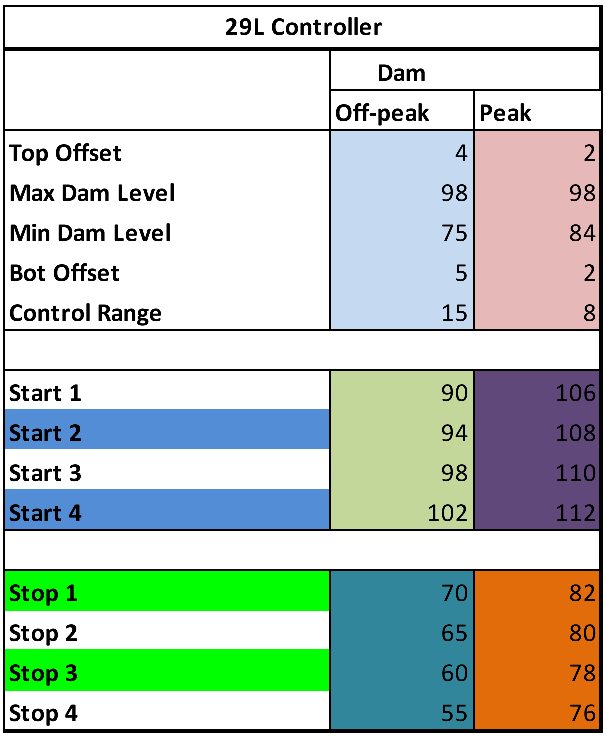
L_{BO} = Bottom offset as specified in the pump controller [%]

The pump controller will start pumps individually according to the rate of inflow into the dam. The pump controller will start the pumps at intervals until the dam level stays constant or starts decreasing. The pump controller will then stop the pumps individually at different intervals until the dam level stops decreasing or stays constant. The order in which the pumps are started and stopped, are determined by their efficiencies. The pump controller can be set so that a certain pump always starts up first and stops last, while the rest of the pumps can be set to stop and start in the same sequence.

The control according to an upstream dam level is explained in the practical example that follows.

Practical example

Figure 29 shows a screenshot of the calculated dam levels for stopping and starting pumps.



29L Controller		
	Dam	
	Off-peak	Peak
Top Offset	4	2
Max Dam Level	98	98
Min Dam Level	75	84
Bot Offset	5	2
Control Range	15	8
Start 1	90	106
Start 2	94	108
Start 3	98	110
Start 4	102	112
Stop 1	70	82
Stop 2	65	80
Stop 3	60	78
Stop 4	55	76

Figure 29: Example pump controller calculations

For demonstration purposes, the effect of pumps on the dam level will be ignored and the levels at which pumps will be started will be indicated. For this example, it will be assumed that the dam level increases at a constant rate from 0% up to 100% and then declines at a constant rate until it reaches 0%. The inputs in Table 1 will be used to demonstrate the way the pump controller starts and stops pumps.

Table 1: Pump controller inputs

Inputs	Variables
Minimum dam level	50%
Maximum dam level	90%
Control range	10%
Top offset	5%
Bottom offset	5%
Maximum number of pumps	4

The graph in Figure 30 illustrates how a pump controller will control dam levels by stopping and starting the involved pumps.

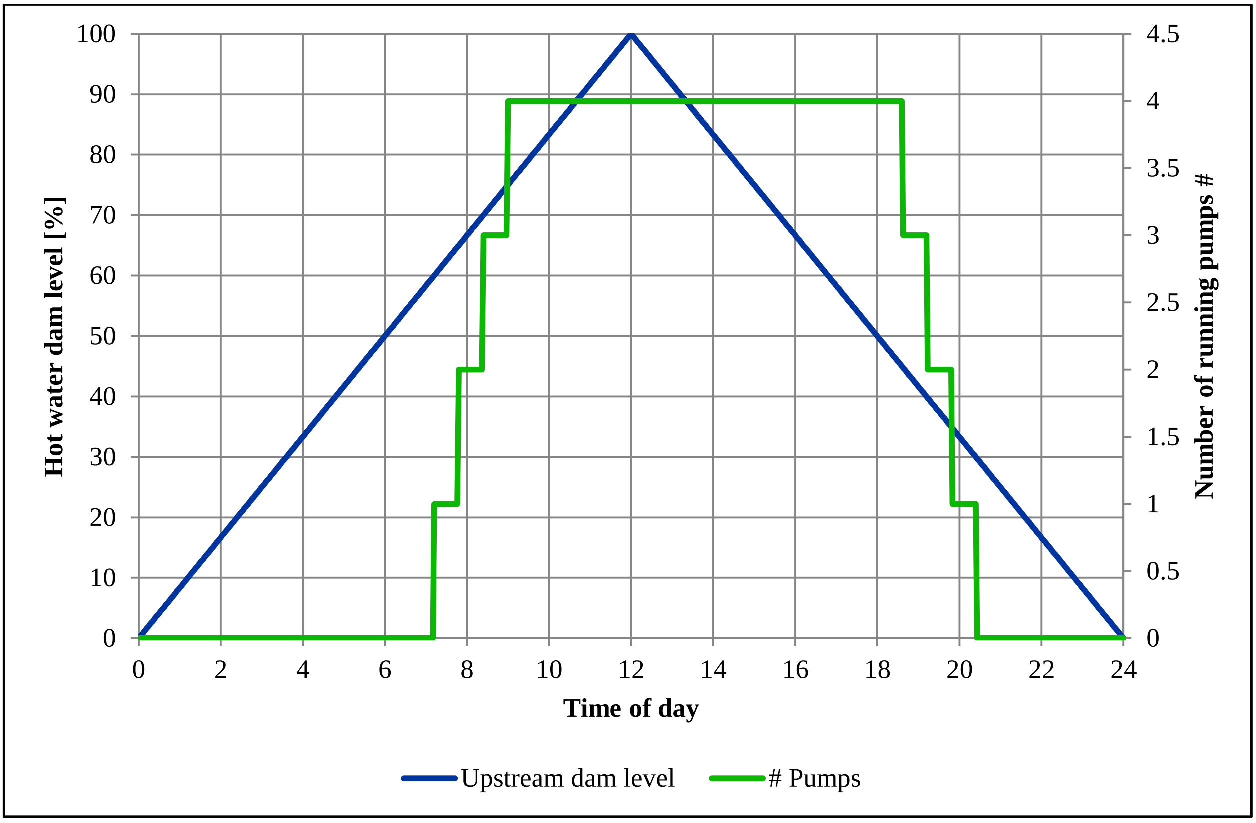


Figure 30: Pump control according to upstream dam level

When looking at Figure 30, it can be seen that the first pump will be started at a dam level of 60%, which is the sum of the "Minimum dam level" and "Control range". The rest of the pumps will be started at increments of the "Top offset" or 5%. In the same way, the first pump will be stopped at 45%, which is the difference between the "Minimum dam level" and the "Bottom offset". The rest of the pumps will be stopped at increments of the "Bottom offset" or 5%.

Pumps need to be prioritised to ensure that the most efficient pump is started firstly in peak periods, while the least efficient pump is started lastly. It is recommended that pumps with extremely low efficiencies not be used during peak periods. The sequence in which pumps should be stopped during peak periods is exactly opposite of their starting sequence. This ensures that the most efficient pumps are run the most during peak periods.

When it comes to off-peak periods, the least efficient pumps should be started first and stopped last, so that the most efficient pumps are running for the shortest duration. This helps prolong the life of the efficient pumps while keeping electricity costs low as discussed in Section 2.3.3. Pumps that are being maintained properly and protected against unnecessary wear will provide a higher flow rate in general and have a better efficiency. This means that they will use less electricity than unmaintained pumps.

In some cases, the pump controller needs to be forced to stop and start pumps without considering the individual dam levels. The balance disc between two dams can be blocked, causing one dam level to stay constant while the other keeps changing. The pump controller is then forced to ignore the dam with the stationary level and start or stop the dewatering pumps according to the changing dam level. This prevents dam levels from exceeding the desired range.

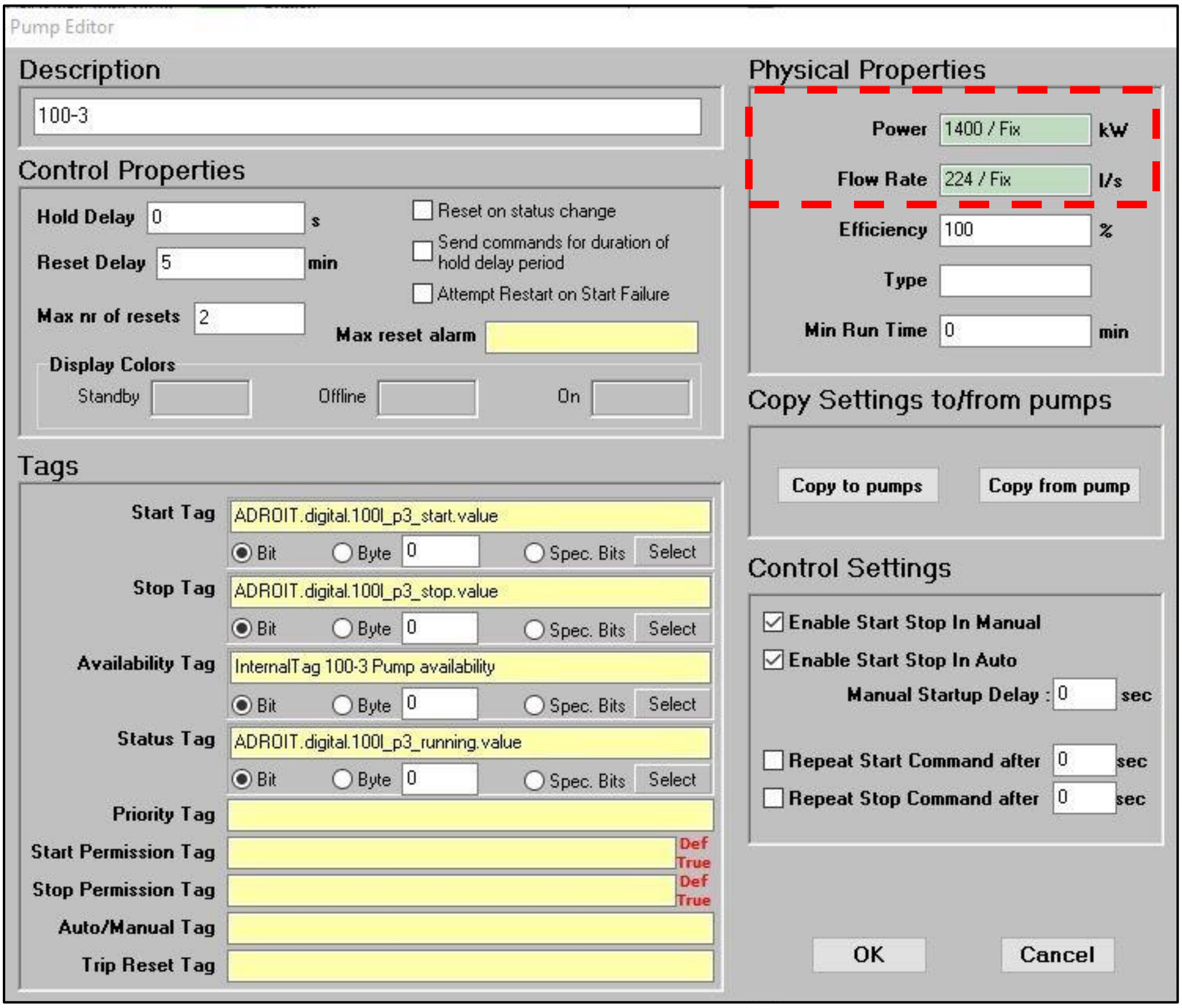
It is a common problem when multiple dam levels need to be monitored by the pump controller, because the pump controller can only monitor one upstream and one downstream dam level at a time. This can be done by setting the maximum and minimum number of running pumps allowed while also programming the pump controller to monitor either the emptiest or the fullest dam. This is used to stop the controller from starting too many pumps when there is a sudden spike in the monitored dam level because of incorrect data from the sensor. When forcing the pump controller, it is important to keep the dam level from becoming too high or too low.

3.3.2 Pumps

The specifications of the pumps in the simulation must be defined to get data such as power consumption and flow rates between dams. On some occasions, there are fluctuations in the pump scheduling of the pump controller. This is caused by inaccurate dam level readings, which can be filtered by introducing a delay for starting and stopping pumps. Running pumps are displayed in green on the software platform, while pumps on standby are displayed in orange. Pumps can also be locked out, which prevents the pump controller or even operators from starting them from the REMS platform as illustrated by Figure 31.

Figure 31: Different REMS pump states

This is a handy feature when a pump is being inspected or serviced. Figure 32 shows the REMS configuration window used to program the pump inputs into the simulation.


Pump Editor

Description
100-3

Control Properties
Hold Delay 0 s
Reset Delay 5 min
Max nr of resets 2
☐ Reset on status change
☐ Send commands for duration of hold delay period
☐ Attempt Restart on Start Failure
Max reset alarm
Display Colors
Standby
Offline
On

Tags
Start Tag ADROIT.digital.100l_p3_start.value
● Bit ○ Byte 0 ○ Spec. Bits Select
Stop Tag ADROIT.digital.100l_p3_stop.value
● Bit ○ Byte 0 ○ Spec. Bits Select
Availability Tag InternalTag 100-3 Pump availability
● Bit ○ Byte 0 ○ Spec. Bits Select
Status Tag ADROIT.digital.100l_p3_running.value
● Bit ○ Byte 0 ○ Spec. Bits Select
Priority Tag
Start Permission Tag Def True
Stop Permission Tag Def True
Auto/Manual Tag
Trip Reset Tag

Physical Properties
Power 1400 / Fix kW
Flow Rate 224 / Fix l/s
Efficiency 100 %
Type
Min Run Time 0 min

Copy Settings to/from pumps
Copy to pumps
Copy from pump

Control Settings
☑ Enable Start Stop In Manual
☑ Enable Start Stop In Auto
Manual Startup Delay : 0 sec
☐ Repeat Start Command after 0 sec
☐ Repeat Stop Command after 0 sec

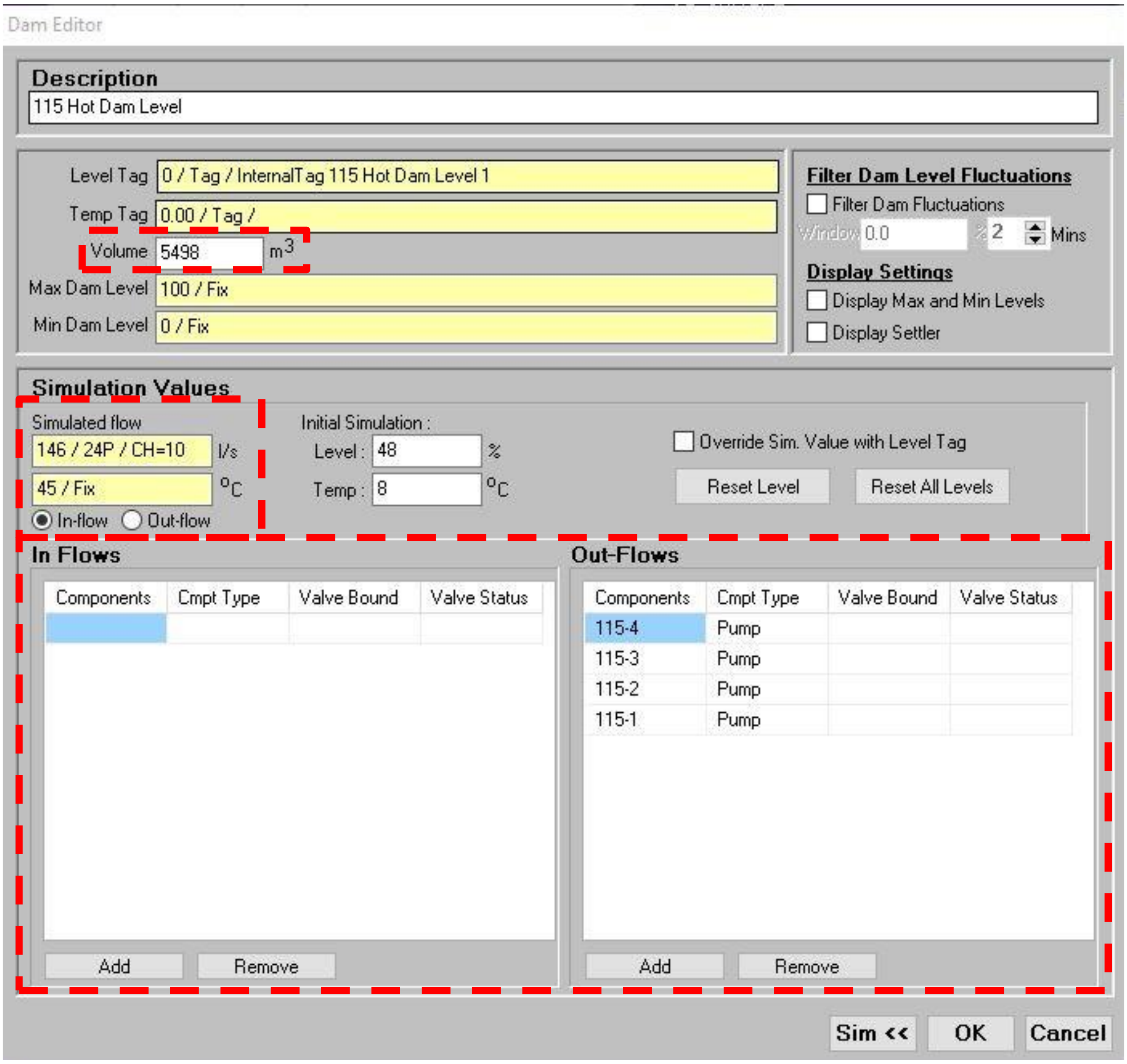
OK
Cancel

Figure 32: REMS pump configuration

In Figure 32, the two fields marked by the red box were used to configure the pumps for the simulation. The first is the “Power” field that refers to the rated power of the pump, while the second is the “Flow Rate” field that refers to the delivery flow rate of the pump. When building the simulation, these fields have to be populated for each pump individually.

3.3.3 Dams

The dams are used as buffers during high water demand or low water supply periods. The dam levels change according to the inflow and outflow rates, as well as the total dam volume. Usually, mines only use one hot water dam per pumping station, but this is unique to the design of each mine. The number of dams used by each mine is determined by the available space on mining levels and required storage capacity. The pump controller is only able to monitor one dam level at a time as mentioned in Section 3.3.1. The REMS configuration window for the hot water dams are shown in Figure 33.



Description: 115 Hot Dam Level

Level Tag: 0 / Tag / InternalTag 115 Hot Dam Level 1
Temp Tag: 0.00 / Tag /
Volume: 5498 m^3
Max Dam Level: 100 / Fix
Min Dam Level: 0 / Fix

☐ Filter Dam Fluctuations
Window 0.0 % 2 Mins
☐ Display Max and Min Levels
☐ Display Settler

Simulated flow: 146 / 24P / CH=10 l/s
45 / Fix °C
● In-flow ○ Out-flow

Initial Simulation :
Level : 48 %
Temp : 8 °C

☐ Override Sim. Value with Level Tag

In Flows

Components	Cmpt Type	Valve Bound	Valve Status

Out-Flows

Components	Cmpt Type	Valve Bound	Valve Status
115-4	Pump		
115-3	Pump		
115-2	Pump		
115-1	Pump		

Figure 33: REMS hot water dam configuration

In Figure 33, the red boxes also mark the input fields that were populated during the development of the simulation model. The “Volume” field refers to the total volume of the dam, while the “Simulated flow” fields refer to the flow rate of water into the hot water dam and the water temperature respectively. The “Inflow” and “Outflow” fields refer to the pumps that pumps water into the hot water dam and out of the hot water dam respectively.

Usually, multiple dam installations at a pumping station use a balancing system to keep the levels of all the dams close to each other. This mechanism fails from time to time and causes the difference between dam levels to increase.

During control of an actual system or simulation, the correct hot water dam needs to be monitored. For control of an actual system, some inputs are programmed to monitor a dam before it gets too empty and instructs the pump controller to stop the pumps. This is also true for a dam that gets too full, but pumps will be started. For the simulation purposes, it is much simpler to create a dam with the combined volume of the actual hot water dams at that pumping station. This way, one dam level can be monitored while considering the correct storage capacity.

3.4 Simulation overview

3.4.1 Simulation inputs

The inputs that need to be considered for this simulation are:

- Water inflow into the hot water dam at the bottom of the dewatering system;
- Maximum number of pumps allowed to run simultaneously;
- Pump delivery flow rates;
- Pump running capacities;
- Number of available pumps;
- Available hot water dam capacity; and
- Water flow rate from the 71L hot water dam.

Either these inputs have to be calculated, or assumptions have to be made based on the available data. Some of the limitations of the system will be based on the system configuration for the period corresponding to the real-time data used to obtain inputs. The data that was logged during the period of March 2014 to February 2015 was used to calculate the majority of the system inputs.

The flow rate of fissure water into the bottom hot water dams was calculated to provide an average flow rate over a 24-hour period. This was calculated on a monthly basis; the month with the highest average flow rates into the dams was used for each day. This assumption was made in order to ensure that a worst-case scenario would be simulated.

3.4.2 Calculations

The flow into the bottom hot water dams was calculated using the change in the water level every two minutes to get a resultant net flow for the dams (Q_{nett}). This net flow was then added to the product of a constant flow rate used for the pumps and the number of pumps running on that level. Equation 10 was used to calculate the inflow into the bottom hot water dams for two data points “n” and “n-1”.

Equation 10: Calculating the nett inflow into bottom hot water dams

$$\boldsymbol{Q_{nett} = \frac{(L_n - L_{n-1})}{100} \times \frac{V_T \times 1000}{\Delta T_n}}$$

With:

Q_{nett} = The nett flow into bottom hot water dams [ℓ/s]

L_n = Hot water dam level at the first data point (n) [%]

L_{n-1} = Hot water dam level at the second data point (n-1) [%]

V_T = Hot water dam volume [m^3]

ΔT_n = Amount of time between the data points [sec]

The flow rates from the bottom hot water dams were obtained from logged data. This creates the opportunity to calculate the rate at which water flows into the settlers and then into the bottom hot water dams. The inflow rate can then be calculated by adding the net flow rate into the hot water dams to the outflow rate for the hot water dams. The inflows and outflows for the 115L hot water dams are shown in Figure 34.

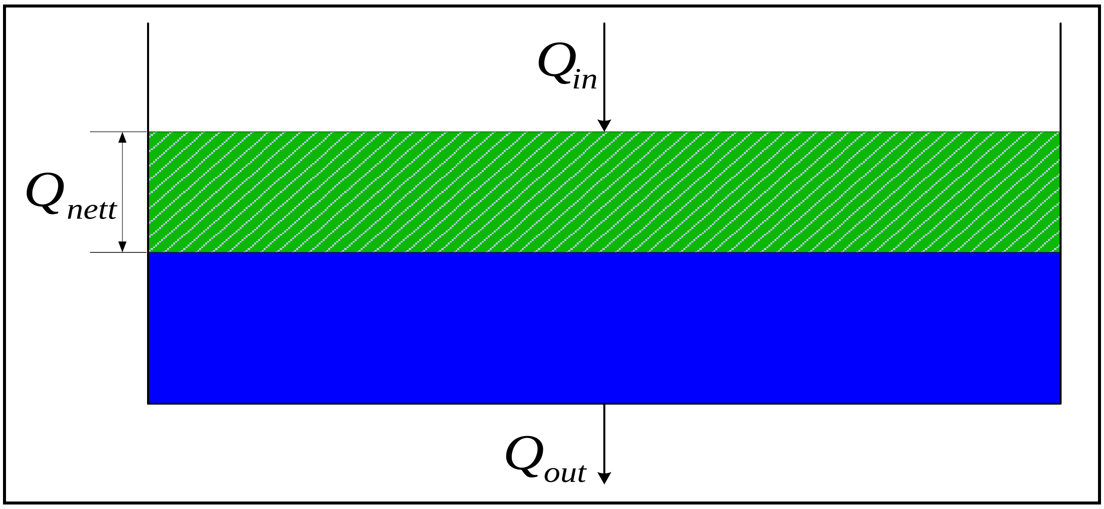


Figure 34: Bottom hot water dam inflows and outflows

The calculation of the inflow into the bottom hot water dam is done using Equation 11.

Equation 11: Inflow into bottom hot water dams from settlers

$$\boldsymbol{Q_{in} = Q_{nett} + Q_{out}}$$

With:

Q_{in}	=	Inflow from settler dams	[ℓ/s]
Q_{nett}	=	Nett flow for the hot water dams	[ℓ/s]
Q_{out}	=	Flow rate out of the hot water dams	[ℓ/s]

These equations can be verified by simply subtracting the daily outflow (measured value) from the daily inflow (calculated value) for these hot water dams. This yields average daily inflow of 713 804 m^3 and average daily outflow of 718 669 m^3, which is a deviation of less than 1% between the two total values. The graphs for average flow rate into and out of the bottom hot water dam for the simulated period are shown in Figure 35.

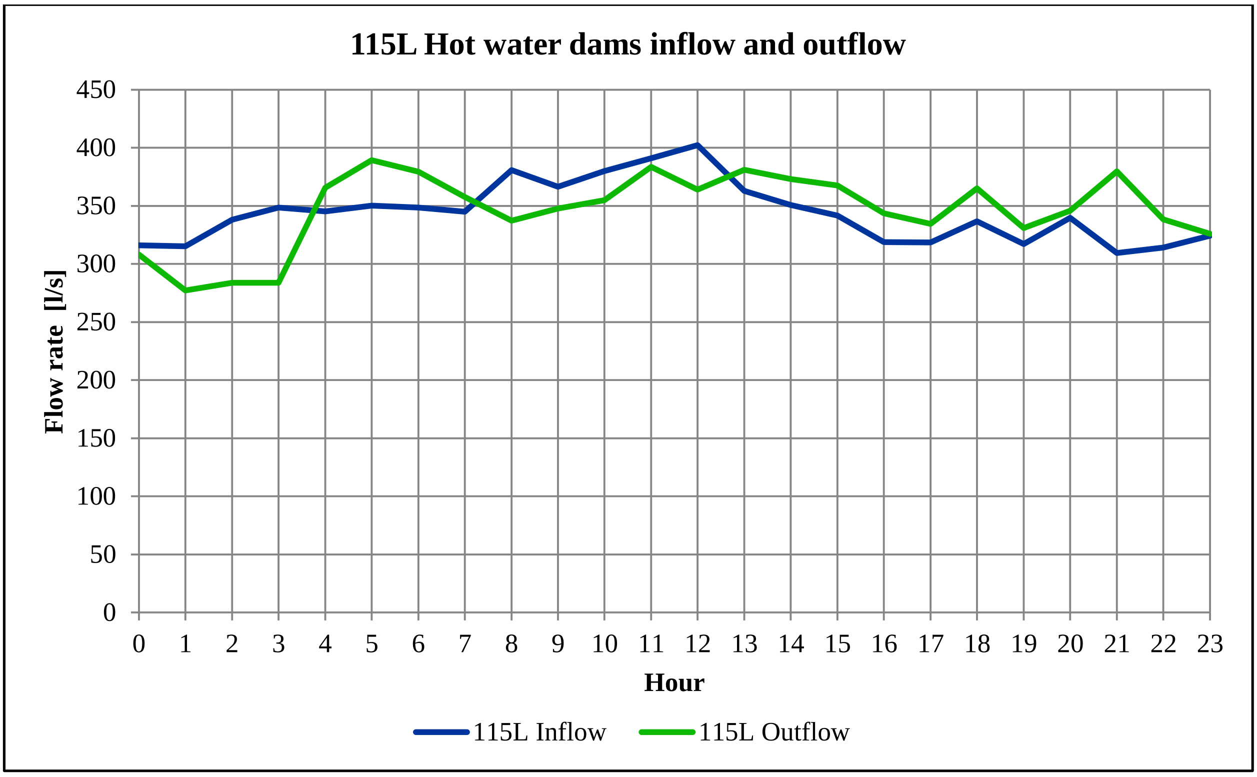


Figure 35: Flow calculations verification

As mentioned in Section 3.4.1, the data with the highest inflow rates was used to calculate the required simulation inputs. The average monthly inflow into the mine from March 2014 to February 2015 is shown in Figure 36.

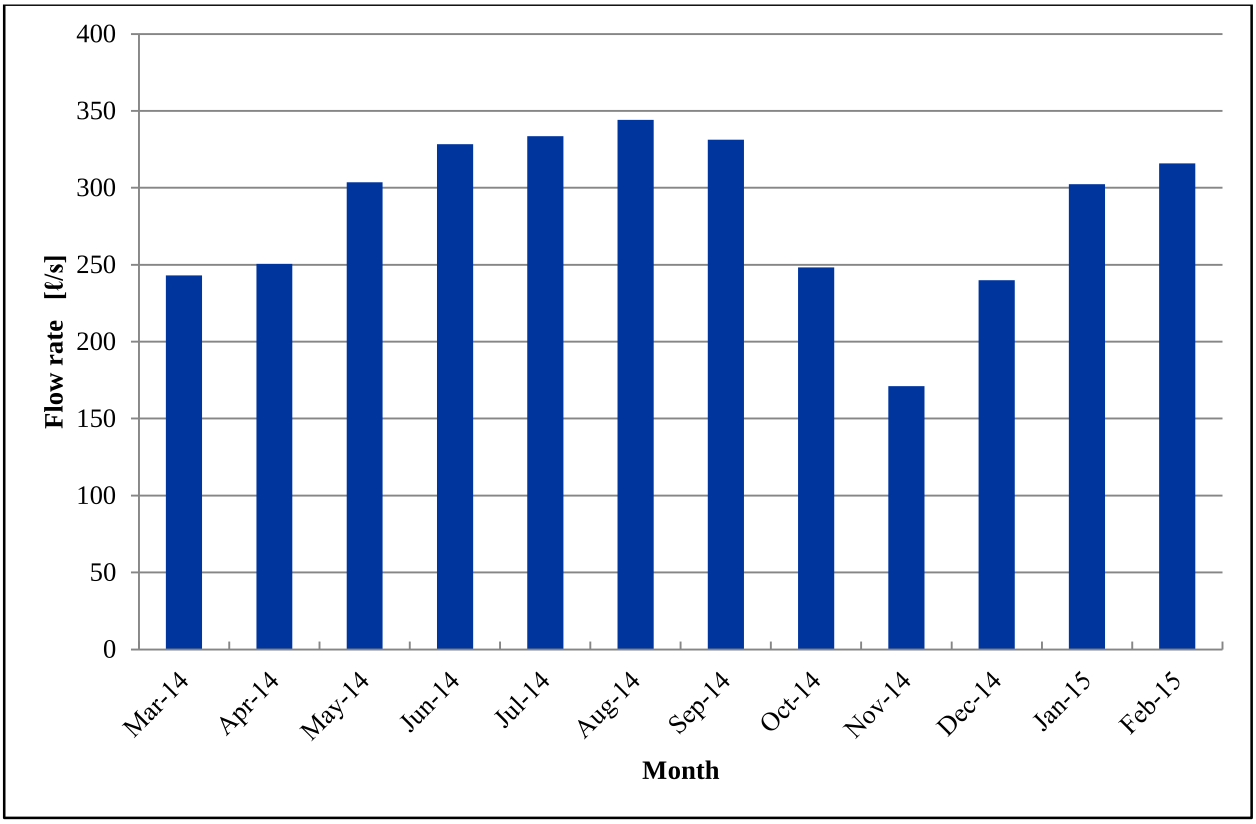


Figure 36: Monthly average flow into mine

This figure shows that the flow into the bottom hot water dams kept changing over time. It is important to remember that the hot water dams' inflows were calculated by using the change in the water level every two minutes to get a resultant net flow for the dams. This nett flow was then added to the product of a constant flow rate assumed for the pumps and the number of pumps running on that level. It is known that the efficiency of the pumps decreased drastically towards the end of 2013 and that explains why the flow rate seemed to keep on increasing. Another factor that influences the inflow into the hot water dams is the amount of water being sent underground from surface for mining purposes.

3.4.3 Simulation verification

A simulation model was developed in REMS to simulate the effects of system constraints on the electricity costs of the dewatering system of Mine A. The simulation model was created according to the descriptions of components and inputs discussed in previous sections. To verify that the simulation model and control were accurate, the simulated power consumption had to be compared with the actual power consumption of the dewatering system. This could only be done correctly by simulating the same circumstances that the actual dewatering system was experiencing. This meant that the inputs for the simulation had to be the same as that of the actual dewatering system. The load shifting achieved by the developed simulation model was compared with the actual load shifting that was achieved for a day on the mine dewatering system. The comparison is shown in Figure 37.

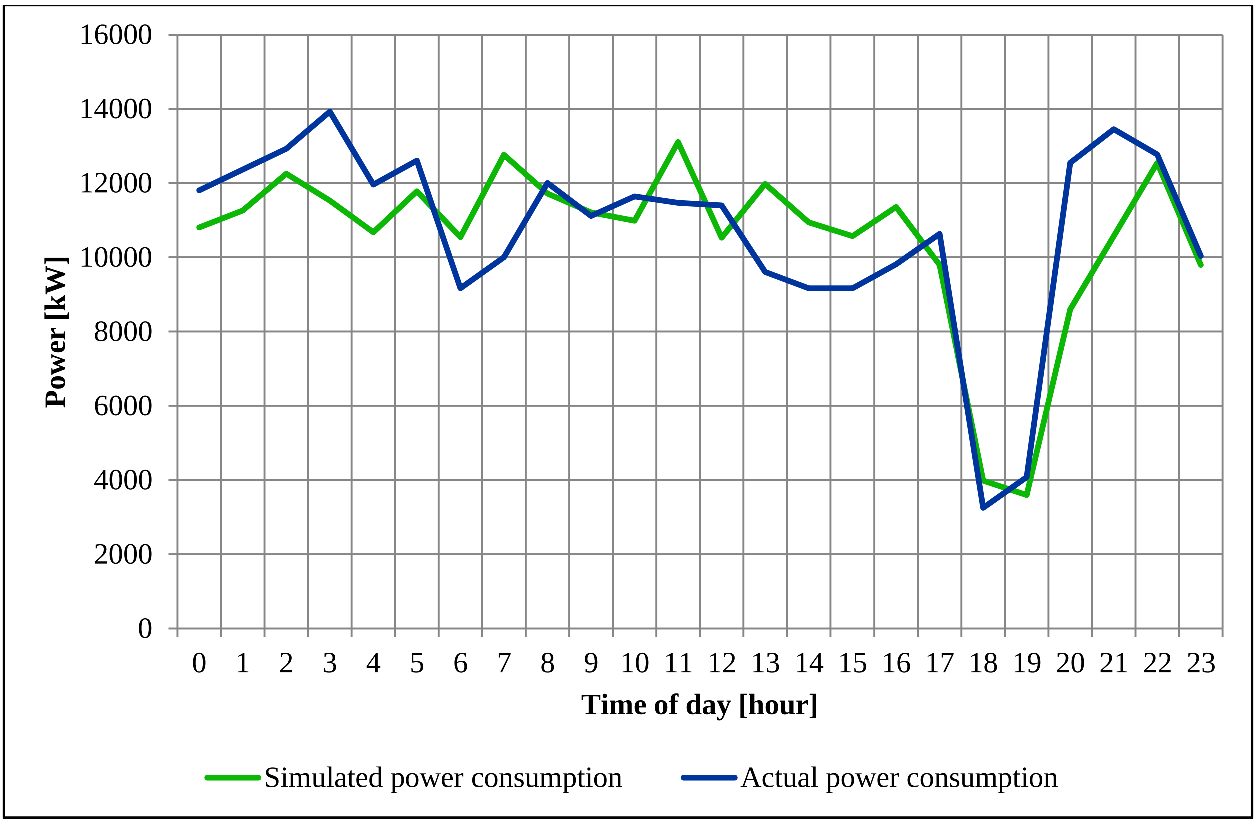


Figure 37: Simulation model verification

Table 2 compares the simulated load shifting with the actual load shifting. This simulation model is the same for simulating the scenario that will be discussed in Section 4.2.

Table 2: Simulated load shifting compared with actual load shifting

	Evening load shifted [MW]	**Total daily energy [kWh]**
Actual load shifting	6.02	256 912
Simulated load shifting	6.15	252 915
Deviation	2%	2%

Since the average daily impact and power consumption of the actual and simulated load shedding are so closely matched, the developed model is accurate enough to quantify the effects that system constraints will have on electricity costs of the mine dewatering system.

3.5 Conclusion

In this chapter, the inputs needed for the simulation were given. There was also a brief description of each of the mining levels involved in the dewatering system. The function and control of the pump controller were described for specific inputs. The format of the simulation outputs were also described and a layout of the simulation model were given.

CHAPTER 4. CASE STUDY

4.1 Introduction

For this chapter the dewatering systems of one mine were considered. The system constraints for the mine will be evaluated and discussed individually. The following optimisation scenarios (cases) will be evaluated:

- Scenario 1: Enable evening load shifting;
- Scenario 2: Increase dam capacity;
- Scenario 3: Increase pump capacity;
- Scenario 4: Enable morning load shifting; and
- Scenario 5: Optimise water supply.

For this simulation, the baseline was calculated by using data for a total of three months. The baseline was scaled so that the total daily power consumption was equal to that of Scenario 1. This baseline was kept unchanged for the rest of the Scenarios to calculate a cumulative impact.

4.2 Scenario 1: Enable evening load shifting

4.2.1 Current constraints

The load-shifting potential is the first constraint that will be addressed to increase the performance of the mine dewatering system. Currently, the mine dewatering system is under pressure due to a shortage of water storage capacity and limited pumping capacity. The pumps are also a problem as they are not always available or keep tripping; the constraints change on a daily basis, making it dangerous to implement a load-shifting project that is controlled by computer software. This is also making it difficult and dangerous for personnel to do load shifting on the mine. The result of this is that load shifting is not being done on Mine A at this point in time.

4.2.2 New constraints

For purposes of the first simulation, it will be assumed that it is possible to implement automated pump control. The inflow into the bottom mining level and flow from the fridge plants on 71L are similar to that of August 2014. Load shifting will only occur in the evening during weekdays.

4.2.3 Simulated results

The resulting power consumption will be compared to the latest scaled baseline and a cost saving can then be calculated. An average daily impact of 5.5 MW was achieved, which amounts to an annual saving of R2.35 million. The resulting power consumption of the system is shown in Figure 38.

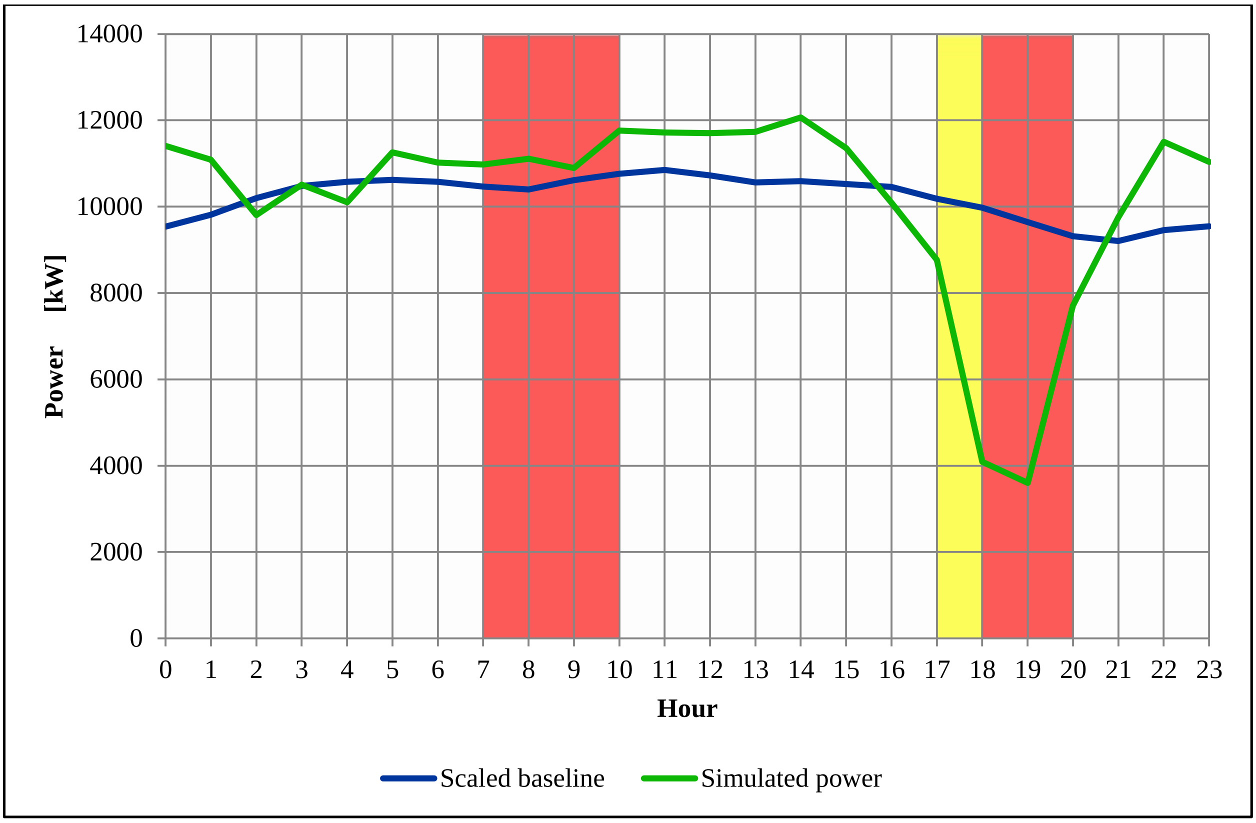


Figure 38: Evening load-shifting results

4.3 Scenario 2: Increase dam capacity

4.3.1 Current constraints

The usable dam capacities are reduced due to sedimentation build-up at the bottom of the hot water dams. This limits the available capacity for load shifting, and the minimum dam levels thus have to increase significantly. This increase in dam capacity will be quantified by comparing the power consumption after the change with the power consumption before this change.

Figure 39 represents the actual minimum hot water dam levels. Unavailable hot water dams are shown with a minimum dam level of 0%.

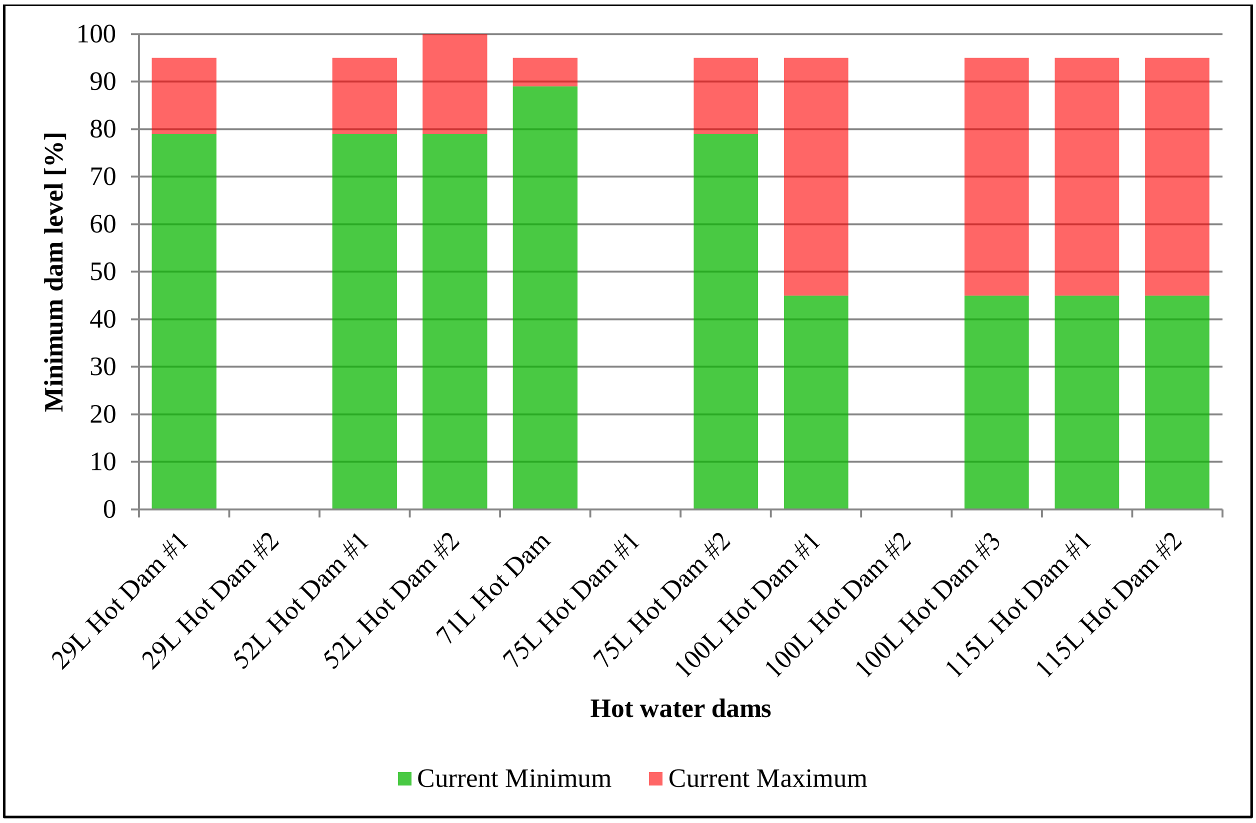


Figure 39: Hot water dam minimum levels

4.3.2 Improvement strategy

The hot water dams have to be cleaned on each level from the bottom level to the surface. This will be done individually and not simultaneously in order to keep mine production running. This means that one dam will be cleaned while the other dams are still being used.

This will decrease the minimum level that the water can reach without endangering the condition of the dewatering pumps. There is also a possibility that old decommissioned dams might be cleaned out and used as hot water dams. This constraint should provide one of the biggest improvements towards load shifting potential and the sustainability thereof.

4.3.3 New constraints

These new constraints, which are based on the improvements that were made, are compared to the old constraints. The information is shown in Figure 40.

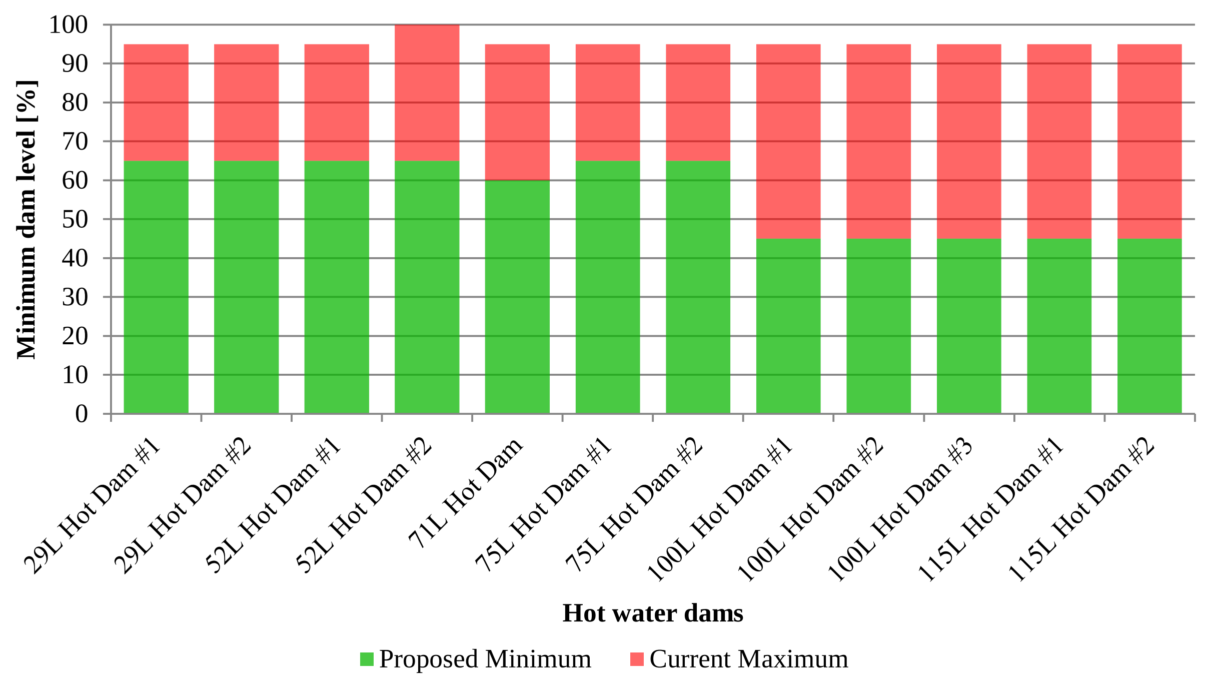


Figure 40: New hot water dam minimum levels

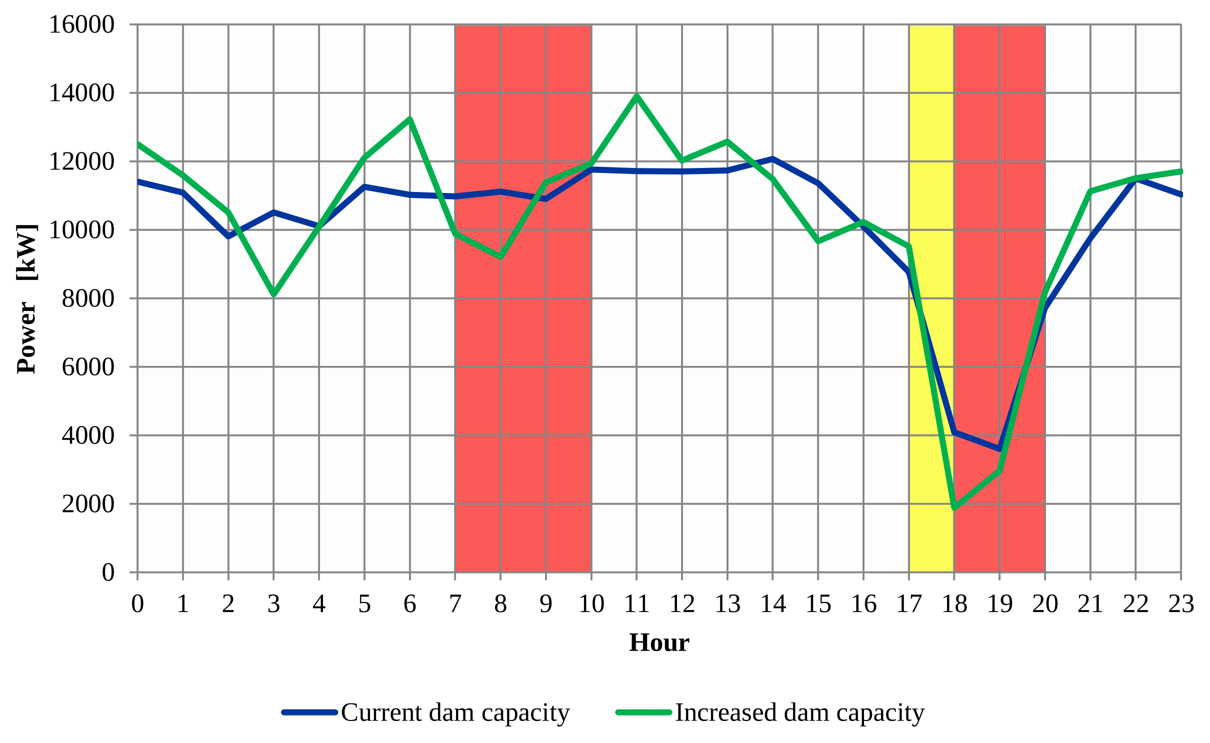


Figure 41: Increased dam capacity

4.3.4 Simulated results

The increased storage capacity, reduced pump cycling and the need for pumping during evening peak periods. The larger storage capacity increased the load-shifting potential and the power consumption of the dewatering system during standard periods, but decreased the need to run pumps during peak periods.

This resulted in an additional daily evening peak load shift of 2.3 MW, which equates to an annual saving of R515 000 as shown in Figure 41. This cost saving is less than the cost savings achieved in the other scenarios. This is because increased dam capacity only has an effect on load shifting performance. It does not result in energy efficiency savings as some of the other constraints evaluated in the other scenarios.

4.4 Scenario 3: Increase pump capacity

4.4.1 Current constraints

The term “increased pump capacity” refers to the rate at which water can be pumped by a pump station. This entails both increased pump efficiencies and increased pump availability. A pump station with a low pump capacity can cause a bottleneck in the mine system. One such example is the pump station on 100L as discussed in Section 3.2.2. The pump efficiencies have decreased significantly during the last months of 2013[1]. This decrease in efficiency forced an increase in the running time of the pumps. This also increased the need for maintenance on the pumps and caused them to wear out even quicker.

Another important factor that should be considered is the number of pumps that is available. The number of available pumps can decrease even more as technical difficulties arise. This limits the maximum rate at which water can be extracted from the mine. The current pump capacities that were used in the simulation until this point are summarised in Table 3.

Table 3: Summarised current pump capacities

Mining level	Number of installed pumps	Number of available pumps
29L	5	3
52L	5	4
75L	5	4
100L	3	2 (One of which can supply 71L hot water dam)
115L	3	2

---

[1] Determined by analysing confidential data obtained from a third party contractor.

The flow rates of the pumps were set to be unique for each pump. These flow rates were obtained from monthly reports that were compiled to show the running capacities, delivery flow rates and efficiencies of each pump. The flow rates of the pumps that were used in the simulation are shown in Table 4 in terms of litres per second (ℓ/s). The pumps that have an indicated flow rate of "NA" and are greyed out, were not used in the simulation as they were unavailable.

Table 4: Simulated pump flow rates

Mining level	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5	Pump 6
29L	124	NA	NA	129	135	NA
52L	103	113	114	112	NA	NA
75L	NA	NA	71	143	77	88
100L	NA	NA	194	219	NA	NA
115L	NA	248	253	NA	NA	NA

4.4.2 Improvement strategy

The efficiencies of the pumps can greatly increase the amount of water that can be pumped while still using the same amount of electricity. The pumps should be inspected regularly to assess their condition. Pumps that cannot be repaired should be replaced as soon as possible. The rest of the pumps should be overhauled one at a time where necessary. This way, the cost will be minimised by restoring the pumps' performance instead of replacing them. It is important to keep the pumps maintained otherwise the money spent on load-shifting initiatives will have been wasted.

There is a number of pumps that is either not working, or has been removed to be replaced. Some of these removed pumps were never reinstalled on the pumping stations. This led to fewer pumps being available, which places more strain on the remaining pumps. It is essential that these pumps be restored to their original condition and reinstalled. The pumps should not be mixed up, as each set of pumps has different specifications and has worked under different circumstances in the past.

Monthly pump reports provide the mine personnel with recommendations about which pumps should be started and stopped first according to their efficiencies. It is highly recommended that this information be integrated into the control philosophy once the problems regarding the number of available pumps and pump efficiencies have been solved.

4.4.3 New constraints

The improvement strategy discussed in Section 4.4.2 should increase the number of permanently available pumps from 15 to at least 18 pumps. To simulate an increased efficiency, the rated flows of the pumps were used in the simulation. It was also assumed that the flow rates for the pumps on each mining level were the same. The pumps should be distributed according to Table 5:

Table 5: Summarised new pump capacities (flow rates from [27])

Mining level	**Number of installed pumps**	**Number of available pumps**	**Rated flow rate [ℓ/s] (per pump)**
29L	5	4	150
52L	5	4	150
75L	5	4	150
100L	3	3 (Two of which can supply 71L hot water dam)	240
115L	3	3	265

4.4.4 Simulated results

The effect of pump efficiency along with the proper pump availability have proven to be the most significant constraint on the dewatering system when evaluating the daily power consumption. This improvement resulted in a 0.46 MW daily saving or annual cost reduction of R8.32 million. The improvements of multiple pump efficiencies increased the overall efficiency of the mine dewatering system. This means that more water can be pumped with the same amount of energy as before. The increased number of pumps also ensured that more efficient pumps were available when needed. By maximising the pumping done during peak periods, the cost of pumping can be reduced significantly as illustrated in Figure 6. The resulting effect on the load shift performance is relatively small, but the overall daily electricity consumption was reduced significantly. The impact of increased pump capacity is shown in Figure 42:

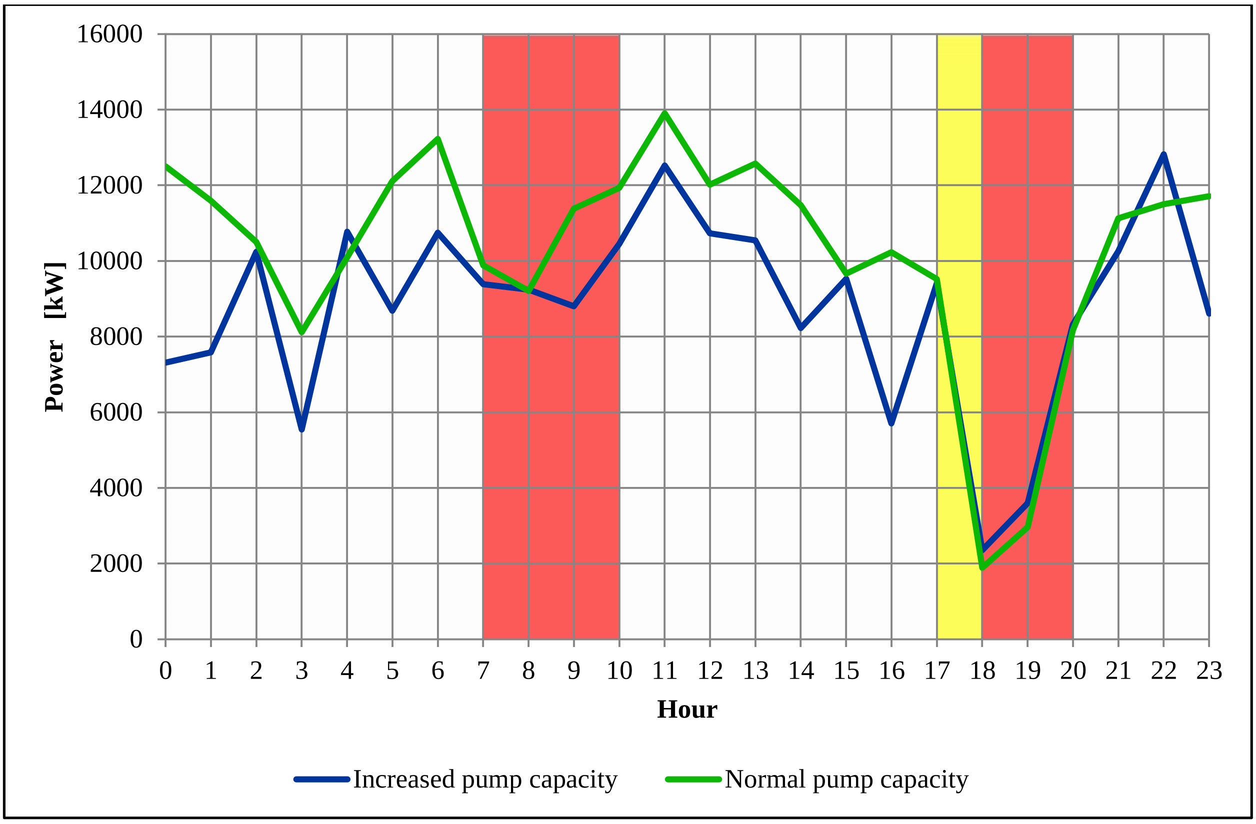


Figure 42: Increased available pump capacity

4.5 Scenario 4: Enable morning peak load shifting

4.5.1 Current constraints

The constant instability of the dewatering system along with limited storage capacity and pumping capacity have eliminated the load-shifting ability on the dewatering system in the past.

4.5.2 Improvement strategy

The previously simulated improvements along with the implemented evening load shift should greatly improve load-shifting opportunities and should increase the morning load-shifting potential. In an effort to further reduce electricity cost, morning load shifting can thus be done along with evening load shifting without any foreseeable problems. The implementation of full daily load shifting will be simulated to determine the magnitude of possible savings.

4.5.3 Simulated results

The results of the simulated load shifting are shown and compared with the previous system change in Figure 43. A morning load shift of 4.98 MW and an annual saving of R2.75 million were achieved.

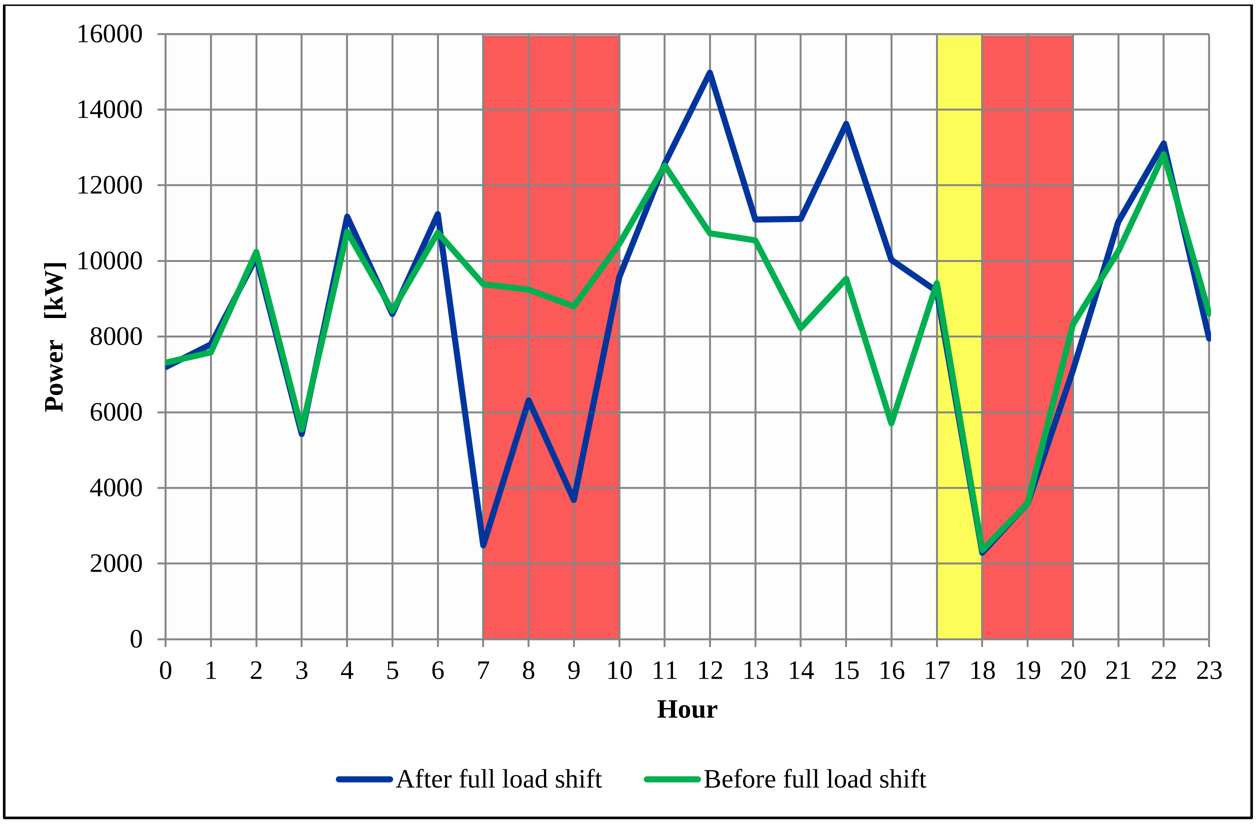


Figure 43: Morning and evening load shifting

4.6 Scenario 5: Optimise water supply

4.6.1 Current constraints

The amount of water that flows into the mine has a big influence on its dewatering system. The inflow can overwhelm the pumps and make it very difficult to maintain a balance between the inflow and outflow on individual levels.

There is currently high inflow rate of water into the mine from a closed mining shaft nearby. Fissure water is also a problem. The greatest amount of unmanaged water flowing into the mine is from the nearby mining shaft. No flow meters are installed that measure the flow rate into the mine. Another source of water flowing into the settler dams, is the used process water sent underground for mining processes.

4.6.2 Improvement strategy

The first and most important step towards addressing this constraint is to find all water leaks and repair them. The flow rate of this water should be determined and the pump capacity of the dewatering system should be adapted accordingly if the flow rate cannot be reduced.

The next strategy would be to minimise the amount of water used by mining processes and the BAC. Control valves should be installed on individual mining levels to control their water-supply flow rate. This will help to reduce water leaks and flows to mining levels that are no longer being actively mined. The control valves can help reduce the amount of water lost through leaks by closing them when water is not needed on these mining levels. This would reduce the water volume that needs to be handled by the mine dewatering system.

4.6.3 New constraints

The same inflow into the 115L hot water dams will be used but it will be reduced by 10%. This is deemed to be a realistic figure, because 10% is the typical reduction in water usage that can be expected as a result of the implementation of WSO projects on gold mines. can reduce the daily water consumption by at least 7% on a typical gold mine [24], [27]. It would not be relevant to look at water reductions significantly larger than the chosen 10% as WSO savings in that order is not achievable on typical WSO projects.

4.6.4 Simulated results

Figure 44 illustrates the effect that the reduction in water being sent underground can have on the power consumption of the dewatering system. This change lead to an average daily impact of 1.2 MW and thus an annual saving of R7.6 million.

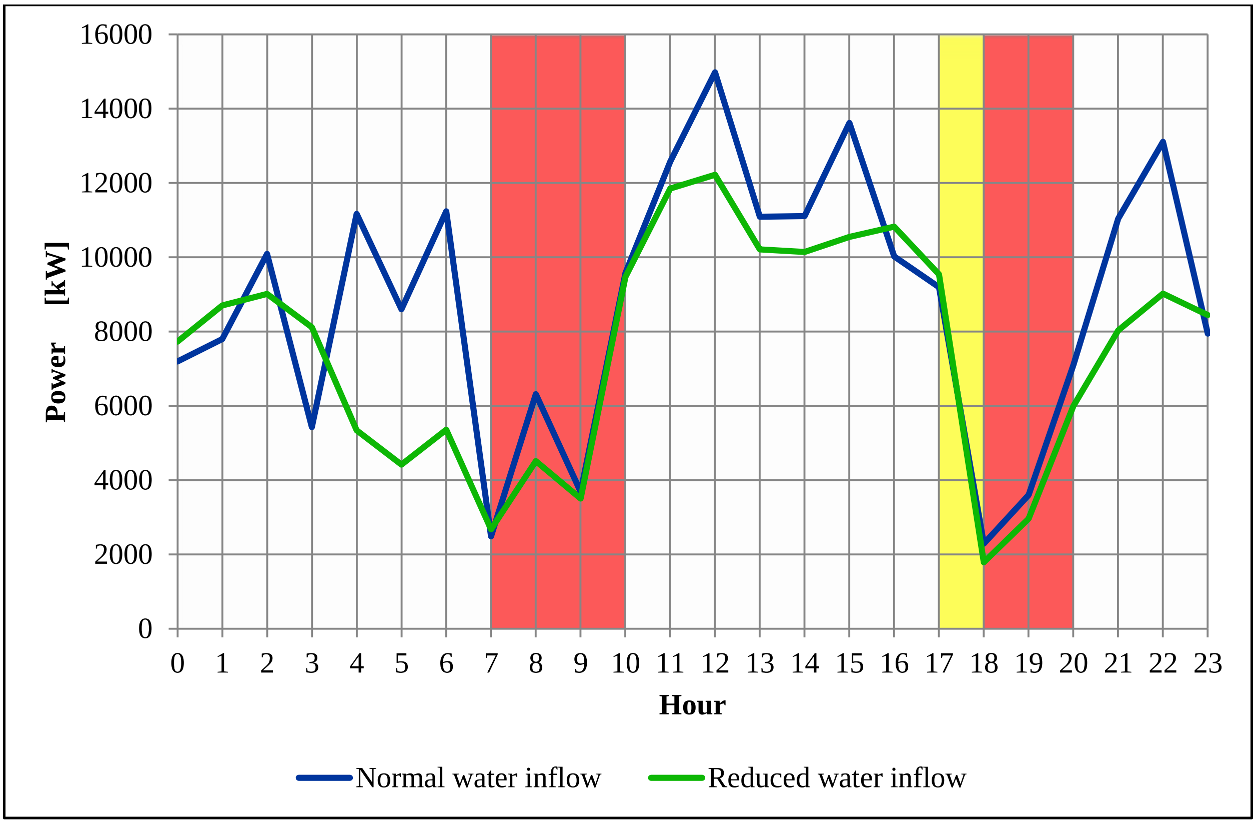


Figure 44: Reduced underground water supply

4.7 Total simulated savings potential

The savings that can be achieved by implementing the above-mentioned strategies have been calculated for this specific mine using 2015/2016 Megaflex tariffs and the TOU schedule of 2014.The 2014 schedule was used instead of the 2015 schedule, because a new tariff schedule was introduced in 2015, which is not applicable to the period of simulation. The process used to calculate these savings is described in Appendix A. The predicted savings are shown in Table 6:

Table 6: Summarised simulation results

System state	Individual annual saving	Cumulative annual savings
Normal operation	R0	R0
Enable evening load shifting	R2 350 672	R2 350 672
Increase dam capacity	R514 570	R2 865 242
Increase pump capacity	R8 317 821	R11 183 063
Enable morning load shifting	R2 752 131	R13 935 194
Optimise water supply	R7 637 545	R21 572 739

4.8 Validation of load-shifting potential

4.8.1 Mine A

The first project on Mine A’s dewatering system was a load-shifting project. The project was completed and implemented in June 2004. During the performance assessment of the project, it achieved an average daily impact of 4.80 MW during the evening peak period. The configuration of the dewatering system changed drastically and the condition of the entire system has deteriorated since implementation.

The capacity of the hot water dams decreased, which reduced storage capacity as well as load-shifting possibilities. The volume of water that flowed into the settlers on 115 level also increased causing the performance of the settlers to decrease. The water quality caused a decrease in the performance of pumps, water distribution network and instrumentation. The reliability and accuracy of the instrumentation decreased and reduced the ability of mine personnel to monitor the system accurately.

Manual load shifting was done on the mine for a three-month period from June to August 2013. Due to the risk of doing load shifting on a poorly maintained dewatering system, the safest way to do load shifting was to do it manually. The small capacity for load shifting under these circumstances also made it possible to load shift only during evening peak periods.

The results of the manual load-shifting attempt varied from day to day because each day had its own unique constraints and challenges that caused the control philosophy to change to keep the risk of flooding to a minimum.

Figure 45 shows the maximum saving that was achieved during the manual load-shifting period of June to August 2013. In the graph, it can be seen that load shifting was done in the evening and partially in the morning because of sufficient storage and pumping capacity. During the manual load-shifting period, the power utility requested that load shifting be done between 17:00 and 20:00 for the evening peak periods. This is why the power usage started to decrease at 17:00. The graph shows that the average daily impact of the manual load shifting was 10.26 MW. This impact equates to an annual saving of R5 542 736.

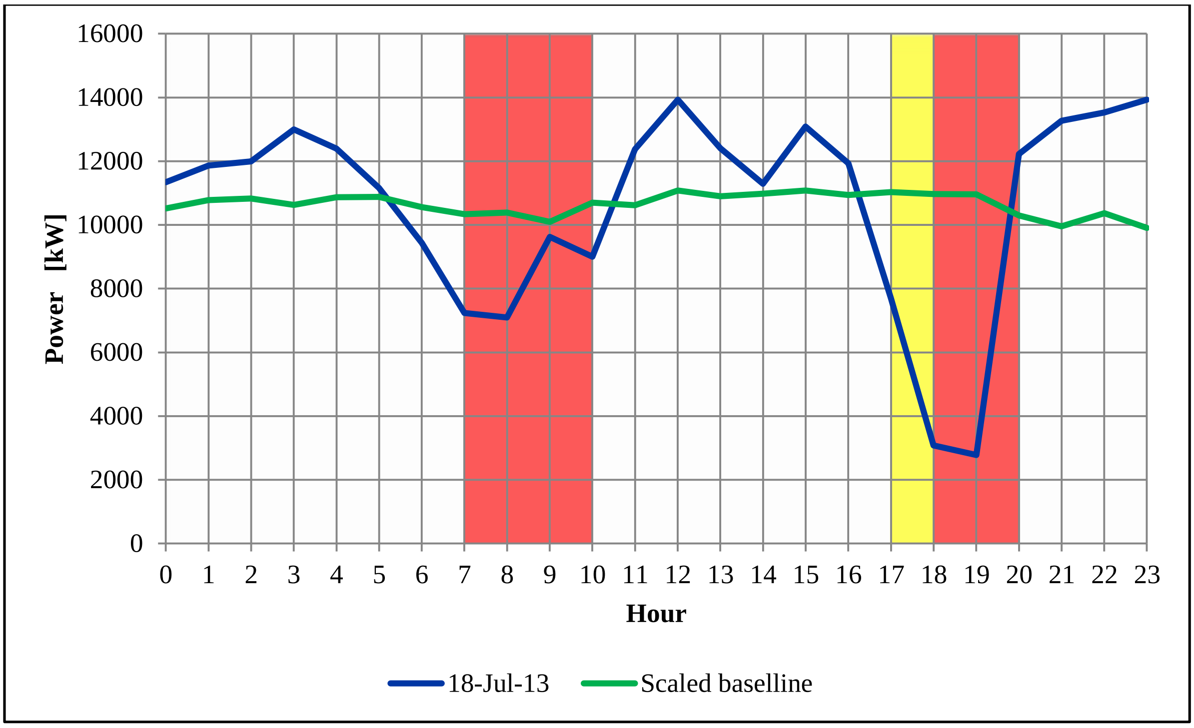


Figure 45: Maximum savings achieved during manual load shifting

Figure 46 shows the average power usage for the entire manual load-shifting period of June–August 2013.

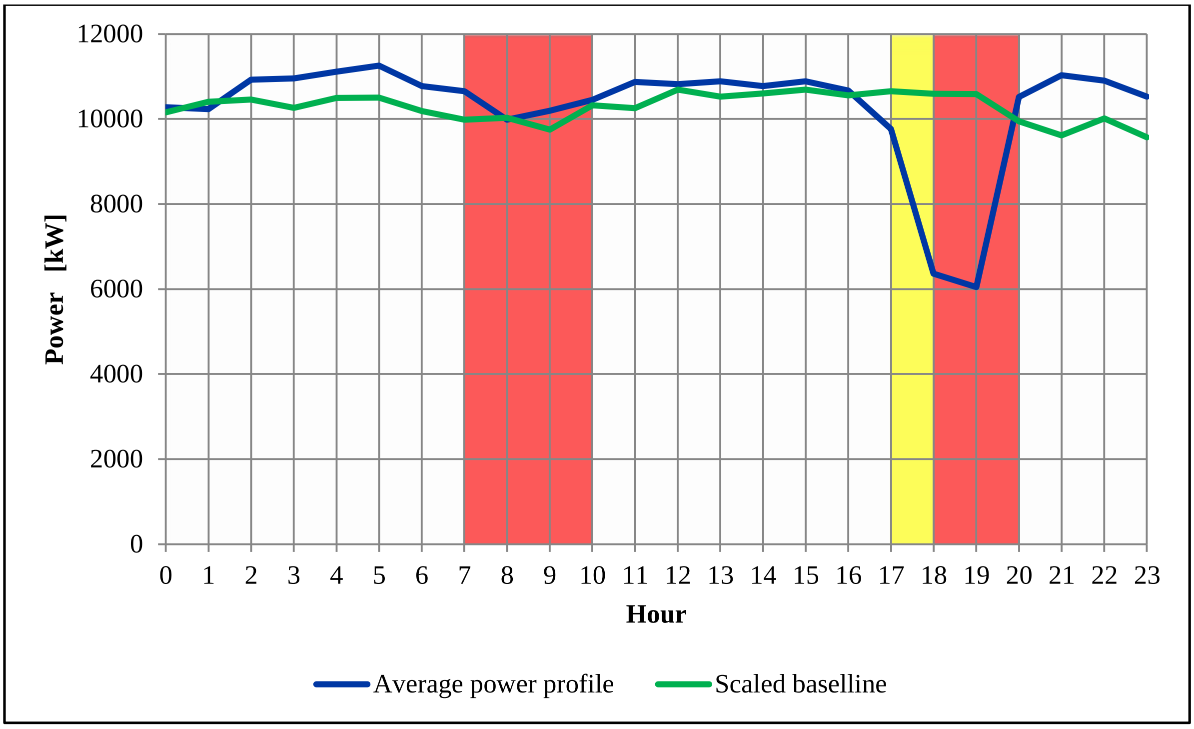


Figure 46: Average impact of manual load shifting

The average daily impact for the manual load-shifting period was 4.5 MW. This equates to an annual saving of R3.93 million. It is important to keep in mind that this was achieved under very difficult circumstances. The reason for the difference between the simulated load shifting in Section 4.2 and the actual load shifting is the changing operational constraints experienced on the mine.

4.8.2 Mine B

The results of an example mine, also referred to as Mine B, are presented to demonstrate a properly working dewatering system. This dewatering system has an installed capacity of 14 MW [27]. The following proactive work is being done by mining personnel:

- The infrastructure of this system is being maintained regularly;
- The control philosophy for the dewatering system is updated continuously;
- The water supply to underground mining levels is being managed actively;
- The pumps are maintained properly; and
- The daily load shifting and electricity consumption of the mine dewatering system are being monitored closely.

The impact of managing these constraints can be seen in the daily power consumption of the mine dewatering system. The average daily power consumption of the mine dewatering system for a month is shown in Figure 47.

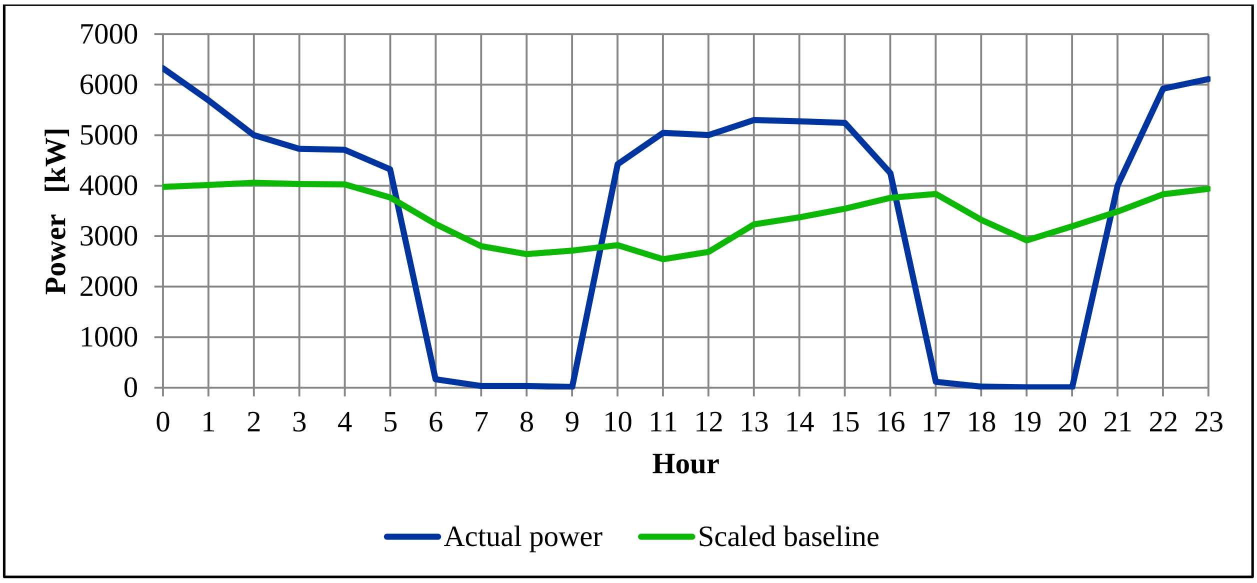


Figure 47: Mine B monthly DSM performance

These savings relate to an average monthly impact of 3.51 MW or R709 993. This project has been a consistently good example of a load-shifting project. This is shown in Figure 48, where "Contracted savings" represents the target of the project.

Figure 48: Mine B cumulative savings

4.9 Conclusion

In this chapter, five different scenarios were simulated to quantify the effects of constraints on the performance of the mine dewatering system. The impact of these changes were expressed in terms of annual savings. By adding the improvements from all of the scenarios, a cumulative saving was found to quantify the combined impact that these changes had on the electricity costs of the mine dewatering system.

This chapter also confirmed that load shifting is possible by using a simulation model and then proving it in reality. When comparing the simulated saving of evening load shifting with the actual saving achieved for similar conditions, the simulation model can be described as conservative. This is because the actual average saving achieved was R1.18 million more than the simulated results.

This chapter also contained an example of a mine where the constraints of the mine dewatering system were being managed properly to show the impact that reduced system constraints could have on the electricity costs in the long term.

CHAPTER 5. CONCLUSION

5.1 Summary

In the first chapter of this dissertation, it was shown that Eskom’s electricity supply constraints have a significant detrimental impact on the economic growth of South Africa. Eskom is dedicated to expanding its generation capacity to provide a sufficient reserve margin. There have been some delays in the execution of the generation capacity expansion programme, but the first new power plants are in their final stages of commissioning. Unfortunately, this alone is not enough and the increased electricity tariffs needed to finance the generation capacity expansion programme might continue to increase above inflation – making it even more difficult for large electricity consumers to stay profitable. DSM initiatives such as pump load shifting projects have become an important measure to offset the rising cost of electricity. It is therefore of extreme importance to correctly maintain equipment and manage pump system constraints in order to minimise operating cost and maximise DSM project performance.

Chapter 2 started with the identification of the main water consumers of a typical gold mine. The most significant components of the mine dewatering system were identified. The function and limitations of each component were discussed. It was seen that the good working condition of settler dams is the determining factor regarding the water quality entering the dewatering system. Reduced dam storage capacity was presented as a main limiting factor that can affect the load shifting potential of a mine dewatering system, sedimentation build-up was identified as the common cause of reduced dam capacity. Pumps used in dewatering systems were also discussed in detail. Their possible configurations were shown and the benefits or limitations of each configuration were discussed. It was also seen that poor water quality significantly reduce the efficiency and lifetime of a dewatering pump.

Chapter 3 commenced with a description of the simulated system. The simulation setup was discussed and the functions of the components used in the simulation were explained. An explanation of the implemented control philosophy was provided. The assumptions and inputs used in the simulation were also presented. Chapter 3 concluded with a the verification of the simulation. The verification was achieved by means of a comparison between the results of the simulation and the actual results achieved with a manual load shift intervention.

Chapter 4 presented the simulated results of progressively improving different system constraints such as dam and pump capacities and improving the control philosophy. The changes were quantified in terms of load shift performance, as well as electricity cost savings. The results of a pump load shifting project on a second mine were also provided as an example of the performance that can be expected when a dewatering system is correctly maintained. Results showed that annual savings of more than R21-million can be achieved if the different components of the dewatering system and load shifting project at Mine A are correctly maintained.

5.2 Recommendations for future work

In the past, the quality of water discarded by mines in South Africa were not always sufficiently regulated. This has changed, and the quality of water being discarded by mines is being strictly monitored. This may cause a gradual increase in the amount of water in the mine dewatering system, which may negatively affect load-shifting performance. It is recommended that further research should be done on improving water treatment efficiency and efficient reuse of mining water.

The incorrect prioritisation of dewatering pumps (described in Section 3.3.2,), due to inaccurate efficiency data is also wasting electricity. It is recommended that a cost-effective solution be found to provide an accurate real-time efficiency reading of each pump. This solution needs to be easy to maintain.

5.3 Conclusion

In this study it was found that improving the control philosophy and system constraints of a load shifting project on mine dewatering pumps can result in significant electricity cost savings. The performance of individual components or constraints, can severely limit the performance of other components, and the entire system.

The most underrated components in the dewatering system are the settler dams. This is because the efficiency of settler dams has a direct effect on the efficiency and lifespan of dewatering pumps. The performance of settler dams can result in either a properly working dewatering system or the exact opposite thereof. The first and most important measure to reduce the electricity costs of the dewatering pumps is DSM initiatives. It was shown that by only doing load shifting during evening peak periods, electricity costs could be decreased drastically. Using the evening load shifting as a basis, more improvements can be made on the constraints of a mine dewatering system to reduce electricity costs even further.

This study also proved that proper maintenance on components can prolong their lifetime and minimise operating costs. It is therefore very important to never underestimate the significance of a proper maintenance programme.

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ANNEXURE A. COST SAVING CALCULATIONS

Cost savings calculations

The calculation of the electricity costs was done for a gold mine with a specific location and voltage requirements. A mine within a direct distance of 300 km from Megawatt Park, Johannesburg was used with a voltage requirement of between 550 V and 66 kV. The voltage requirement is relevant as it is used to determine the network charges and tariff range. As mentioned earlier, the 2015/2016 Megaflex tariff structure was used to calculate electricity costs.

The transmission tariffs [R/kVA/m] are mainly determined by the location of the mine and the range of the supply voltage. Transmission tariffs are therefore not influenced by the implementation of a load shifting project on mine dewatering pumps. The NMD charges is a predetermined charge according to the maximum demand, measured in kVA, of the mine. The maximum demand of a mine is largely determined by the production rate of the mine. The implementation of a load shifting initiative on dewatering pumps is not considered to affect the maximum demand of a mine.

The first input is the average daily power profile or baseline for the system before load shifting was implemented. This is then compared to an optimised power profile, which represents the power profile after load shifting was implemented. The difference between these power profiles is used to calculate the load shifted during peak periods. An example of such a calculation is shown in Table 7.

Table 7: Optimised power profile

	Select one
Transmission Zone	≤ 300 km
Voltage	≥ 500 V & < 66 kV
Year	2015

Hour of day	Baseline	Optimised
1	9539.36	11408
2	9812.70	11090
3	10196.84	9803
4	10482.70	10510
5	10574.72	10105
6	10621.09	11256
7	10575.15	11024
8	10466.01	10976
9	10394.98	11113
10	10613.07	10896

Hour of day	Baseline	Optimised
11	10764.34	11762
12	10850.13	11717
13	10723.91	11703
14	10564.81	11734
15	10591.75	12069
16	10523.31	11356
17	10454.21	10092
18	10185.68	8771
19	9973.18	4090
20	9643.47	3600
21	9314.20	7710
22	9202.35	9751
23	9460.02	11502
24	9543.92	11035
Total	245,072	245,072
Average hourly consumption [kW]		10,211

MW shifted in morning	-503.8267
MW shifted in evening	5963.0915

The difference in these two power profiles is then converted to costs, according to the TOU tariff structure selected. The costs are also different for specific times of the day and change along with the demand or tariff season. The conversion to cost is done for the low demand or summer tariff season. Table 8 shows the price distribution for the high demand season.

Table 8: TOU tariff distribution

	Summer Tariff	**Summer Tariff**	**Summer Tariff**
	Weekday	**Saturday**	**Sunday**
1	R47.21	R47.21	R47.21
2	R47.21	R47.21	R47.21
3	R47.21	R47.21	R47.21
4	R47.21	R47.21	R47.21
5	R47.21	R47.21	R47.21
6	R47.21	R47.21	R47.21
7	R70.14	R47.21	R47.21
8	R98.54	R30.48	R47.21
9	R98.54	R30.48	R47.21
10	R98.54	R30.48	R47.21

	Summer Tariff	Summer Tariff	Summer Tariff
	Weekday	Saturday	Sunday
11	R70.14	R30.48	R47.21
12	R70.14	R30.48	R47.21
13	R70.14	R47.21	R47.21
14	R70.14	R47.21	R47.21
15	R70.14	R47.21	R47.21
16	R70.14	R47.21	R47.21
17	R70.14	R47.21	R47.21
18	R70.14	R47.21	R47.21
19	R98.54	R30.48	R47.21
20	R98.54	R30.48	R47.21
21	R70.14	R47.21	R47.21
22	R70.14	R47.21	R47.21
23	R47.21	R47.21	R47.21
24	R47.21	R47.21	R47.21

The cost saving is the calculated by multiplying the difference between the normal power profile and optimised power profile. The resulting savings for the low demand season is shown in Table 9.

Table 9: Calculated cost savings

	Summer Tariff	Summer Tariff	Summer Tariff
	Weekday	Saturday	Sunday
1	-R882.35	-R882.35	-R882.35
2	-R602.90	-R602.90	-R602.90
3	R185.74	R185.74	R185.74
4	-R12.65	-R12.65	-R12.65
5	R221.90	R221.90	R221.90
6	-R299.68	-R299.68	-R299.68
7	-R314.62	-R211.77	-R211.77
8	-R502.61	-R155.47	-R240.80
9	-R707.78	-R218.93	-R339.10
10	-R279.02	-R86.30	-R133.68
11	-R699.80	-R304.11	-R471.02
12	-R607.78	-R264.12	-R409.08
13	-R686.68	-R462.19	-R462.19
14	-R819.77	-R551.77	-R551.77
15	-R1,036.02	-R697.33	-R697.33
16	-R584.35	-R393.32	-R393.32
17	R254.19	R171.09	R171.09
18	R992.33	R667.92	R667.92

19	R5,796.83	R1,793.05	R2,777.23
20	R5,955.23	R1,842.05	R2,853.12
21	R1,125.27	R757.40	R757.40
22	-R384.64	-R258.89	-R258.89
23	-R964.11	-R964.11	-R964.11
24	-R703.75	-R703.75	-R703.75
Total	**R4,442.97**	**-R1,430.49**	**R0.00**

The calculation of the hourly savings in Table 9 can be done according to Equation 12.

Equation 12: Calculating hourly cost savings

$$\boldsymbol{C_s = \frac{(P_b - P_o)}{1000} \times C_h}$$

With:

C_s – Cost saving for the hour involved [R]

P_b – Average power usage before load shifting for the hour involved [kW]

P_o – Average power usage after load shifting for the hour involved [kW]

C_h – TOU tariff price for the hour involved [R/MW]

The total daily savings is then calculated by adding the cost saving for each of the 24 hours of the specified day. This can be done using Equation 13.

Equation 13: Calculating total daily savings

$$\boldsymbol{C_{s,total} = \sum_{i=1}^{24} C_{s,i}}$$

With:

$C_{s,total}$ – Total daily cost saving [R]

$\sum_{i=1}^{24} C_{s,i}$ – Sum of 24 hourly cost savings [kW]

The average daily savings is calculated by adding five weekday savings, one Saturday saving and one Sunday saving and dividing the total by seven as shown by Equation 14.

Equation 14: Average daily cost saving

$$\boldsymbol{C_{average} = \frac{(C_{s,total,wd}\ x\ 5) + C_{s,total,Sat} + C_{s,total,Sun}}{7}}$$

With:

$C_{average}$ – Average daily cost saving [R]

$C_{s,total,wd}$ – Total daily weekday cost saving [R]

$C_{s,total,Sat}$ – Cost saving for a Saturday [R]

$C_{s,total,Sun}$ – Cost saving for a Sunday [R]

The low demand savings is then calculated by multiplying the average daily cost savings by the number of days in the high demand season and subtracting the total cost savings for Saturdays and Sundays. This calculation is represented in Equation 15.

Equation 15: Total low demand cost savings

$$\boldsymbol{C_{hd} = \left(C_{s,total,wd} \times D_{wd}\right) - \left(C_{s,total,Sat}\ x\ D_{Sat}\right) - \left(C_{s,total,Sun} \times D_{Sun}\right)}$$

With:

C_{hd} – Total high demand cost saving	[R]
$C_{s,total,wd}$ – Daily weekday cost saving	[R]
$C_{s,total,Sat}$ – Cost saving for a Saturday	[R]
$C_{s,total,Sun}$ – Cost saving for a Sunday	[R]
D_{wd} – Number of weekdays in the low demand season	[-]
D_{Sat} – Number of Saturdays in the low demand season	[-]
D_{Sun} – Number of Sundays in the low demand season	[-]

This procces is then repeated for the high demand or winter tariff season, but with some changes. The TOU tariff structure for high demand season, the peak periods for high demand season and the number of days in the high demand season are used. The totals for each of these seasons are then added up to give an annual cost saving.