

Optimum water distribution between pumping stations of multiple mine shafts

Nicolas Laurens Oosthuizen

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Supervisor: Dr R Pelzer

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ABSTRACT

Title: Optimum water distribution between pumping stations of multiple mine shafts

Author: Nicolas Laurens Oosthuizen

Supervisor: Dr R Pelzer

Degree: Master of Engineering (Electrical and Electronic)

In 2011 the mining industry purchased 14.5% of the electrical energy generated by Eskom. During 2011 in South Africa, dewatering pump systems on gold mines were the fourth largest electrical energy consumer on South African mines therefor making dewatering pumps ideal candidates to generate significant financial savings. These savings can be realised by controlling time-of-use (TOU) schedules.

Previous studies concentrated on the impact of improving a pumping scheme of a single mineshaft. This dissertation will focus on the operations of a complete dewatering system consisting of multiple mineshafts. The case study will consist of a gold mine complex comprising of five different shafts - each with its own reticulation system - as well as the larger interconnected water reticulation system.

Various pumping options were investigated, simulated and verified. The interaction between shafts was determined when load-shifting was scheduled for all the shafts taking each shaft's particular infrastructure into account. The underground dewatering system was automated and optimised based on the simulation results. Mine safety protocols were adhered to while optimal pump operational schedules were introduced.

SAMEVATTING

Titel:	Optimale waterverspreiding tussen pompstasies van meervoudige mynskagte
Outeur:	Nicolas Laurens Oosthuizen
Promotor:	Dr R Pelzer
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Die mynbedryf het in 2011 14.5% van die elektriese energie wat deur Eskom gegeneer is aangekoop. Die ondergrondse pompstelsels in goudmyne was die vierde grootste elektriese energieverbruiker in die Suid-Afrikaanse mynbou-industrie gedurende 2011. Dit maak dié pompstelsels ideaal om aansienlike finansiële besparings te genereer. Besparings word gegeneer deur die gebruik van elektriese energie gedurende piektye te beperk.

Vorige studies was daarop gemik om die pompstelsel van 'n enkele mynskag te optimeer. Hierdie verhandeling fokus op die optimering van 'n volledige kompleks wat bestaan uit verskeie mynskagte. Die gevallestudie sal handel oor 'n goudmynkompleks bestaande uit vyf verskillende skagte, elk met sy eie retikulasiestelsel sowel as die groter koppelende waternetwerkstelsel.

Verskeie pompopsies is ondersoek, gesimuleer en geverifieer. Die interaksie tussen die skagte is bepaal deur elke skag se besondere infrastruktuur in ag te neem en dan 'n lasskuifbenadering te volg. Die ondergrondse pompstelsel is geoutomatiseer en die skedules gebaseer op die simulasiresultate. Mynveiligheidsprotokolle is nagekom terwyl optimale operasionele skedules in gebruik geneem is by elke mynskag se pompstelsel.

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LIST OF ABBREVIATIONS

°C	–	Degrees Celsius
BOT OFFSET	–	Dam level bottom minimum offset
CR	–	Control range
dB	–	Decibel
DE	–	Drive end
DSM	–	Demand side management
HMI	–	Human-machine interface
IP	–	Internet protocol
IPC	–	Intermediate pump chamber
kg/m ³	–	Kilogram per cubic metre
km	–	Kilometre
kWh	–	Kilowatt-hour
l/s	–	Litre per second
m	–	Metre
M&V	–	Measurement and verification
m/s	–	Metre per second
m/s ²	–	Metre per squared second
MARVIN	–	Automatic reporting tool
MAX DL	–	Maximum specified dam level
MIN DL	–	Minimum dam level
MW	–	Megawatt
NDE	–	Non-drive end
Pa	–	Pascal
pH	–	A measure of the activity of the hydrogen ion
PID	–	Proportional-integral-derivative
PLC	–	Programmable logic controller
R ²	–	Coefficient of determination
SCADA	–	Supervisory control and data acquisition
TCP/IP	–	Transfer control protocol / Internet protocol
TOP OFFSET	–	Dam level upper range offset
TOU	–	Time-of-use

Chapter 1

1. ELECTRICAL ENERGY AND WATER USAGE IN SOUTH AFRICA

1.1. WATER TRANSFER USING ELECTRICAL ENERGY

Water transfer in the mining industry consumes large quantities of electrical energy. The electrical energy is supplied by Eskom, a public, limited liability company, entirely owned by the South African government (Eskom, 2011). The pie chart shown in Figure 1-1 indicates the relative distribution of the various electrical energy consumers in South Africa.

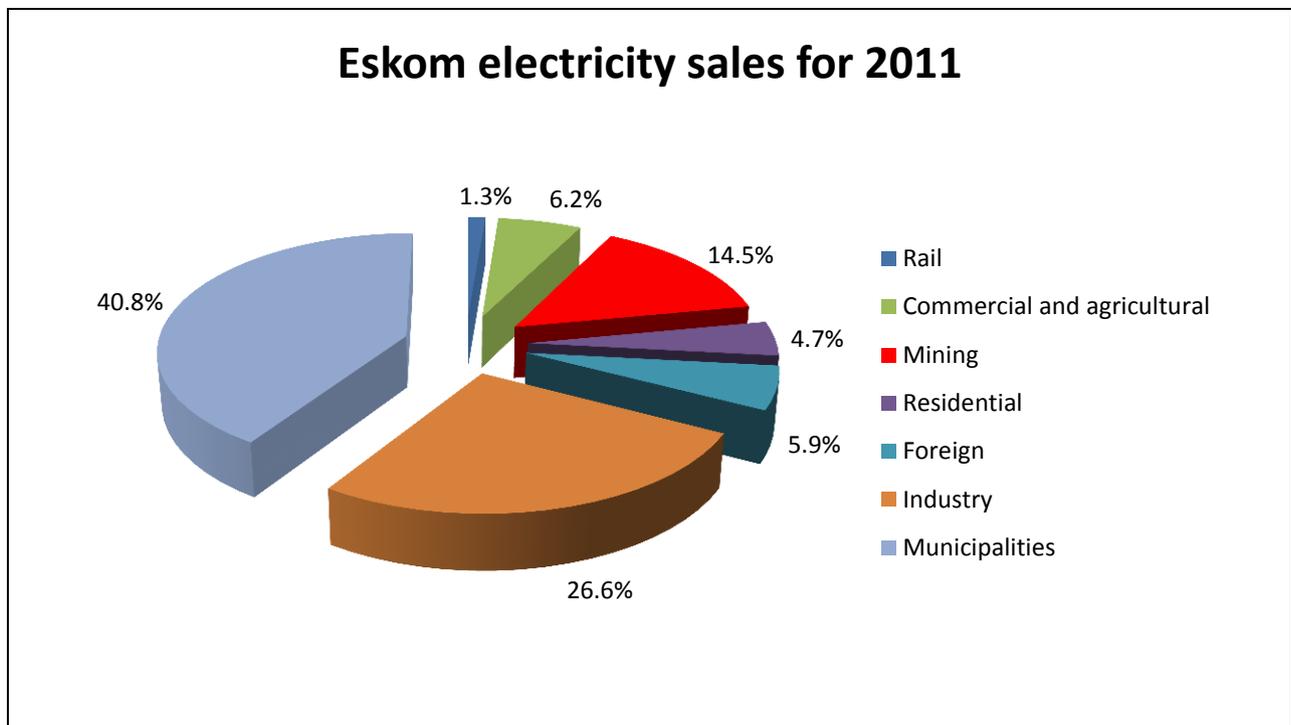


Figure 1-1: Eskom electricity sales for 2011 (adapted from (Eskom, 2011))

Figure 1-1 shows that the mining industry purchased 14.5% of electrical energy generated by Eskom in 2011. Gold mines in South Africa consume 47% of the total electrical energy used in the mining industry (Eskom, 2008). The mining industry uses electrical energy for various purposes including materials handling, processing, compressed air systems, pumping, ventilation fans, industrial cooling and lighting. The relative electrical energy consumption on a typical South African gold mine is shown in Figure 1-2.

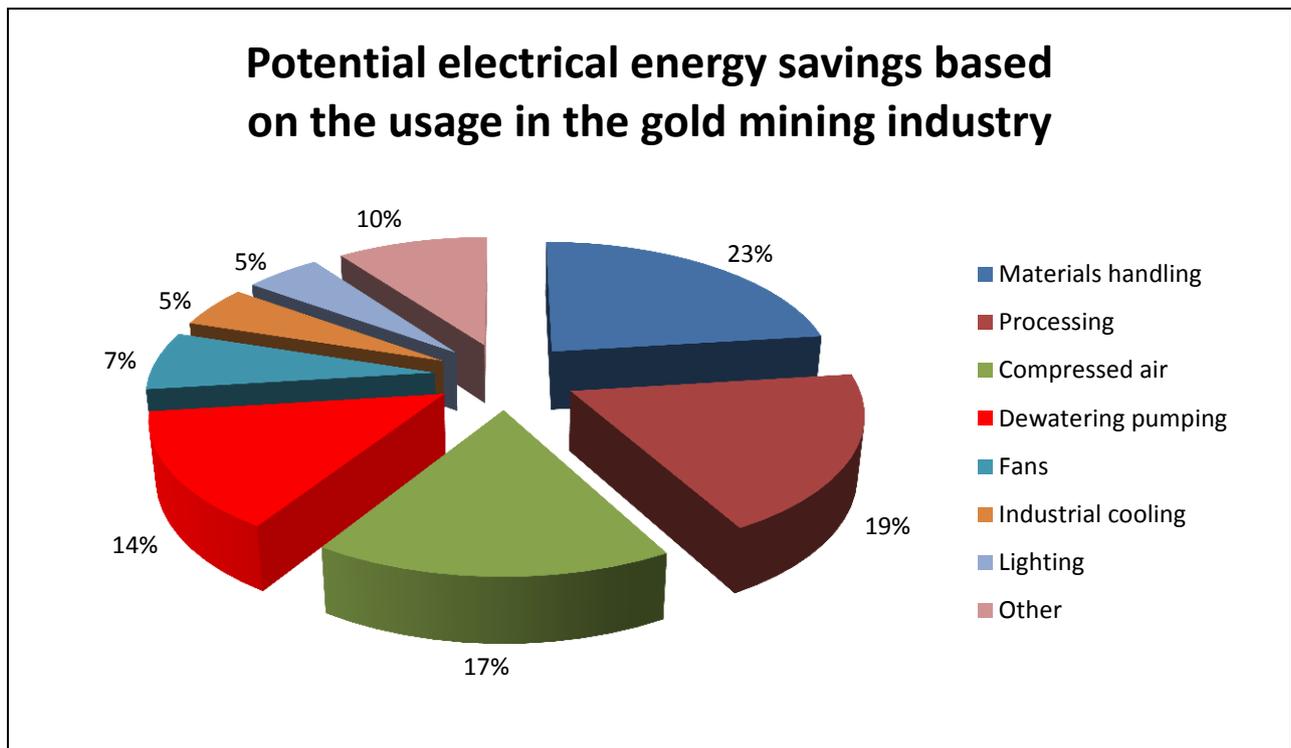


Figure 1-2: Electrical energy savings potential in the South African mines (adapted from (Eskom, 2008))

It is clear from Figure 1-2 that the dewatering pumping system is the fourth largest electrical energy consumer on mines. The largest electrical energy consumers are generally the most favourable candidates for implementing demand side management (DSM) projects as the savings potential is much greater when more electrical energy is used. DSM was introduced to reduce electrical energy usage in peak periods and prevent load-shedding (Eskom, 2008).

Many mines have overengineered pumping stations to ensure backup pumps are available in an emergency. A safety factor of 10% is incorporated to compensate for higher solids concentration in the fluids when installing pumps in a pumping station. This 10% buffer may not be enough when pump efficiencies deteriorate (Jones, Sanks, Bosserman, & Tchobanoglous, 2006). Higher solids concentration may increase pump deterioration.

Deep-level mines require multistage dewatering pumps that are able to pump large water volumes of up to 140 l/s against head pressures of up to 1 600 m (Eskom, 2008; Sulzer Pumps). The head pressure can be determined by the vertical drop and a rule of thumb indicates that 100 kPa is added to the pressure for every 10 m added to the distance. The vertical distance from the lower pumping station to the upper dam is known as the “head” (Syed, Ali, Haque, & Siddique, 2011).

In the case studies investigated in this dissertation the most commonly found pumps were Grifo multistage high-pressure dewatering pumps. Grifo Engineering is located in Germiston, thus better support can be given to gold mines that are situated in the area. Also, service parts are manufactured locally, therefore reducing the maintenance cost of dewatering pumps (Grifo Engineering).

Several high-pressure pumps driven by three-phase electrical motors can be installed on a particular level to increase pumping capacity. Higher pumping capacities require multiple columns to accommodate the additional water transferred. Various parameters must be considered when designing a pumping station. These parameters are discussed in Section 1.4.

1.2. CASCADING WATER RETICULATION SYSTEMS BACKGROUND

South Africa has the deepest gold mines in the world (Vosloo, Kleingeld, & van Rensburg, A new minimum cost model for water reticulation systems on deep mines, 2009). These mines can reach depths of up to 4 km below the surface. Intricate cascading pump systems are used for dewatering of the underground working areas (Vosloo, Kleingeld, & van Rensburg, A new minimum cost model for water reticulation systems on deep mines, 2009; Vosloo, A new minimum cost model for water reticulation systems on deep mines, 2008). These cascading pump systems consist of multiple pumping stations on different levels. A typical cascading water reticulation system can be seen in

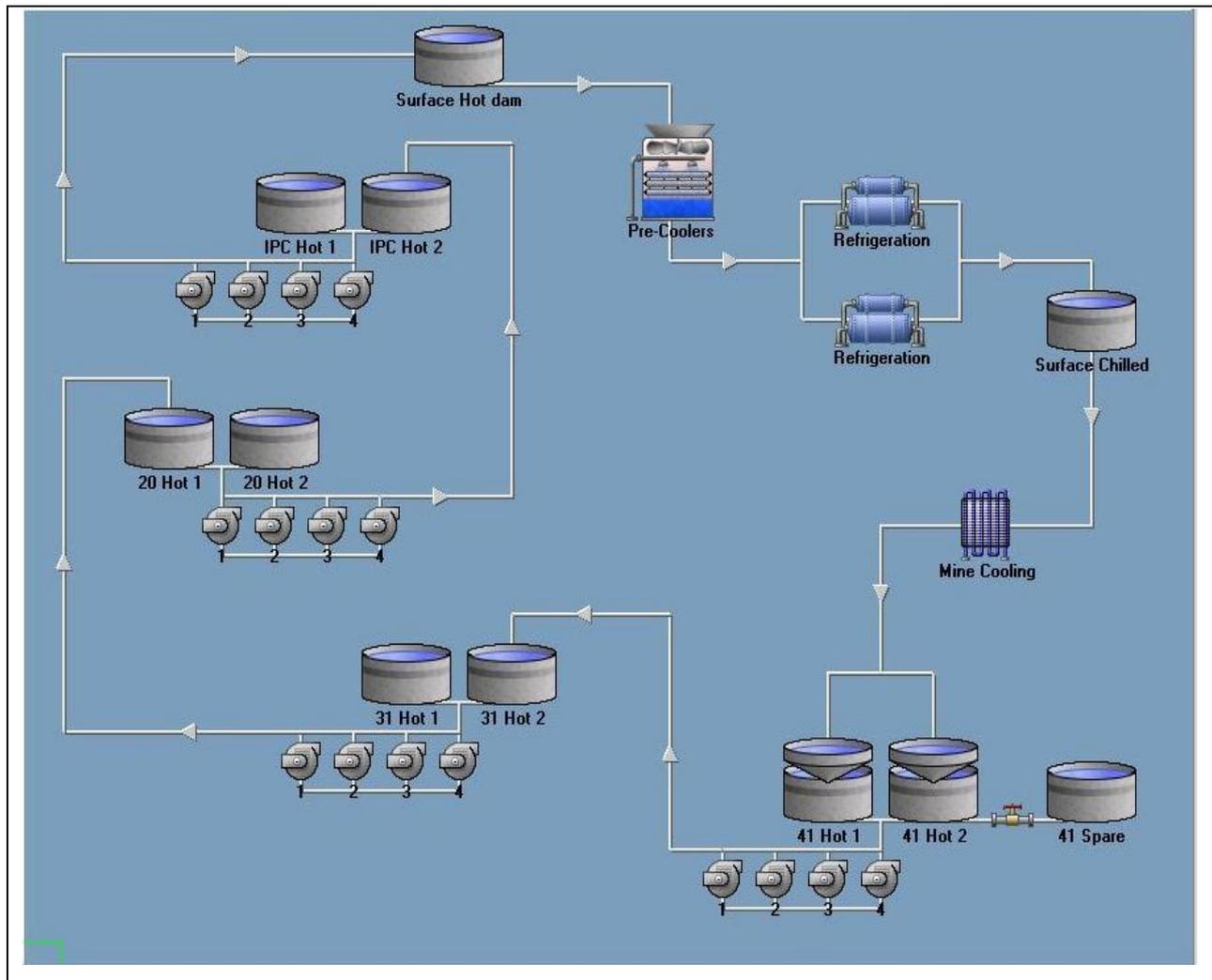


Figure 1-3: Typical cascading water reticulation system (Schoeman, Van Rensburg, & Bolt, 2011)

Water used for mining, cleaning, cooling of the work areas and other purposes usually end up on the bottom of each tunnel and is gravity-fed through trenches and plugholes to settlers. The settlers filter the water to remove sand particles. Lime is added to the filtered water to neutralise the low pH (Vosloo, van Rensburg, & Botha, Optimising the demand of a mine water reticulation system to reduce electricity consumption, 2010; Tutu, McCarthy, & Cukrowska, 2008). After treatment and filtering, the water is stored in a clear-water holding dam, normally situated above or on the same level as the dewatering pumping station.

Pumping stations located on various underground levels can consist of multiple clear-water pumps. The number of pumps and their sizes depend on the inflow of water into the dams, available storage capacity, discharge column capacities and the number of available discharge columns. The final pumping station transfers the water to the surface clear-water holding dam. Once on surface, water is pumped to a filter plant where it is filtered and then transferred to the fridge plant.

The fridge plant comprises of two stages and is referred to as a “lead-lag cooling plant”. The first stage consists of cooling towers where ambient air is blown by electric fans through heat exchangers to disperse heat into the atmosphere. The water temperature is reduced from approximately 30°C to between 12°C and 16°C, depending on atmospheric conditions or seasonal changes (Vosloo, Kleingeld, & van Rensburg, A new minimum cost model for water reticulation systems on deep mines, 2009).

The second stage involves an evaporator and a condenser where the water is cooled to approximately 3°C. If the water temperature falls below 3°C, the possibility of ice crystals forming increases, making water transfer difficult or impossible. The cooled water is stored in service water dams and then gravity-fed through a column in the shaft, where it can be used again (Vosloo, A new minimum cost model for water reticulation systems on deep mines, 2008).

1.3. LOAD-SHIFT AND POTENTIAL SAVINGS

Electricity used by the mining sector is based on Eskom’s “time-of-use” (TOU) pricing structure called Megaflex. Three TOU periods can be identified using Megaflex where a 24-hour day is divided into peak, standard and off-peak periods (Eskom, 2011/12). Figure 1-4 shows the TOU periods used by Eskom. When comparing the pricing structure per unit measured in kWh, the cost during peak periods is significantly higher than the cost during the off-peak periods (Eskom, 2011/12). Eskom has various projects in the mining sector to reduce electrical energy use during peak periods (Volschenk, 2008).

Cost savings can be realised by shifting electrical energy consumption from peak periods to off-peak periods. This load-shift strategy results in financial savings but is energy neutral. The average electrical energy consumption over a 24-hour profile remains the same as before the load-shifting intervention. Thus, the volume of water pumped each day remains approximately the same (Kleingeld, Vosloo, & Swanepoel, 2011).

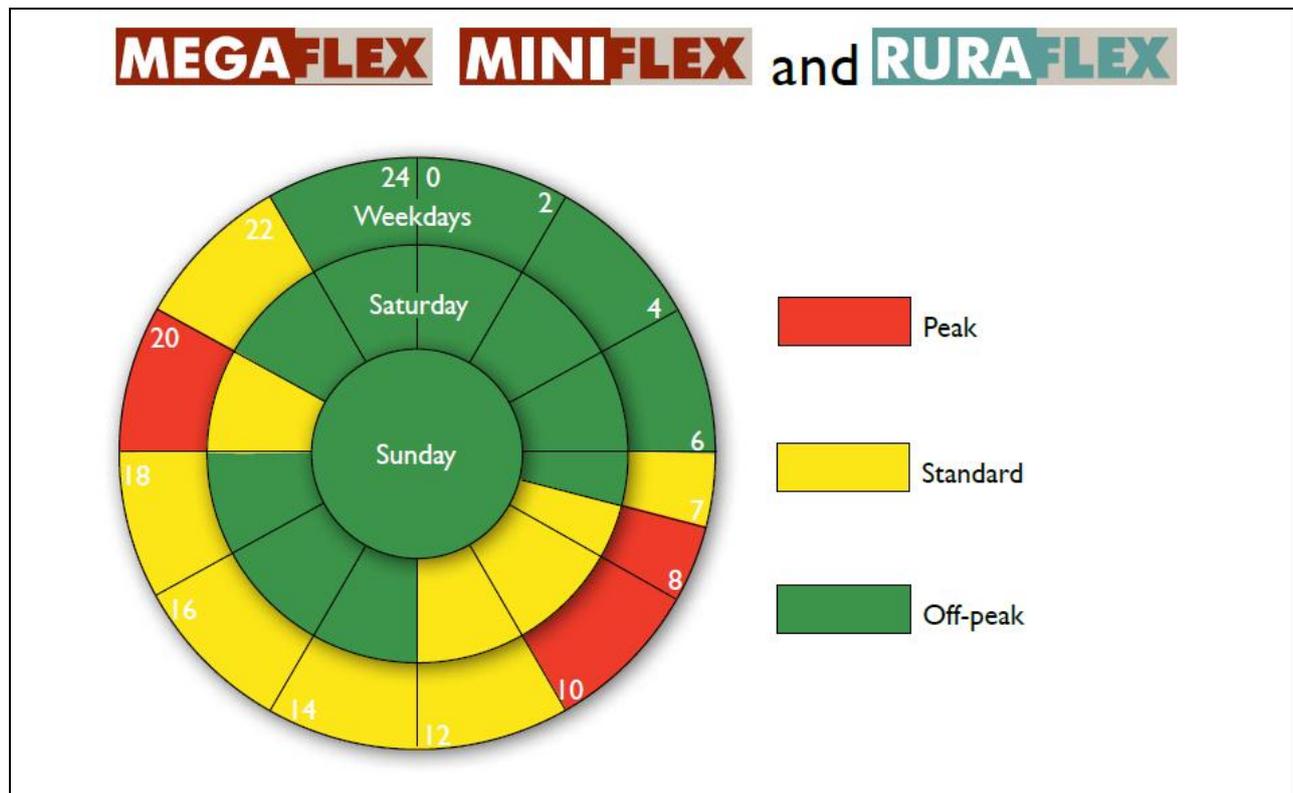


Figure 1-4: Eskom TOU periods used for Megaflex (Eskom, 2011/12)

Although on average the same amount of electrical energy is used over a 24-hour period. The savings are realised during the peak period by “shifting” the electrical energy usage out of the peak periods. The comeback load reflects in the standard and off-peak periods, thus resulting in financial savings. A dewatering pump system for example, realising a load-shift of 8.5 MW in the evening peak will result in an estimated financial saving of R5.97 million per annum, based on the Eskom 2011/12 tariff structure (Eskom, 2011/12).

This financial saving was calculated using the MARVIN software savings calculator (APPENDIX A: MARVIN SAVINGS CALCULATOR). The financial savings generated will vary from day to day depending on the specific production and pumping schedules. Other contributing factors recorded were washing of dams and pump maintenance, causing less storage of water and less running pumps respectively.

To determine a load-shift strategy a general infrastructure audit must be completed to ensure that the savings generated are realistic and sustainable. The data captured from the audit can then be used to simulate the operational procedures and schedules of the dewatering pumping stations. It can be expected from this study that water pumped to surface will consume more electrical energy than water transferred to neighbouring shafts.

Load-shifting will only be possible if each pumping station has extra pumping and storage capacity to compensate for the additional load required during the off-peak periods. More water has to be stored during peak TOU periods. Restricting factors are pump sizes, motor sizes, the number of pumping columns, column size, the number of clear-water storage dams and dam capacities (Schoeman, Van Rensburg, & Bolt, 2011).

If the simulations indicate that savings can be realised, actual data (captured onsite at the mine) will be used to test and verify the accuracy of the simulation models. After the simulations have been verified it will be adapted to transfer all the mine water located at Mine Shaft A to neighbouring shafts where it will be pumped to surface. From the two simulation models (Simulation X and Y) an optimised pumping strategy can be determined and implemented to generate maximum financial savings on the total electricity consumed.

Figure 1-5 shows a dewatering pumping station in a typical gold mine. The picture was taken during a full instrument audit conducted on each pumping station to determine existing instrumentation. Instrumentation providing information to the pump operator is installed to ensure safe starting or stopping of pumps from the surface control room (President's office, 1996 (revised 2009)). The installed instruments give feedback on the safe running conditions of each pump.



Figure 1-5: Typical underground dewatering pumps

1.4. BEST PRACTICES AND POSSIBLE BENEFITS

Centrifugal pump drives

Centrifugal pumps can be powered by various means. The most common are electrical motors, diesel engines and gas turbines. The drive unit used depends on the size, application and location of the pump. Electrical motors are preferred but diesel engines are used in instances where power failures are encountered often, or where no electricity is available. Gas turbines are used only in exceptional circumstances (Sulzer Pumps, 2010).

Only three-phase electrical motors are used in the underground pumping stations to power the dewatering pumps. The two types of three-phase motors used to drive high-pressure pumps are squirrel-cage motors or slip-ring motors. Squirrel-cage motors are the most popular choice as capital outlay and running costs are lower than for slip-ring motors (Sulzer Pumps, 2010).

Matching an electric motor to a pump is dependent on the pump specifications, surroundings, electrical power supply ratings and Health and Safety regulations (President's office, 1996 (revised 2009); Department of Minerals and Energy, 2008). These requirements usually cause oversizing of motor specifications (Sulzer Pumps, 2010). Excessive oversizing will cause the motor and the pump to run inefficiently.

Pumping columns

Pumping columns serve as suction and discharge columns between levels of the cascading pump system. When designing a cascading pump system the following factors have to be considered:

- Pipe manufacturing material must be suitable (galvanised steel is used to prevent corrosion due to the low pH of used mine water);
- pipe sizing must be done correctly according to the flow and the pressure requirements of the pumps;
- pipes must be anchored properly as water hammers may cause columns to get dislodged when pumps trip;
- pipe sections must be accessible; and
- maintenance is crucial (Sulzer Pumps, 2010; Bachus & Custodio, 2006).

Parallel pump operations

The cascading pump installations require multiple pumps per pumping station. For the cascading pump installations encountered in this dissertation, pumps were installed in parallel. Different pumps made use of the same discharge column or columns, thus the focus in this section will be on parallel pumping configurations.

When considering the three centrifugal pumps: A, B and C in Figure 1-6. For parallel operations the head pressure (H) for the pumps remain constant and the flow capacity for each pump is added together to get the total flow (Q_R). The result for Q_R is not linear due to head losses in the discharge columns (Sulzer Pumps, 2010; Bachus & Custodio, 2006). The head losses are caused by the surface roughness on the inside of the discharge column, the pipe length and the viscosity of the fluid (Sulzer Pumps, 2010).

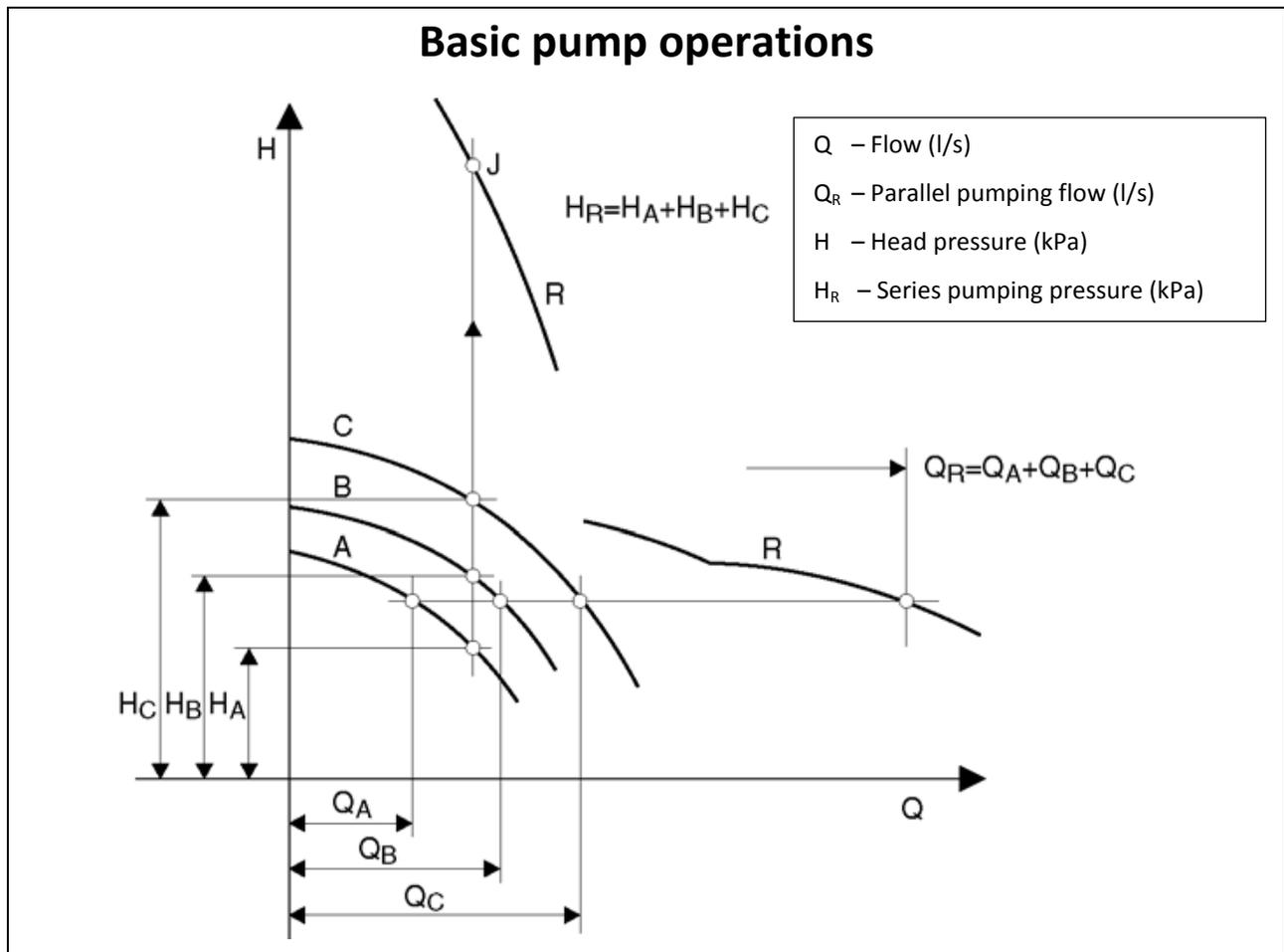


Figure 1-6: Series and parallel pump operations adapted from (Sulzer Pumps, 2010)

When automating the system, parallel operations will have to be taken into consideration. When a second column is available between pumping stations, the next pump to be started would be a pump that pumps water into the unused column - rather than the used column - to minimise pipe friction and optimise the pumping of water.

1.5. OBJECTIVES OF THIS STUDY

Previous studies concentrated on the impact of improving a pumping scheme on a single mineshaft. The aim of this study is to optimise the water pumping scheme of an entire dewatering system consisting of multiple mineshafts. The optimisation process is expected to generate financial saving reflecting in the mine's electrical utility bill by shifting load from the evening peak periods to the off-peak periods.

1.6. OVERVIEW OF THIS DISSERTATION

Chapter 2 – Optimising a water reticulation system

A case study will be identified and analysed in detail. Each mine shaft in the complex will be described in terms of its particular water reticulation system. Special attention will be given to pumping and storage capacity. The interaction between shafts will be described and possible pumping scenarios identified. The underground dewatering system will be discussed based on these pumping scenarios. Automation will be discussed in terms of instruments required to safely stop and start a pump remotely.

Chapter 3 – Analysis of results

The results of the optimising case study will be simulated, analysed and verified. Previous electrical energy usage baselines for each shaft will be compared to the baseline generated after the load-shifting project intervention. The simulated reticulation systems will be compared to actual measurements to verify the simulation models. Predicted savings will be simulated and possible financial savings quantified. The advantages of automatic control will be discussed and compared to conventional manual control.

Chapter 4 – Conclusion

A summary of the dissertation, with recommendations for future studies, will be given based on the research conducted.

Chapter 2

2. OPTIMISING A WATER RETICULATION SYSTEM

2.1. PREAMBLE

This chapter describes typical shaft layouts and the simulated optimisation of water reticulation systems. A load-shifting strategy for each shaft will be introduced and optimised to generate maximum financial savings. The respective water reticulation systems of each shaft at this mine interconnect underground and various pumping strategies will be investigated.

Optimal financial saving on electrical energy usage will be determined by optimising pumping procedures throughout the complex. Automated control will be introduced and the advantages discussed over manual control procedures. A detailed control philosophy will be discussed including all the mimics (SCADA objects in the form of interactive pictures used to monitor and control pumps) required for the automated control procedure.

2.2. TYPICAL SHAFT LAYOUT

Shaft reference point

The datum line (Oxford University Press, 2012) or shaft reference is a reference point used to measure the depth of each shaft below the surface. This information is obtained from the engineering blueprints supplied by the mine¹.

Shaft overview

The case study that will be investigated in this dissertation has five independent shafts in the complex. For the purpose of the study these shafts were called Mine Shaft A, Mine Shaft B, Mine Shaft C, Mine Shaft D and Mine Shaft E. Mine Shaft A has two independent sub-vertical shafts. Mine Shaft B, Mine Shaft C and Mine Shaft D have one or more sub-vertical shaft each. Mine Shaft E is a single-shaft mine, meaning that there are no sub-vertical shafts and only a single mine shaft serving all the levels.

¹R. Pretorius, Interviewee, *Shaft Engineer, KDC East Thuthukani Shaft*. [Interview]. 21 Feb. 2012.

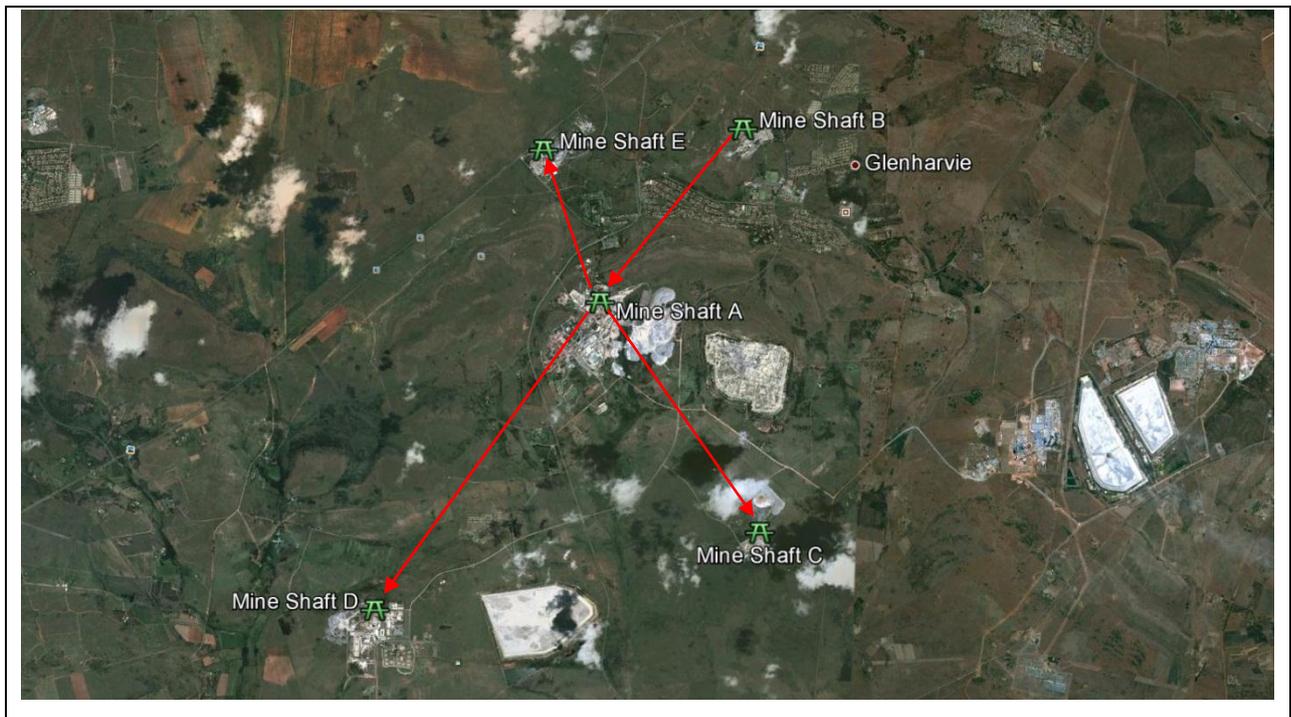


Figure 2-1: Clear water pumping schematic

Mine Shaft A pumping layout

Mine Shaft A consists of four independent cascading pumping levels of various capacities. A layout of Mine Shaft A can be seen in Figure 2-2. All the water pumped to surface is stored in two surface dams with 5 Ml capacity each. Mine Shaft A does not have a refrigeration plant on surface. Transfer pumps on surface, transfer water to Mine Shaft B for ammonia treatment and cooling.

Figure 2-2 was taken from the real-time supervisory control and data acquisition (SCADA) and represents the cascading pump system installed at Mine Shaft A. The shaft layout and the different possible pumping schemes were discussed with the shaft engineer². Mine Shaft A consists of a main shaft and two sub-vertical shafts. The main shaft contains two pumping stations: 2-5 Level and 23-60 Level. 2-5 Level contains a pumping station housing seven pumps.

²R. Pretorius, Interviewee, *Shaft Engineer, KDC East Thuthukani Shaft*. [Interview]. 21 Feb. 2012.

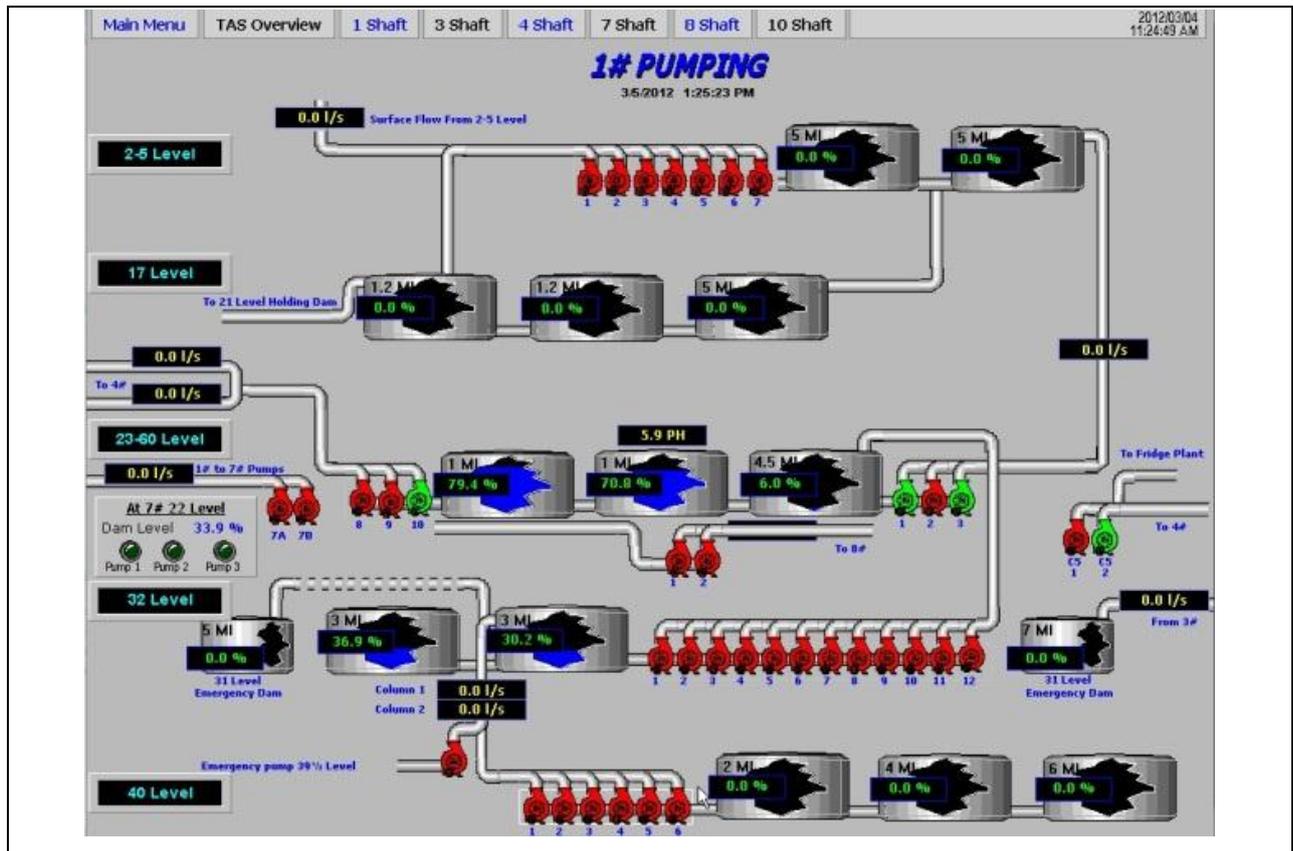


Figure 2-2: Pumping SCADA screen for Mine Shaft A

23-60 Level contains different pump types and pump sizes. Three high-pressure pumps supply water to 2-5 Level and several smaller transfer pumps transfer water from Mine Shaft A to Mine Shaft C (three pumps), Mine Shaft A to Mine Shaft D (two pumps) and Mine Shaft A to Mine Shaft E (two pumps), in this order of priority. The transfer pumps are started according to priority, based on the pumping capacity of the receiving shaft. The pump installed capacities for Mine Shaft A can be seen in Table 2-1.

Table 2-1: Mine Shaft A pump sizes

Pumping station	Pump	Pump installed capacity (kW)
Level 2-5	1	1800
	2	1800
	3	1800
	4	1800
	5	1800
	6	1800
	7	1800
Level 23-60	1	3600
	2	3600
	3	3600
	8	900
	9	900
	10	900

Pumping station	Pump	Pump installed capacity (kW)
	7A	1100
	7B	1100
	8A	900
	8B	900
Level 32	1	1500
	2	1500
	3	1500
	4	1500
	5	1500
	6	1500
	7	1500
	8	1500
	10	1500
	12	1500
Level 40	1	1350
	2	1350
	3	1350
	5	1350

Table 2-2 shows the control philosophy used for the transfer pumps. The transfer pumps are controlled based on high to maximum allowable dam levels of Dam 1 and Dam 2 located on 23-60 Level. The pumps are started in sequence as seen in the table and the priority is determined by the pumping capacity of the receiving shaft. The transfer water is then pumped to surface by each receiving shaft.

Table 2-2: Mine Shaft A transfer pump control

Mine Shaft C transfer pumps running	Mine Shaft D transfer pumps running	Mine Shaft E transfer pumps running	Dam 1 Level	Dam 2 Level
1	0	0	>80%	<80%
2	0	0	>80%	>80%
2	1	0	>90%	<90%
2	1	1	>90%	>90%

The two sub-vertical shafts each house a pumping station at its lowest level. 1 Sub-vertical has a pumping station on 32 Level with two separate pump banks. A total of twelve pump platforms are installed on 32 Level, but at the time of writing only ten pumps were installed. Six pumps were installed on Bank A and four pumps on Bank B.

2 Sub-vertical is the deepest point in the shaft and shaft bottom is situated at 3 300 m below the datum. 40 Level is the lowest working level and houses the last pumping station. 40 Level is also a conveyer belt level where rock ore is gravity-fed through an ore pass and caught on the conveyer belt where it is loaded in a skip and hoisted out using the rock winder on 22 Level above the sub-bank on 23 Level.

In February 2010 the shaft bottom and 40 Level were flooded. The column in the main shaft between 2-5 Level and surface failed due to metal fatigue caused by rust. Part of the column fell down the shaft with no injuries to any of the mine employees. The accident forced the mine to disable the 2-5 Level pumping station as well as part of the 23-60 Level pumping station.

The pumping stations in the main shaft were out of action between March and December 2010 and all the incoming water had to be transferred to the neighbouring shafts in the complex. The water transfer resulted in less electrical energy being used on the dewatering pumps at Mine Shaft A between March and December of 2010; this can be seen in Figure 2-3.

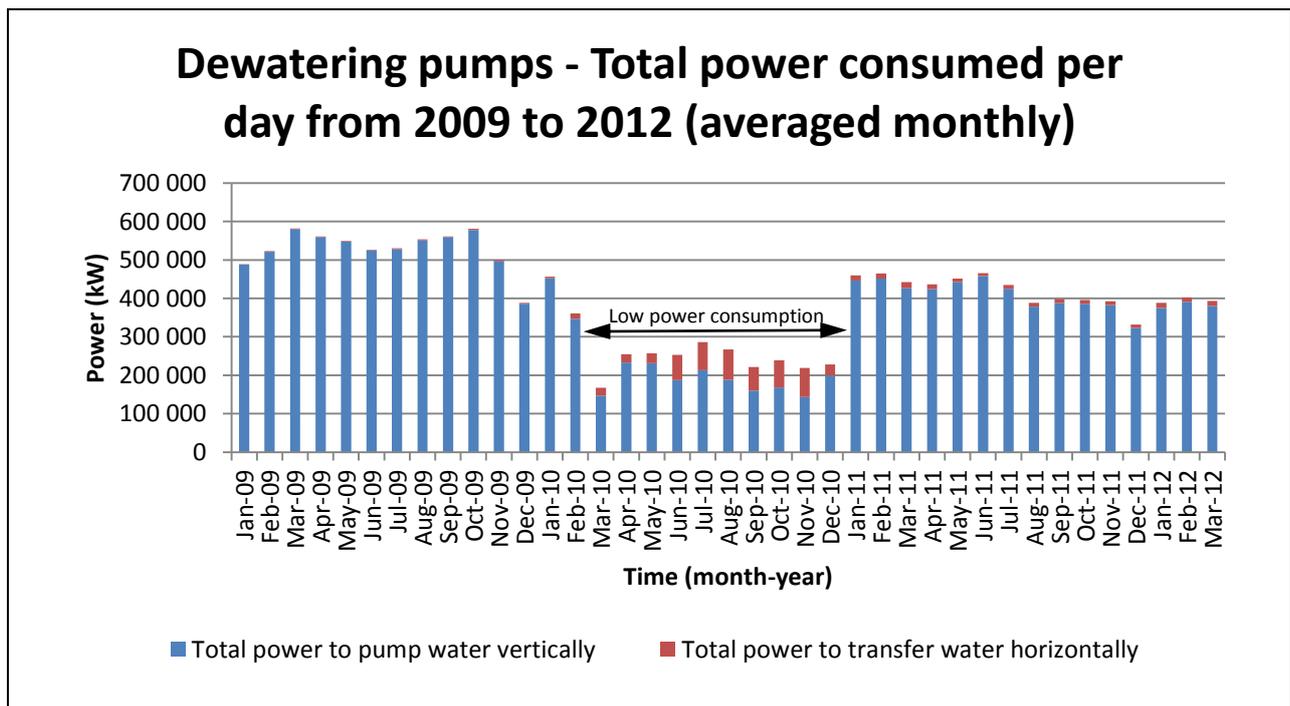


Figure 2-3: Monthly average power consumed by Mine Shaft A's pumps

The damage was repaired during 2010 and normal pumping resumed in January 2011, however, some water was still transferred between shafts. Figure 2-4 shows the average power consumption from 2009 to 2011. From 2010 the electrical energy consumed by water transfer pumps had a significant impact on the total electrical energy consumed. The smaller transfer pumps to neighbouring shafts use less power (kW) to transfer water at the same flow rates (l/s) as the high-pressure pumps transferring water to the surface.

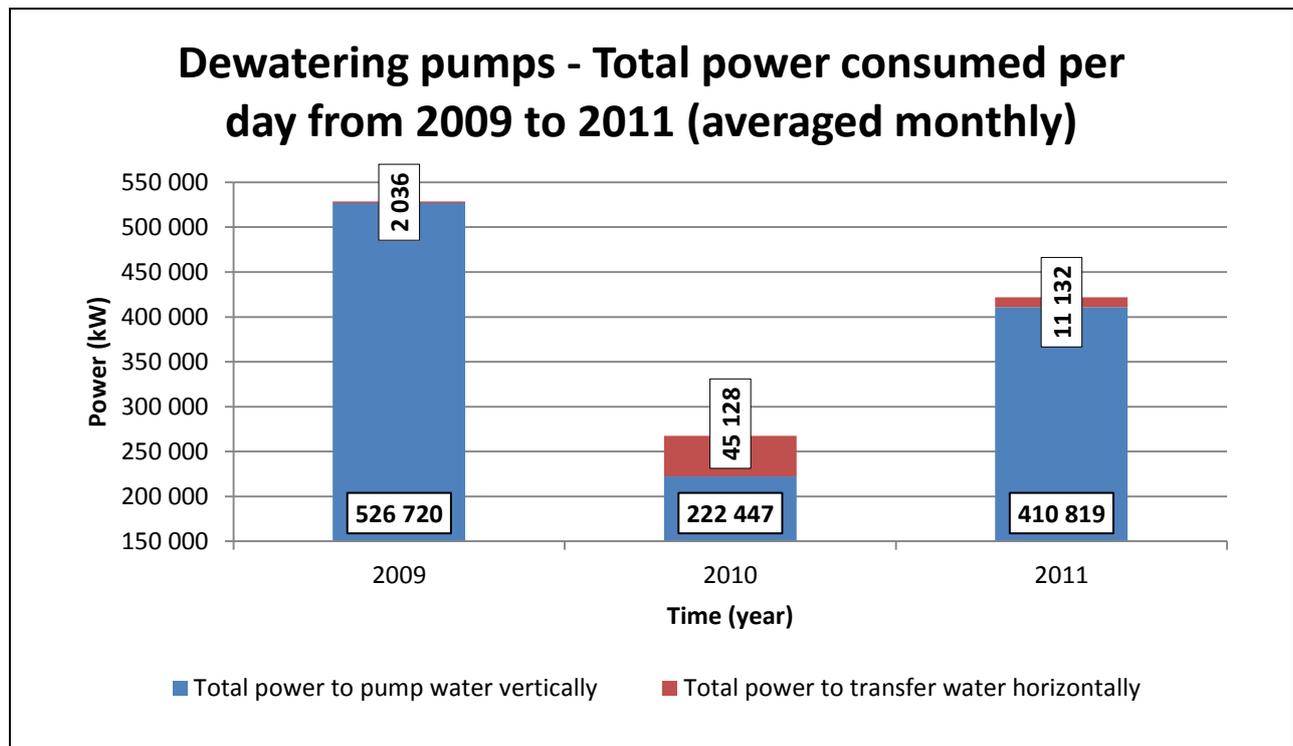


Figure 2-4: Annual average power consumed by Mine Shaft A's pumps

Level control valves were installed on the sub-shafts during 2010 and 2011 to control the cold water sent down the shaft. These major infrastructure changes resulted in massive electrical energy savings. The average electrical energy consumed by pumps for 2009 was 526 720 kW vertically and 2 036 kW horizontally. In 2011, when normal pumping commenced, these figures changed to 410 819 kW vertically and 11 132 kW horizontally thus resulting in an average saving of 129 069 kW per weekday.

Mine Shaft B pumping layout

Mine Shaft B is located on the datum line and its head gear (shaft tower housing sheave wheels) is located on a small hill in the complex. Due to its higher locality Mine Shaft B only has one pumping station on 44 Level. As seen in Figure 2-5, the 44 Level pumping station, with four high-pressure pumps, supplies mine water to the clear-water dams on 30 Level. Mine Shaft A pumps all of Mine Shaft B's water to surface, thus resulting in lower pump maintenance and a lower pumping head.

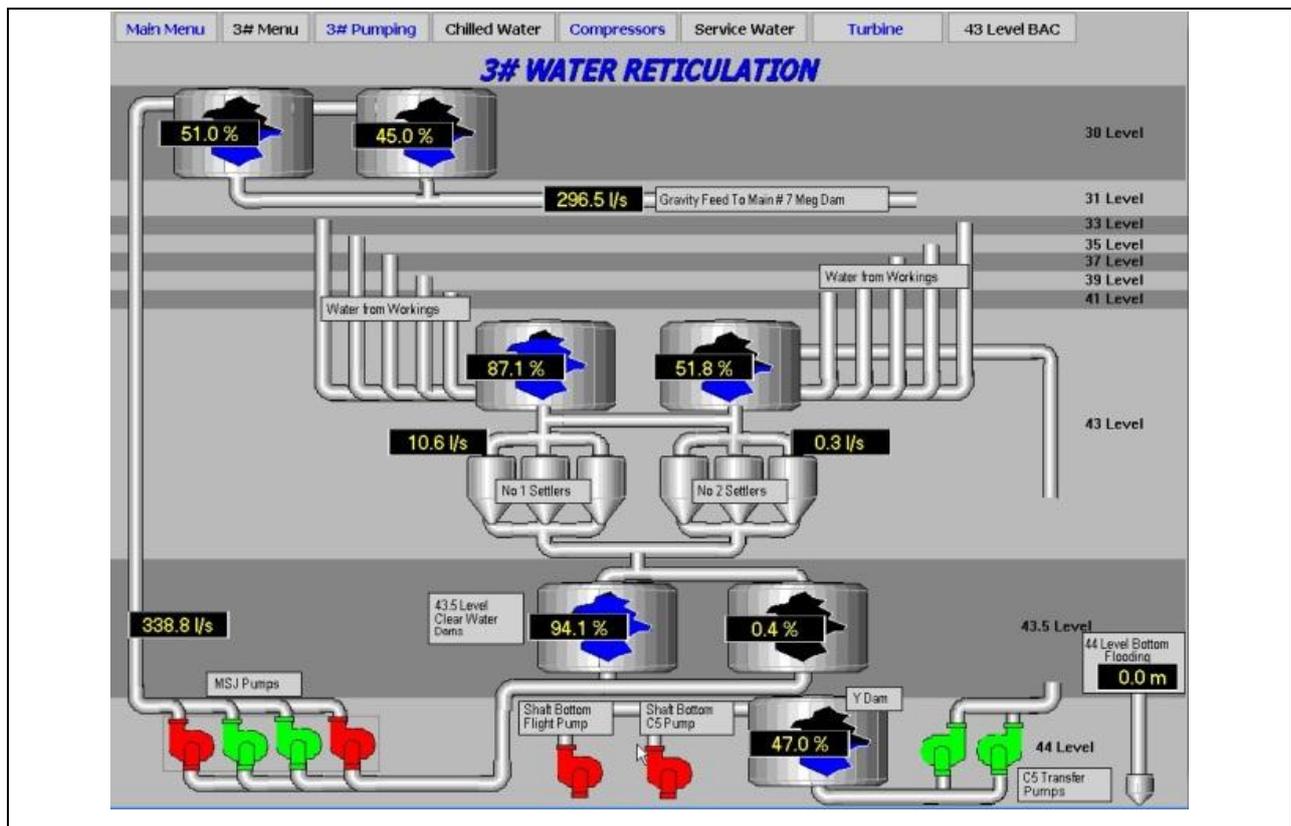


Figure 2-5: Pumping SCADA screen for Mine Shaft B

Mine Shaft B has several smaller sub-shafts serving as service shafts. These sub-shafts house conveyer belts and ventilation systems. The sub-shafts are 3 Sub-vertical, 3A Sub, 3B Sub and 3D Sub. The mining taking place at Mine Shaft B is done on 3 Sub-vertical. All the water sent down to 3 Sub-vertical that is used for mining and cleaning ends up in the 44 Level pumping station holding dam.

The water from the 30 Level clear-water dams is gravity-fed to Mine Shaft A through a pipeline located on 31 Level. The pipeline connects into Mine Shaft A's cascading pump system on the 32 Level pumping station, where the water is pumped to the higher Minus Level. The incoming water flow is controlled by Mine Shaft A control room personnel³.

Mine Shaft C pumping layout

Mine Shaft C is the only hydro shaft in the complex. Compressed air driven power tools are gradually being replaced with hydropower tools. A larger quantity of service water is being used at Mine Shaft C than at the other shafts. Also, more water ends up on the floor of the haulages at Mine Shaft C than at the other shafts. This water has to be pumped back to surface for treatment, cooling and then reused.

³R. Pretorius, Interviewee, Shaft Engineer, KDC East Thuthukani Shaft. [Interview]. 21 Feb. 2012.

Mine Shaft C has two water columns installed on the shaft: a dedicated hydropower service water pipeline that gravity-feeds cold water to the work areas; and a second pipeline that is used for feeding cold water for general use in ventilation system radiators, cooling of work areas, and so forth. Due to the larger water usage than other shafts the pumping system on Mine Shaft C is of greater importance than the other shafts in the complex.

In Figure 2-6 it can be seen that Mine Shaft C contains four pumping levels. Two pumping levels are located on the main shaft and two pumping levels are located on 4 Sub-vertical. Each shaft contains an intermediate pump chamber (IPC). Each IPC pumping level has no production or development taking place on the level and is dedicated to pumping water. IPC levels were installed to reduce the head pressure on the lower pumping level.

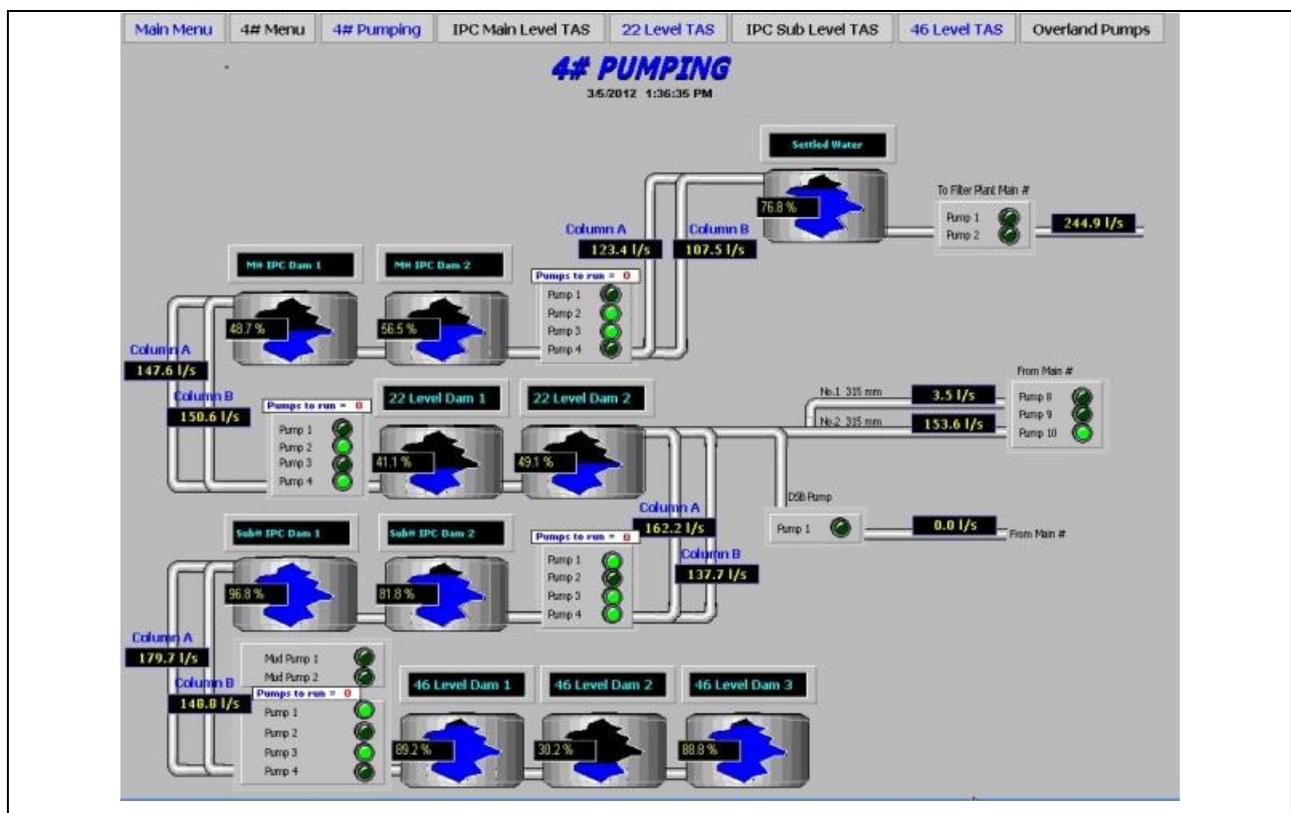


Figure 2-6: Pumping SCADA screen for Mine Shaft C

IPC main pumping station is the closest pumping station to surface; it contains four high-pressure pumps supplying water to the surface dam used by the Mine Shaft C fridge plants. 22 Level pumping station is located at 2 042 m below the datum which is 26 m above Mine Shaft A's 23-60 Level. The transfer water from Mine Shaft A is mixed with Mine Shaft C's mine water at the 22 Level pumping station. The four pumps on 22 Level transfer the incoming water to IPC main pumping station.

4 Sub-vertical Shaft houses two pumping stations: the IPC Sub pumping station and the 46 Level pumping station. IPC Sub has four pumps transferring water to 22 Level. 46 Level is the lowest pumping station on Mine Shaft C and is located at 3 650 m below the datum. Water from the four pumps on 46 Level is transferred to IPC Sub clear-water dams. The pump installed capacities for Mine Shaft C can be seen in Table 2-3.

Table 2-3: Mine Shaft C pump sizes

Pumping station	Pump	Pump installed capacity (kW)
IPC Main Level	1	2100
	2	2100
	3	2100
	4	2100
22 Level	1	1800
	2	1800
	3	1800
	4	1800
IPC Sub Level	1	1800
	2	1800
	3	1800
	4	1800
46 Level	1	1800
	2	1800
	3	1800
	4	1800

Mine Shaft D pumping layout

Mine Shaft D has four pumping levels as seen in Figure 2-7. An IPC pumping level is located on the main shaft and supplies the surface dams with water to be cooled by the surface fridge plants. This water can later be reused. Similar to the IPC levels discussed for Mine Shaft C, IPC Level on Mine Shaft D is a dedicated pumping level. Mine Shaft D's IPC Level contains five high-pressure pumps. The next pumping level, 20 Level, is located on the main shaft and feeds water to IPC Level using four pumps.

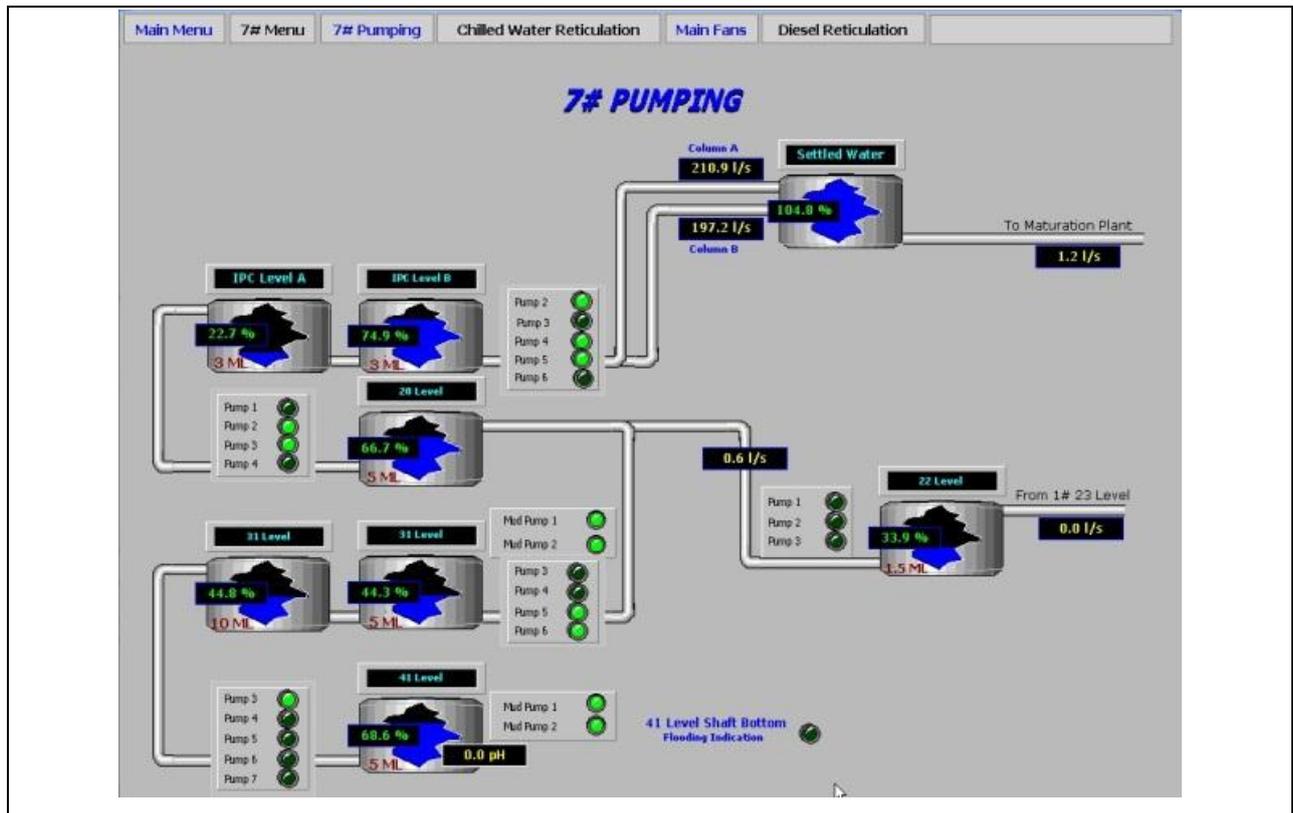


Figure 2-7: Pumping SCADA screen for Mine Shaft D

The Mine D Sub-vertical Shaft houses two pumping levels located on 31 Level and 41 Level. 31 Level has four pumps pumping to 22 Level and 41 Level has five pumps pumping to 31 Level. The water transferred from Mine Shaft A’s 23-60 Level is stored in the 22 Level holding dam and pumped to 20 Level where it is mixed with Mine Shaft D’s mine water. Afterwards it is pumped to surface for reuse. The pump installed capacities for Mine Shaft D can be seen in Table 2-4.

Table 2-4: Mine Shaft D pump sizes

Pumping station	Pump	Pump installed capacity (kW)
IPC Level	2	2100
	3	2100
	4	2100
	5	2100
	6	2100
20 Level	1	2100
	2	2100
	3	2100
	4	2100
	5	2100
31 Level	2	2100
	3	2100
	4	2100
	5	2100

Pumping station	Pump	Pump installed capacity (kW)
	6	2100
41 Level	3	2100
	4	2100
	5	2100
	6	2100
	7	2100

Mine Shaft E pumping layout

The smallest cascading pump system in the complex is located at Mine Shaft E. This shaft has only two pumping levels as seen in Figure 2-8. Mine Shaft E is also the smallest shaft in the complex with no sub-vertical shafts. The first pumping level is 3165 Level; it contains four pumps feeding to a surface dam. The water from the surface dam is cooled on surface for reusing at Mine Shaft E. Surplus water is transferred to Mine Shaft A’s surface dams where the water is filtered and transferred to Mine Shaft B for cooling.

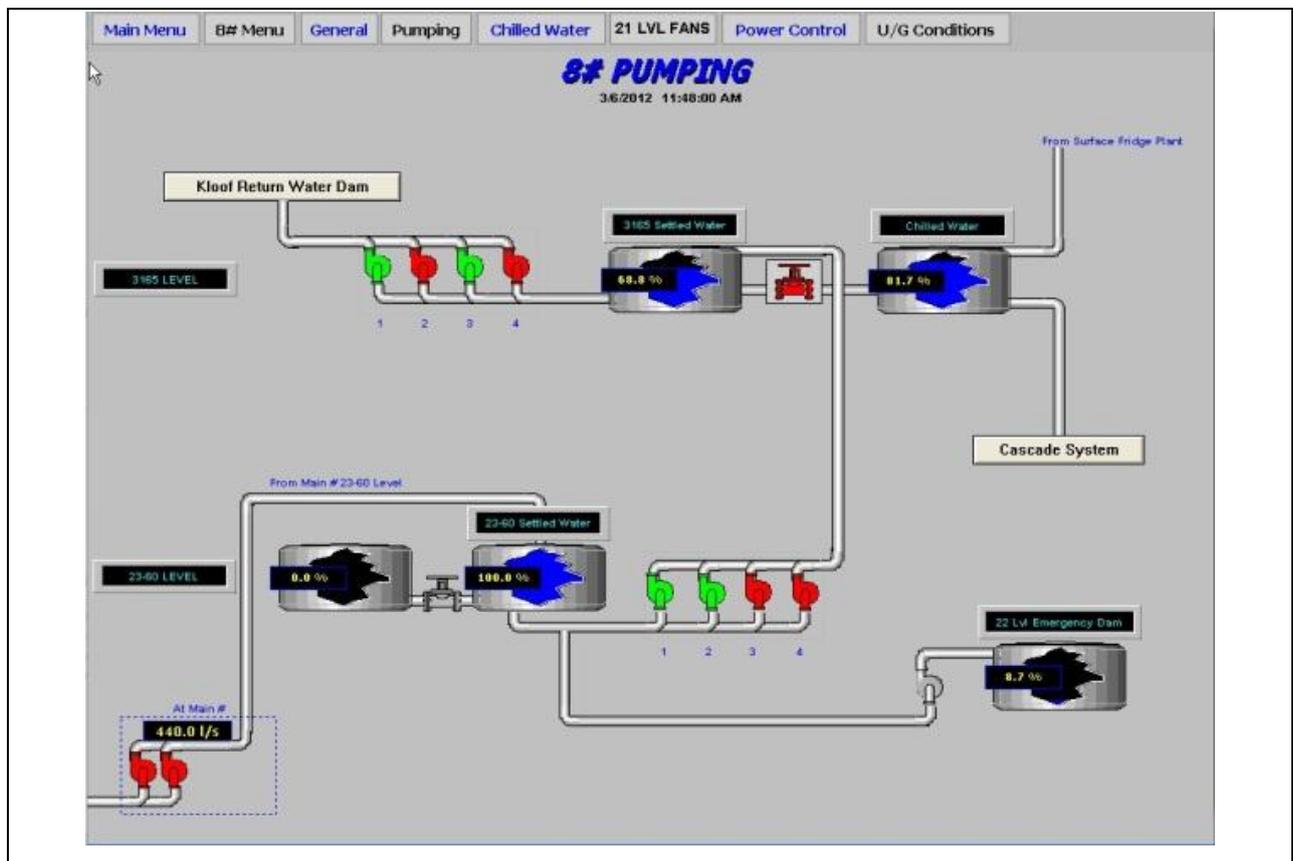


Figure 2-8: Pumping SCADA screen for Mine Shaft E

The lowest pumping level is located on 23-60 Level and supplies water to 3165 Level. Water from Mine Shaft A's 23-60 Level is mixed on Mine Shaft E's 23-60 Level for dewatering at Mine Shaft E. Mine water from Mine Shaft A will only be pumped to Mine Shaft E if the storage dams on 23-60 Level at Mine Shaft A reach dam levels above 90% (as seen in Table 2-2). The installed capacities for the pumps used at Mine Shaft E can be seen in Table 2-5

Table 2-5: Mine Shaft E pump sizes

Pumping station	Pump	Pump installed capacity (kW)
3165 Level	1	1567
	2	1567
	3	1567
	4	1567
23-60 Level	1	1567
	2	1567
	3	1567
	4	1567

2.3. PUMPING STRATEGIES FOR MULTIPLE MINE SHAFTS

The column failure discussed previously forced the upgrade of the transfer pipelines to neighbouring shafts. Because the shafts are interconnected underground various pumping strategies must be considered to ensure that the optimal pumping costs are realised. The shafts were monitored for three months or more before the simulation model was completed. This ensured reliable accuracy of the simulation model.

At the time of writing the mine launched a project to install PowerLogic® ION power meters on all of its electrical feeders to the substations on all the interconnected shafts. However, the project would not be finished in time to form part of this dissertation. The requirement for PowerLogic® ION power meters was included in Mine Shaft A and Mine Shaft C's pump automation DSM projects (Schneider Electric, 2010; Schneider Electric, 2010).

The assumption was made that all of the pumps have an efficiency of 85% and the installed capacities would be used for pumps without power meters. The installed capacities would be multiplied by 0 or 1 depending on the running status of each pump; where 1 indicates that a pump is running and 0 indicates that a pump is standing.

Mine Shaft A is located geologically on a lower elevation and has the biggest dewatering pump network in the complex. With the highest pumping capacity Mine Shaft A pumps the most water to surface each day. The water pumped includes water from Mine Shaft B. To ensure that the simulation model was accurate and consistent the simulations were designed around Mine Shaft A.

The column failure in 2010 resulted in upgrades to the pumping system. Prior to the column failure incident at Mine Shaft A the incoming water capability from Mine Shaft B to Mine Shaft A was estimated at 255 l/s. This water was gravity-fed from 30 Level via the 31 Level column to the 32 Level pumping station. All the incoming water was stored on 32 Level on 1 Sub-vertical. The water had to be pumped from 32 Level up to 23-60 Level (APPENDIX B: SHAFT ENGINEER'S SLIDESHOW – PUMPING STRATEGIES).

The cold water flow feed underground at Mine Shaft A was sent down the column installed on 1 Sub-vertical at 100 l/s where it was used for mining, cooling, and so forth. After being used the water was filtered and treated by the settlers to be stored and pumped from the 32 Level pumping station. Water flow sent down 2 Sub-vertical was measured at 130 l/s and stored on 40 Level for pumping to 32 Level after use. Therefore, the total incoming water flow to 32 Level was 485 l/s⁴.

From 32 Level water was pumped to 23-60 Level and then via 2-5 Level to surface. The main shaft pumping columns installed between 32 Level and surface were rated to handle 500 l/s safely. The mine water was filtered by Mine Shaft A's surface filter plant and then pumped to Mine Shaft B's surface fridge plant for recooling as shown in Figure 2-9.

The cold water column from the Mine Shaft B fridge plant down the shaft is rated to handle a flow of 490 l/s in total. 3 Sub-vertical's cold water column is rated to handle a flow of 240 l/s. The remaining flow of 250 l/s is gravity-fed to Mine Shaft A using the 21 Level pipeline where the water is stored in the 23 Level service dam at Mine Shaft A, then used again⁴.

⁴R. Pretorius, Interviewee, *Shaft Engineer, KDC East Thuthukani Shaft*. [Interview]. 21 Feb. 2012.

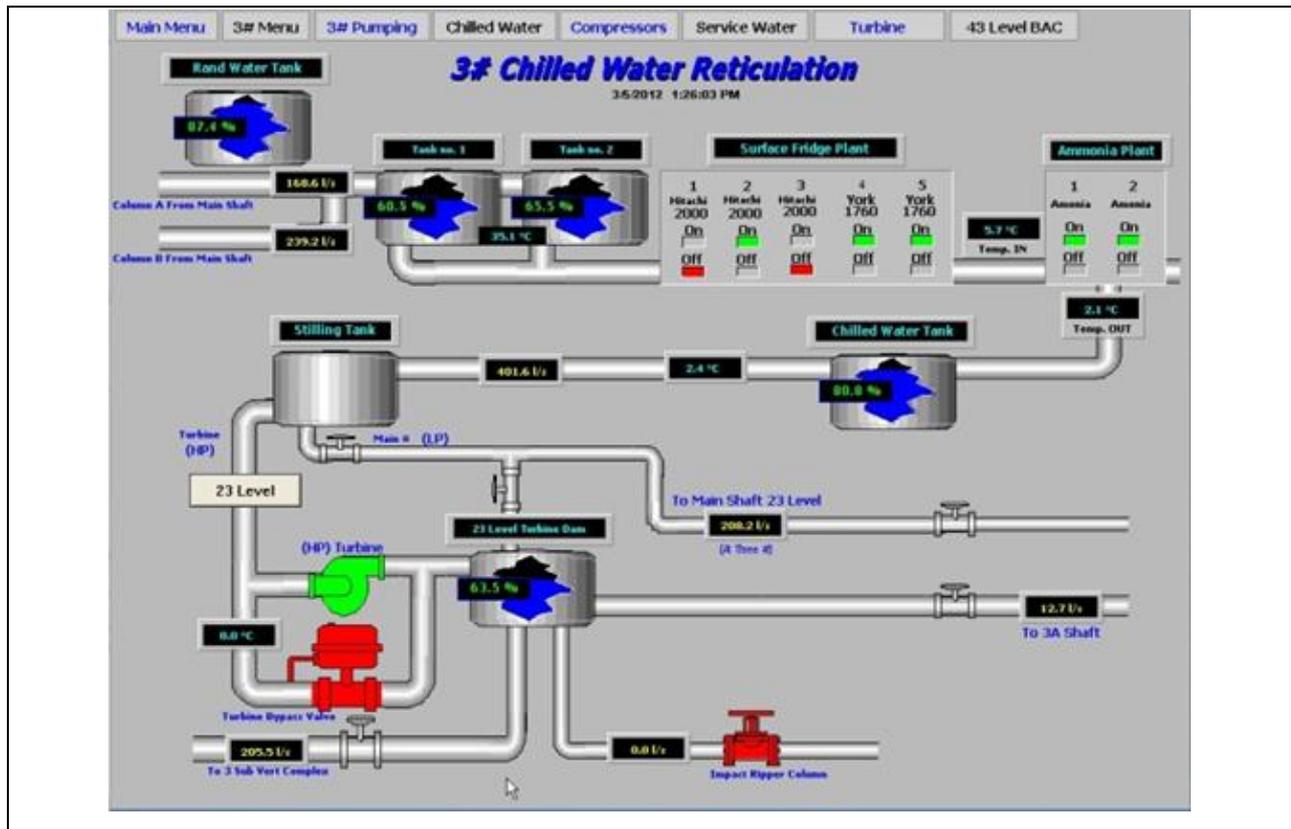


Figure 2-9: Cold water reticulation SCADA screen for Mine Shaft B

Emergency pipelines existed before the column failure. These emergency pipelines were not designed for everyday use. After the column failure at Mine Shaft A the emergency columns had to be used on a daily basis. Also, installing horizontal pipes on a level is less intensive than shaft installations due to the high logistical impact and extreme safety risks. If installations are done in the shaft, the cage cannot be used for travel between levels.

The first transfer pumps to be used daily were transfer pumps to Mine Shaft D at 190 l/s. This forced Mine Shaft B to only gravity-feed 180 l/s to Mine Shaft A as transfer to Mine Shaft D had to accommodate water pumped at 10 l/s to drain the 2 Sub-vertical Shaft's bottom. One high-pressure pump was installed on the higher 39½ Level as a backup to prevent future floods at Mine Shaft A. The increased mine water caused Mine Shaft D pumping to increase from 300 l/s to 490 l/s.

Initially 190 l/s of water was pumped away from the shafts at Mine Shaft D as Mine Shaft A's 2-5 Level and 23-60 Level pumping stations were off-line and incoming water could not be pumped to surface at Mine Shaft A. The pumps and column to Mine Shaft D were upgraded to handle 250 l/s enabling a flow of 550 l/s to be pumped out at Mine Shaft D. The incoming water from Mine Shaft B could now be increased to a flow of 240 l/s.

The transfer pumps to Mine Shaft E were installed to handle a flow of 50 l/s via the stopes from Mine Shaft A. This caused an increase in pumping capacity from 244 l/s to 294 l/s. The initial water figures pumped at Mine Shaft E was rated for a flow of 186 l/s of fissure water and 70 l/s of mine water. Mine Shaft E's primary task is to pump fissure water located in the complex. This is essential for the survival of the complex due to large underground lakes situated in the Westonia district (Lippmann-Pipke, et al., 2011).

The underground water body, known as the Witwatersrand Basin, is located within the Archaean Kaapvaal Craton of South Africa. The basin is located around the Vredeford Dome with the north-eastern axis stretching approximately 320 km and the north-western axis stretching 160 km, with the intersection over the dome. The deepest samples taken by Lippmann-Pipke et al. were measured at up to 3 540 m, thus proving the existence of large water quantities in the Westonia district (Lippmann-Pipke, et al., 2011).

The next upgrade to the pumping network was the installation of two 315 mm columns from Mine Shaft A to transfer water to Mine Shaft C using three transfer pumps. The additional rated flow of 250 l/s enabled Mine Shaft A's pumping to be restored to normal. Service water could now be sent underground at 100 l/s on 1 Sub-vertical and at 130 l/s on 2 Sub-vertical thus restoring the full production as prior to the column failure. The total rated flow from 23-60 Level to neighbouring shafts was estimated at 550 l/s.

The engineering team had to prevent future incidents at Mine Shaft A and a 305 mm transfer column to Mine Shaft E was installed increasing the total rated flow from 50 l/s to 130 l/s. This enabled the 23-60 Level pumping station to transfer water quantities of up to 630 l/s to other shafts in the complex ensuring 100% production could be achieved on 1 Sub-vertical and 2 Sub-vertical and adding a 26% safety factor to the previous 500 l/s.

As the pumping of water was restored the engineering team installed new columns in the main shaft so that the 2-5 Level pumping station and the 23-60 Level pumps to surface could be recommissioned. Two new columns were installed to enable Mine Shaft A to pump 500 l/s through each column, totalling 1 000 l/s. Due to dam capacity on 23-60 Level some water was still transferred as seen in Figure 2-4.

2.4. AUTOMATED CONTROL INTERVENTION

During the DSM intervention the most popular control methodology encountered was the manual control of pumping systems. Due to lack or failure of infrastructure manual control is done via telephone from the surface control room. Pump operators underground can only see the pumps and dams on their levels making them dependent on the surface control room operator.

Pump operators underground know the pumps on the level and starts and stops each pump based on the number of pumps required by the control room. Pumps are not always cycled properly (Pelzer, Richter, Kleingeld, & van Rensburg, 2009) causing certain pumps to run more frequently than others, thus increasing wear and decreasing the mechanical efficiency of the pumps.

Failure to open a discharge valve on the delivery side of a pump could cause a pump to be started against a closed valve (Pelzer, Richter, Kleingeld, & van Rensburg, 2009). Starting and running a pump against a closed valve could cause the water in the pump to evaporate. The pump will run too hot causing damage to the pump by increased wear and tear (Sulzer Pumps, 2010; Decatur Professional Development, 2012).

Overheating and vibration of bearings can cause pumps to cease and can be invisible to the naked eye. HMI and SCADA interfaces assist in monitoring these safety conditions correctly (Pelzer, Richter, Kleingeld, & van Rensburg, 2009; Ning, Cheng, & Wu, 2011). Bearings can be replaced before failure preventing damage to pumps. Temperature probes and vibration monitoring show real-time bearing conditions and will alarm if irregular levels are reached. The PLC will trip the pump before catastrophic failure occurs.

Savings depend on human skill and ability. If the control room operator fails to prepare dams to accommodate the peak periods, pumps cannot be stopped, increasing the total electricity cost for the day. When the system is automated calculations can be done using logic and measured variables making the decision to stop or start pumps more accurate (Pelzer, Richter, Kleingeld, & van Rensburg, 2009; Davidson, 2007).

When comparing manual with automated systems the automated systems achieved 96% of the simulated savings. Manual interventions only achieved 60% of the expected savings making the automated intervention by far a more desirable solution for the managing of electrical energy on cascading pump systems for deep-level gold mines (Pelzer, Richter, Kleingeld, & van Rensburg, 2009).

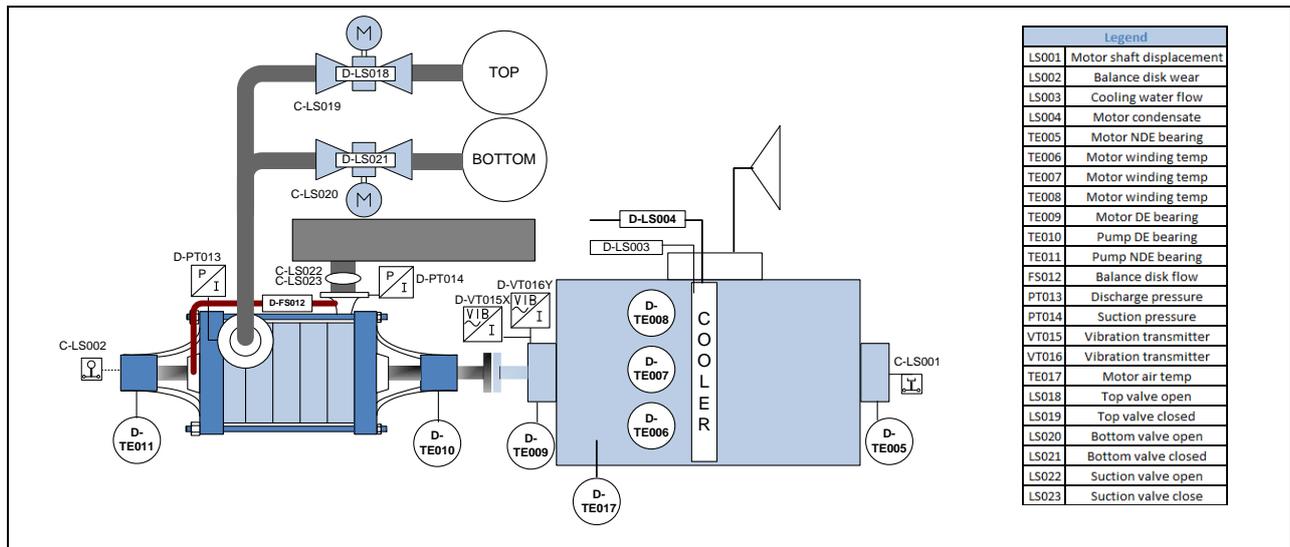


Figure 2-10: Typical pump and motor critical instrumentation (Schoeman, Van Rensburg, & Bolt, 2011)

Automated control was done from the surface control room. Instruments were installed on all the pumps to ensure that each pump could be started and stopped safely. This was done to comply with the Mine Health and Safety Act (President's office, 1996 (revised 2009); Department of Minerals and Energy, 2008). The automation process required installation and commissioning of the equipment listed in Table 2-6, Table 2-7, Table 2-8, Table 2-9 and Table 2-10.

Table 2-6: Control instrumentation (Zoli, 2012)

System control instruments	Purpose
Plant programmable logic controller (PLC)	Monitors environmental conditions and feeds data to surface where the data is analysed and used to control the underground pumps.
Machine PLC	Monitors a single pump and is programmed to automatically start and stop that pump safely. Any alarms or trips are sent through the fibre-optic network to the SCADA in the surface control room.
PowerLogic® ION7300 and ION6200 power meter (Schneider Electric, 2010; Schneider Electric, 2010)	Measures the voltage and current on each phase to give feedback on power, phase, voltage, current, and so forth. The mine requested use of this meter as each meter has a unique IP address and data could be imported to their existing ION database (Schneider Electric, 2010; Schneider Electric, 2010).

Control instrumentation was linked to surface using a fibre-optic network. The signal was converted by a copper-to-fibre switch underground and sent to surface via fibre-optic network. Fibre-optic network was used because the communication distance was beyond the maximum rated range of 100 m (for copper network cable using RJ45 connectors). Each device communicated with other devices using a Profinet protocol through a wired industrial Ethernet connection (Pigan & Metter, 2008).

Table 2-7: Motor instrumentation (Zoli, 2012)

Motor control instruments	Purpose
Winding temperature (blue, red and white phases)	Monitors each of the three windings in the motor to ensure that coils do not overheat and damage the motor.
Air temperature	Measures the air temperature to determine the environmental temperature inside the motor's protective housing and prevents overheating of the motor.
Drive end (DE) and non-drive end (NDE) bearing temperatures	Monitors bearing temperatures after installation on the white metal bearing's housing of the electrical motor. The bearings can overheat due to the friction that is caused by pressure on the driveshaft.
Shaft displacement proximity switch	Monitors the position of the rotor running on the white metal bearings according to the magnetic running centre of the rotor. If the motor is not running at its magnetic centre the balance disk wear on the pump may be worn out. If the balance disk is worn, the pump does not run at its peak efficiency.
Bearing vibration transmitter	Measures bearing vibration to ensure that the pump and motor is lined up and the shafts are not bent. Bearing vibrations can cause physical damage to the shafts or bearings.

All instruments on the motors had to be installed to monitor each motor so it could be controlled from surface. Each motor is monitored and controlled by its machine PLC and the start-up and stop sequence is programmed into the machine PLC. All safety monitoring instruments as mentioned in Table 2-6 and Table 2-7 must be in a safe state before the motor can be started to drive its high-pressure pump.

Table 2-8: Pump instrumentation (Zoli, 2012)

Pump control instruments	Purpose
Balance disk wear switch	Trips the pump if the pump reaches the end of its lifetime due to wear from long-term use.
Balance disk flow transmitter	Moves as the pump efficiency deteriorates to restrict the water flow. If the pump has to be reconditioned the balance disk flow rate decreases causing the pump to trip when a critical condition is reached.
Discharge pressure transmitter	Monitors water pressure. The water pressure in the discharge side of the pump should be in the order of 10 MPa or 100 Bar. This ensures that the pump is not pumping into an empty column.
DE and NDE bearing control temperature	Monitors bearing temperatures after installation on the white metal bearing's housing of the pump. The bearings can overheat due to the friction that is caused by pressure on the shaft.
Suction pressure transmitter	Ensures that the pump does not run dry as this could damage the impellers.

Pump control instruments	Purpose
Bearing vibration transmitter	Measures bearing vibration to ensure that the pump and motor is lined up and the shafts are not bent. Bearing vibrations can cause physical damage to the shafts or bearings.
Mine water flow switch	Ensures that water flows into the pumps and prevents the pump from running dry. The mine water flow switch is installed on the suction side of the pump.

On each of the dewatering pumps the machine PLC monitors the pump and motor simultaneously to ensure safe operation. Any alarm or trip condition is displayed on the local human-machine interface (HMI) and is transferred to the surface to be represented by a mimic object on the control room SCADA screen. An alarm condition will stop the pump in a controlled manner by closing the discharge valve first preventing damage to the column. Trips are more critical than alarms and will stop the motor instantly and then close the valve.

Table 2-9: Environmental feedback (Zoli, 2012)

Environmental control instruments	Purpose
Dam level indicator	Monitors dam levels to ensure the correct number of pumps is running to compensate for the inflow of water into the dam.
Column pressure transmitter	Monitors the water pressure in the column between two levels. When low pressure is encountered, a column may have failed.

Each of the dams was previously fitted with an ultrasonic level transmitter. These transmitters were not functioning correctly on all levels and it was required to replace the dam level transmitters as the automatic control depends on the accuracy and reliability of the dam level feedback. The pumps were controlled based on the upstream and downstream dam levels. Minimum levels would cause stoppage of all the pumps and maximum levels would cause starting of the maximum allowable pumps.

Table 2-10: Actuator feedback signals (Zoli, 2012)

Actuator feedback signals	Description
Actuator status	A healthy status is preferred and errors can be detected on the actuators.
Fully open	Each actuator was tested and this digital feedback signal gives a true value if the valve is 100% open.
Fully closed	Each actuator was tested and this digital feedback signal gives a true value if the valve is 0% open, thus 100% closed.
Torque trip	If objects are stuck in the valve and the actuator reaches its maximum torque limit it will cause the valve to stick. The actuators trips on torque to prevent damage to its motor. To reset this state the valve had to be driven in the opposite direction to reset the torque trip state.

Actuator feedback signals	Description
Power failure	In case of a power failure on the actuator this digital signal will give a true feedback signal.
0 - 100% control position to actuator	The control actuator can be programmed to open or close the valve to a predefined percentage based on the pressure, flow or motor ampere. The control is programmed using a feedback proportional-integral-derivative (PID) loop.
Feedback on the valve position	The present valve positions are monitored using an analogue 4-20 mA signal. Ranging from 0–100%.

The feedback from each actuator is essential as the manufacturer's guarantee on a pump will be annulled if a pump is started against a closed discharge valve as this may damage the pump (Sulzer Pumps, 2010). An error on the actuator has to trip the pump to prevent damage to the pump. Starting or stopping of a pump requires the machine PLC to control the discharge valve. When the valve and actuator reaches an open percentage of 8% to 10% the motor is started or stopped.

The discharge valves' open range differs for each pump depending on the valve specifications, the check valve (non-return valve) installed and pump characteristics. When stopping the pump the head pressure from the pump column is supported by the check valve. The check valve has to close with an audible yet controlled thud to ensure that the valve is seated firmly; else it will leak causing differential pressures on the gate of up to 12 MPa.

Control philosophy

Each pumping system investigated was dynamic and the pump control was based on changes made to the pumping schedule for each shaft. The schedule required various inputs received via the fibre-optic network from the machine PLCs and the plant PLCs underground. Internal system tags were programmed to comply with prescribed system limitations. The basic system flow chart for altering the pump schedule is shown in Figure 2-11.

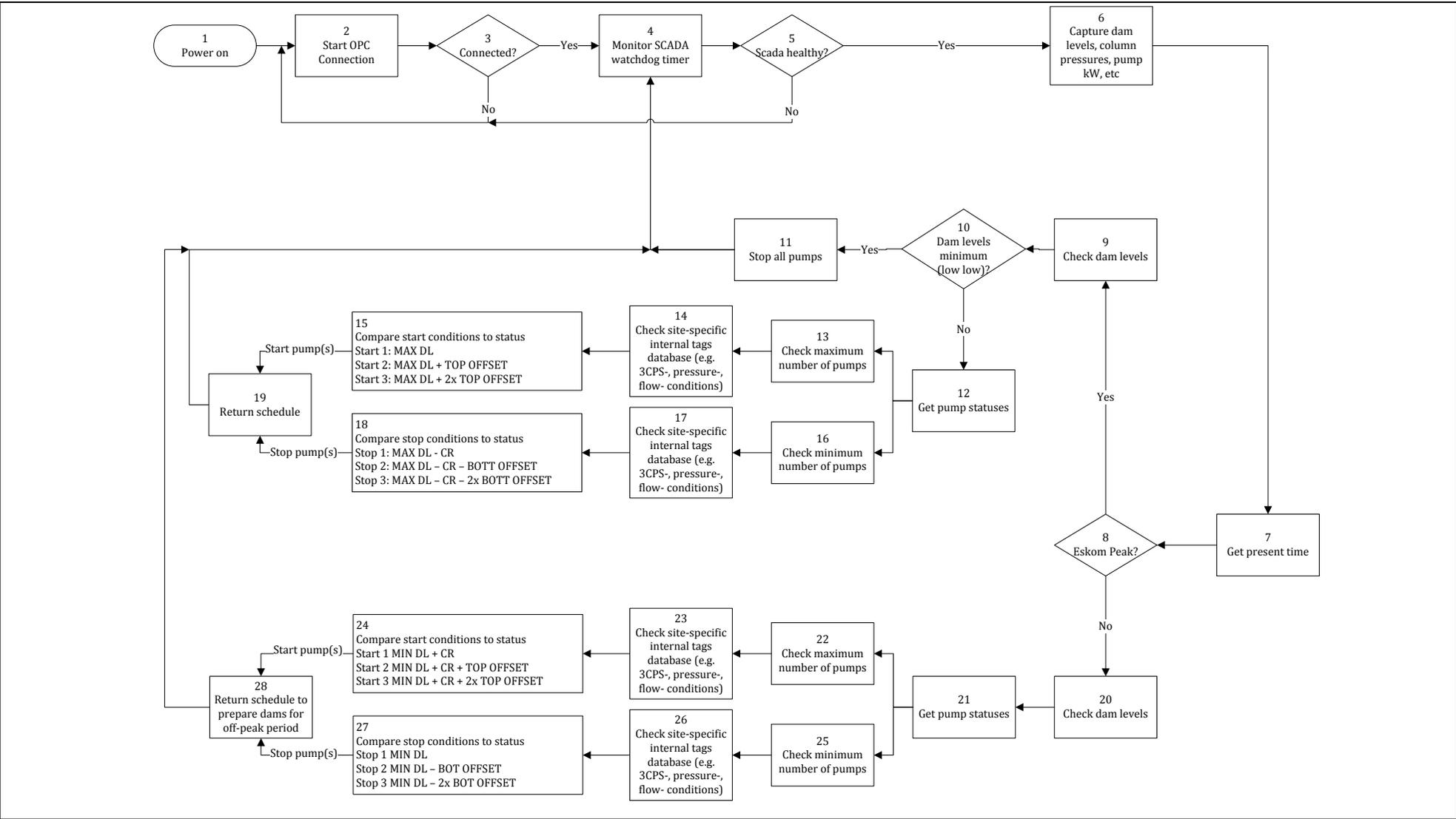


Figure 2-11: Pump control flow diagram

The pump schedule will determine the number of pumps that is scheduled to run based on the present dam levels on the upstream and downstream dams. Looking at the availability of the pumps within the controlled group of pumps, the control will either increase the number of pumps; or decrease the number of pumps running. The number is continuously monitored and the schedule is changed to adapt to the required pumping capacity on each level.

The site-specific control is achieved by interlocking site-specific conditions. The internal tag manager permits direct access to the process tags for unique site-specific manipulation and control. The internal tags are created according to the requirements of the application. The internal tag manager is shown in below in Figure 2-12.

Tag	Type	Value
InternalTag DE- PumpGroupIII-PumpGroupIII 23-60 to 2-5-Status	Memory	0.00
InternalTag DE- PumpGroupIII-PumpGroupIII 2-5 to Surface-Status	Memory	0.00
InternalTag DE- PumpGroupIII-PumpGroupIII 23-60 to 7#-Status	Memory	0.00
InternalTag DE- PumpGroupIII-PumpGroupIII 23-60 to 4#-Status	Memory	0.00
InternalTag DE- PumpGroupIII-PumpGroupIII 32 to 23-60-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P1-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P2-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P3-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P4-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P5-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P6-Status	Memory	0.00
InternalTag DE- Pump-L2-5_P7-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P1-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P2-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P3-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P8-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P9-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P10-Status	Memory	0.00
InternalTag DE- Pump-L40_P1-Status	Memory	0.00
InternalTag DE- Pump-L40_P2-Status	Memory	0.00
InternalTag DE- Pump-L40_P3-Status	Memory	0.00
InternalTag DE- Pump-L40_P4-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P7A-Status	Memory	0.00
InternalTag DE- Pump-L23-60_P7B-Status	Memory	0.00
InternalTag DE- Pump-L32_P1-Status	Memory	0.00
InternalTag DE- Pump-L32_P2-Status	Memory	0.00
InternalTag DE- Pump-L32_P3-Status	Memory	0.00
InternalTag DE- Pump-L32_P4-Status	Memory	0.00
InternalTag DE- Pump-L32_P5-Status	Memory	0.00
InternalTag DE- Pump-L32_P6-Status	Memory	0.00
InternalTag DE- Pump-L32_P7-Status	Memory	0.00
InternalTag DE- Pump-L32_P8-Status	Memory	0.00
InternalTag DE- Pump-L32_P9-Status	Memory	0.00
InternalTag DE- Pump-L32_P10-Status	Memory	0.00
InternalTag DE- Pump-L32_P11-Status	Memory	0.00
InternalTag DE- Pump-L32_P12-Status	Memory	0.00
InternalTag Total kW	Programmable	0.00
InternalTag DE- Dam-40 Level Dam (2ML)-Level	Memory	60.08
InternalTag sv 32 bot	Stable Value	60.09
InternalTag Name	Programmable	60.09

Figure 2-12: Internal tag manager

The screen shot of an internal tag manager (Figure 2-12) was taken from Mine Shaft A. The tags are manipulated using the tag editor. The tag editor seen in Figure 2-13 has a script-based interface to enable the programming of internal tags. The programming script is based on basic “if-else” statements that return the programmed result.

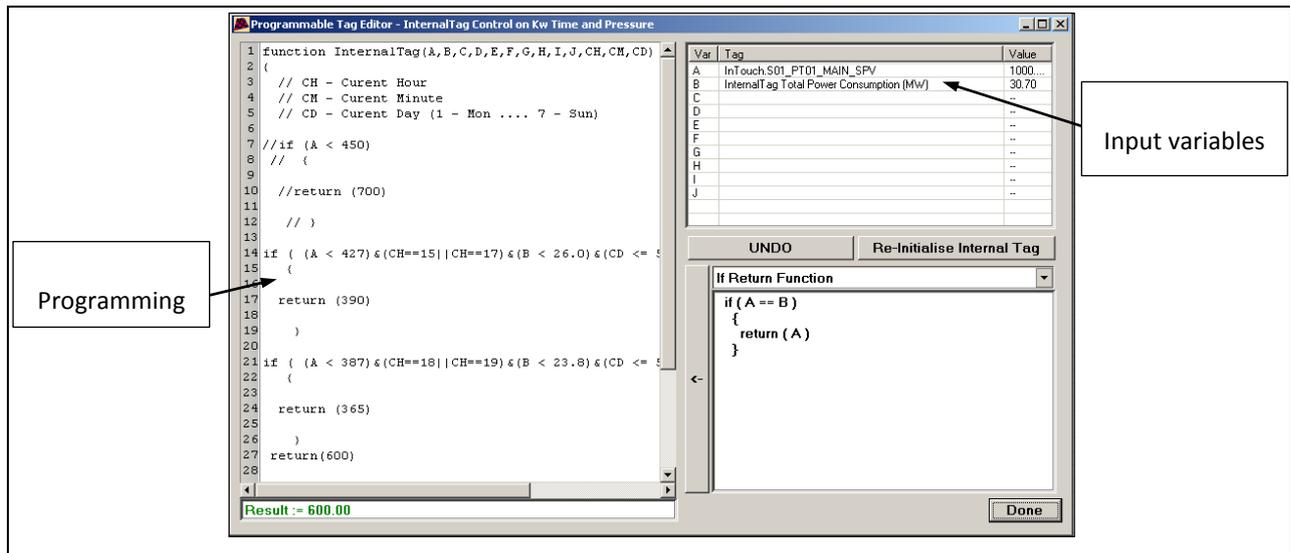


Figure 2-13: Internal tag editor script interface

Pump automation projects differ in the control strategy implemented at each site. The PLC tags are used in conjunction with internal tags to restrict or allow certain scenarios:

- Restricting the number of pumps pumping into the same column simultaneously.
- Minimising the number of pumps running during the comeback load to prevent a demand spike and tripping the breaker.
- Interlocking or specific control as specified by the foreman or shaft engineer can be programmed using the internal tag editor.

The pump group controller controls a specified group of pumps in an allocated pumping station. The controller in Figure 2-14 displays the number of scheduled pumps and the running status of the grouped pumps controlled by this controller. The control mode can also be seen; in this case the controller is in manual mode and the control room operators will control the underground pumps.

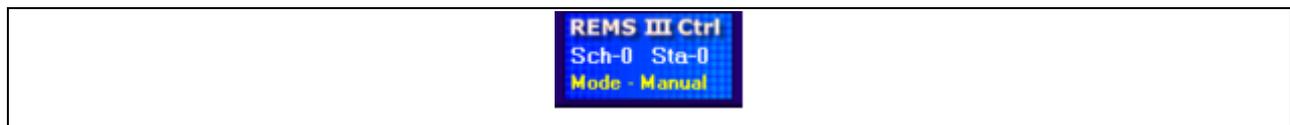


Figure 2-14: Pumps group controller

If the scheduled pumps and the total running status are equal the controller will neither stop nor start a pump when in automatic control mode. The controller interface is used for basic information inputs/outputs. Tags are monitored by the controller based on certain control parameters, such as dam levels, to cycle the pumps in the correct order. The controller interface is shown in Figure 2-15.

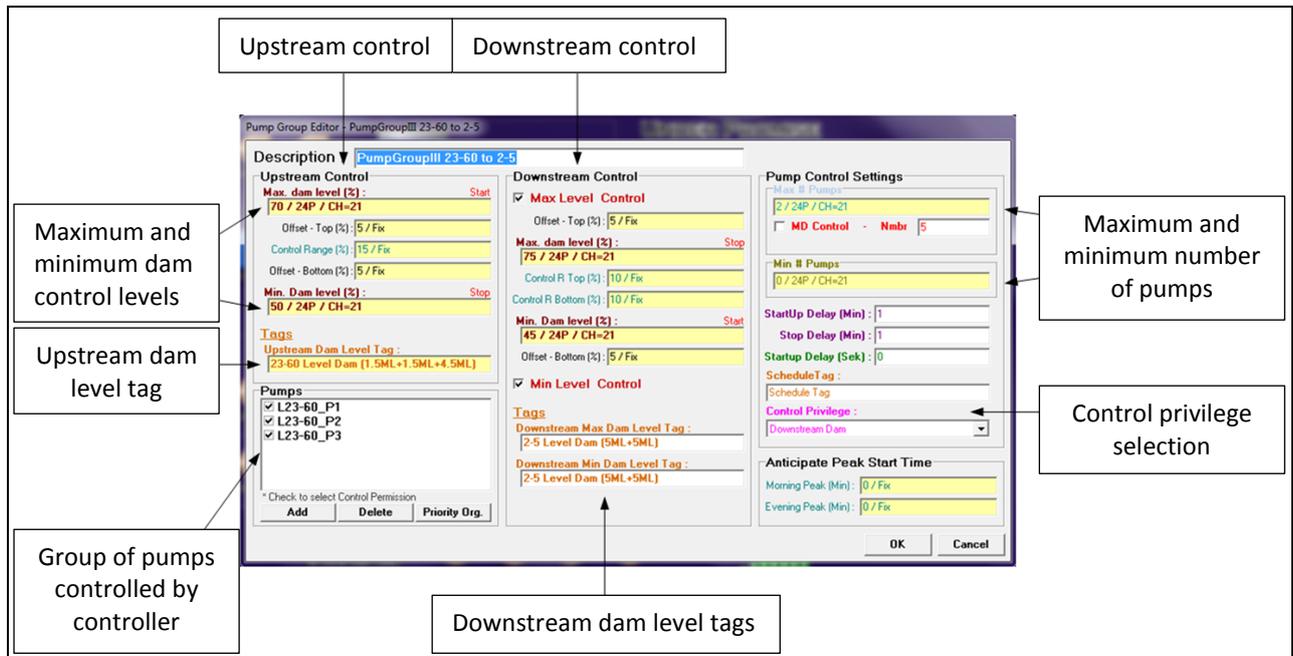


Figure 2-15: Pumps group controller interface

The control range and offset in Figure 2-15 are programmed into the controller using the controller rules. The controller determines whether the current hour falls in the peak, standard or off-peak TOU periods and alters the pump schedule accordingly. The controller will ensure that the dam levels are kept safely within a minimum and maximum specified value range.

The values of each of the dam level items described above are used for control. Each has a specific value based on percentage of the dam level. These values are captured in the controller and determined by the system characteristics - for instance hot water dam inrush flow, pump discharge flow, and so forth. Control calculations during Eskom off-peak and standard TOU periods are as follow:

Starting of pumps

- Start 1 → MIN DL + CR
- Start 2 → MIN DL + CR + TOP OFFSET
- Start 3 → MIN DL + CR + 2x TOP OFFSET

Stopping of pumps

- Stop 1 → MIN DL
- Stop 2 → MIN DL – BOT OFFSET
- Stop 3 → MIN DL – 2x BOT OFFSET

During the morning and evening peak TOU periods the control range and offset are used by the controller to determine the schedule using the maximum dam levels. Pumps are stopped if possible and dam levels are monitored during the Eskom peak TOU period to prevent overflow. The opposite applies during the Eskom off-peak and standard TOU periods and the controller controls on the minimum dam level. Control calculations during Eskom peak TOU periods are as follow:

Start

Start 1 → MAX DL

Start 2 → MAX DL + TOP OFFSET

Start 3 → MAX DL + 2x TOP OFFSET

Stop

Stop 1 → MAX DL - CR

Stop 2 → MAX DL – CR – BOTT OFFSET

Stop 3 → MAX DL – CR – 2x BOTT OFFSET

The dam object, as seen in Figure 2-16, displays the dam level and water temperature of a specific dam. The water temperature is optional and is not installed in any of the mine shafts in the case study. The dam level tag is captured in the dam editor and used for indication as well as for control via the pump controller. The dam editor is shown in Figure 2-17.



Figure 2-16: Dam level control object

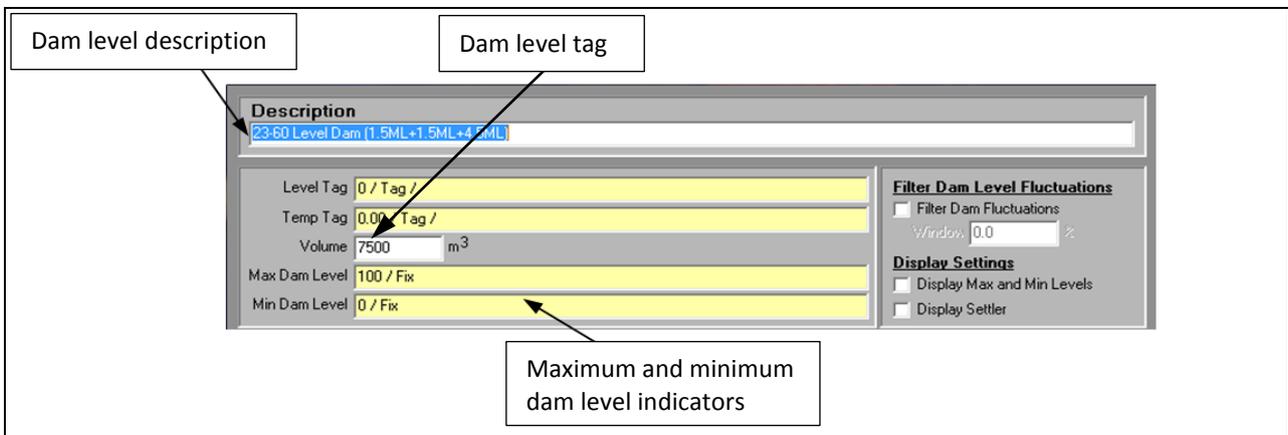


Figure 2-17: Dam level control object editor

The pump object displays the status of the pump using colours: red indicates a pump is off-line, orange indicates a pump is in standby and ready to start, and green indicates the pump is running. Each pump is added to the pump group using the pump controller to enable the stopping and starting of the pump according a schedule and the pump’s priority. The pump object is shown in Figure 2-18 and the pump object interface in Figure 2-19.



Figure 2-18: Pump object



Figure 2-19: Pump object editor

2.5. CHAPTER SUMMARY

Each shaft was described based on its water reticulation system. The description included incoming water from neighbouring shafts and outgoing water to neighbouring shafts. Different possible pumping scenarios were discussed and all the safety signals required on a pump were identified. The instruments required for the safe stopping or starting of pumps remotely were identified (See 2.4). An automated control procedure was introduced using mimics (SCADA objects in the form of interactive pictures used to monitor and control pumps) and a control philosophy was discussed using the various components.

Chapter 3

3. ANALYSIS OF RESULTS

3.1. PREAMBLE

A simulation model for the case study was developed, tested and verified. Various pumping procedures were investigated using the simulation model. Electrical energy savings were quantified and were verified by independent institutions. The advantages of automated control were compared to manual control philosophies.

3.2. MEASURED RESULTS AND SAVINGS GENERATED

Baselines

Before the savings generated could be quantified, a baseline was determined for each shaft. The load-shifting strategy requires that electrical power usage over a 24-hour period has to remain energy neutral (den Heijer & Grobler, The measurement and verification of the combined impact of energy efficiency and load shifting on mine pumping projects, 2006). Thus savings generated were calculated over a 24-hour period and each shaft's baseline was scaled to evaluate the running power profile of that shaft.

The baseline for each shaft had to be plotted and each simulation verified by comparing it to the actual running data that was collected from each shaft. The most recent data available was used only if it was accurate and complete. The partial missing data would not affect the simulation in any way as corrupt data would be discarded.

For each shaft the baseline data would be included for weekdays, Saturdays and Sundays as compiled from data measured and verified by measurement and verification (M&V) teams (den Heijer & Grobler, The role of measurement and verification in Eskom integrated demand management's performance contracting initiative, 2011). This study only includes weekdays as the maximum financial saving could be realised by managing electrical energy usage during peak TOU periods. The electrical energy demand on the Eskom network was also higher during weekdays. Reducing strain on the network would prevent load-shedding (van der Zee, Kleingeld, & Mathews, 2012; Hammons, Musaba, Mari, & Naidoo, May 2010).

Each simulation was run for one week using actual power data obtained from each mine. During working Saturdays a similar load-shift strategy was attempted. During the off Saturdays and Sundays the service water sent down from surface was closed manually. If service water was not closed for a particular shaft, the dam levels were maintained at safe percentages. The minimum number of pumps were started to maintain safe levels on each pumping level.

Savings calculation

Savings generated during the peak periods were recovered in the standard and off-peak TOU periods as each pumping strategy was neutral for electric energy. In each case similar quantities of water were pumped each day. Due to load-shifting, the running power profile could not be compared to the baseline directly. The baseline was scaled to the running power profile so savings could be quantified (den Heijer & Grobler, The measurement and verification of the combined impact of energy efficiency and load shifting on mine pumping projects, 2006; Marais, Kleingeld, & van Rensburg, 2011).

In each case the scaling process was calculated using Microsoft Excel® (Microsoft, 2012; Liengme & Ellert, 2009). An example of the spreadsheet can be seen in Figure 3-1. The savings were calculated using Excel’s Solver (Microsoft, 2012; Arora, 2012). Solver manipulated the applied scale (marked as A in Figure 3-1). The difference between the scaled baseline and the running power profile was calculated for each hour (marked as C in Figure 3-1). The scale (A) was manipulated to ensure the average load-shift (B) tended to 0.

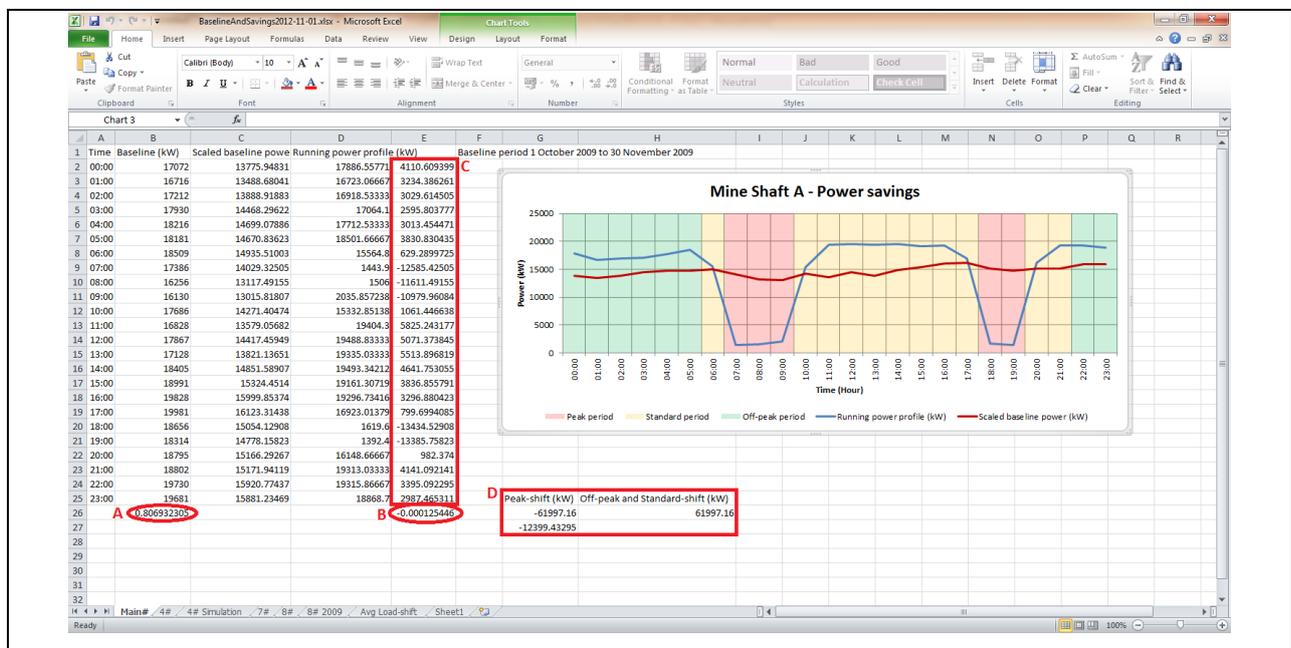


Figure 3-1: Savings calculated using Microsoft Excel® (Microsoft, 2012; Liengme & Ellert, 2009)

The calculation was verified by calculating the total load shifted from of the peak period and comparing the total comeback load. The peak TOU hours and the remaining hours were multiplied with 5 and 19 respectively to determine the total load above and below the baseline, thus the total load-shift. The calculation was accepted as correct if the two figures were equal. The savings (D) were quantified as the average electrical energy per hour saved during the peak periods.

Mine Shaft A results and savings

Mine Shaft A has the highest pumping capacity in the whole complex at 50.8 MW. As previously discussed, Mine Shaft A dewateres all of Mine Shaft B's water. Mine Shaft B is situated on a small hill resulting in a higher total pumping head. Mine Shaft A's baseline can be seen in Figure 3-2. The three profiles seen in Figure 3-2 represent the average weekdays, Saturdays and Sundays. The data was measured from 1 October 2009 to 30 November 2009.

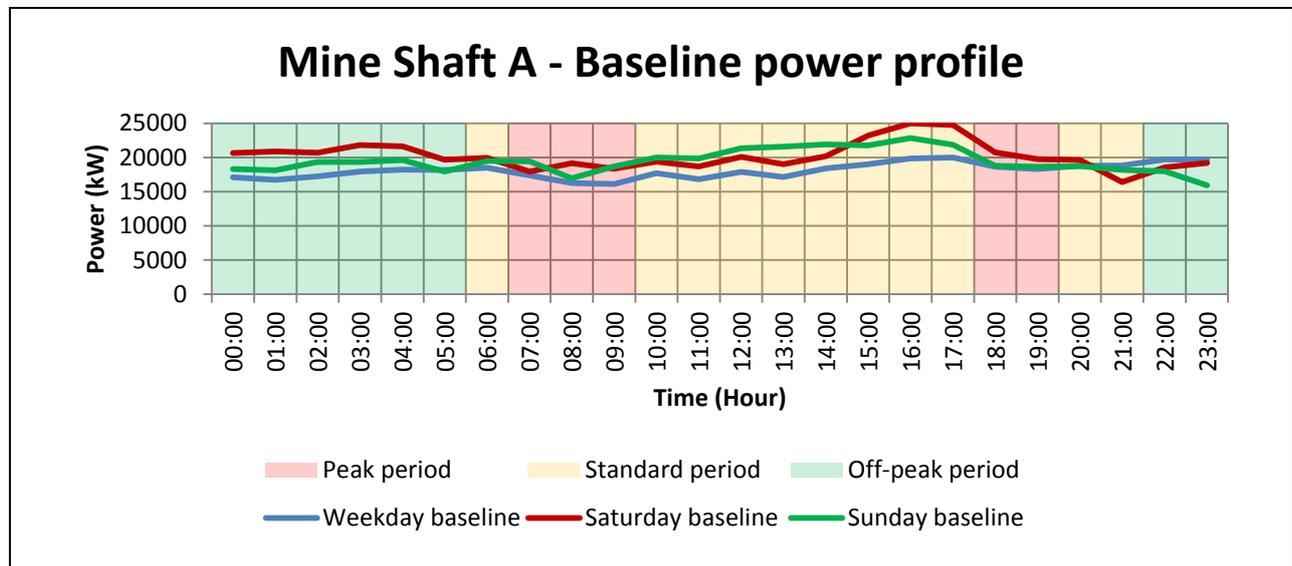


Figure 3-2: Mine Shaft A baseline power profile

The actual running power profile can be seen in Figure 3-3 with a scaled weekday baseline. Data for 2012 was compiled from the actual pump statuses and multiplied by the installed capacities to determine the running power profile. Each weekday was averaged per hour and plotted in Figure 3-3. Data was collected from 2 July 2012 to 13 September 2012. Data loss occurred from 7 - 12 July 2012.

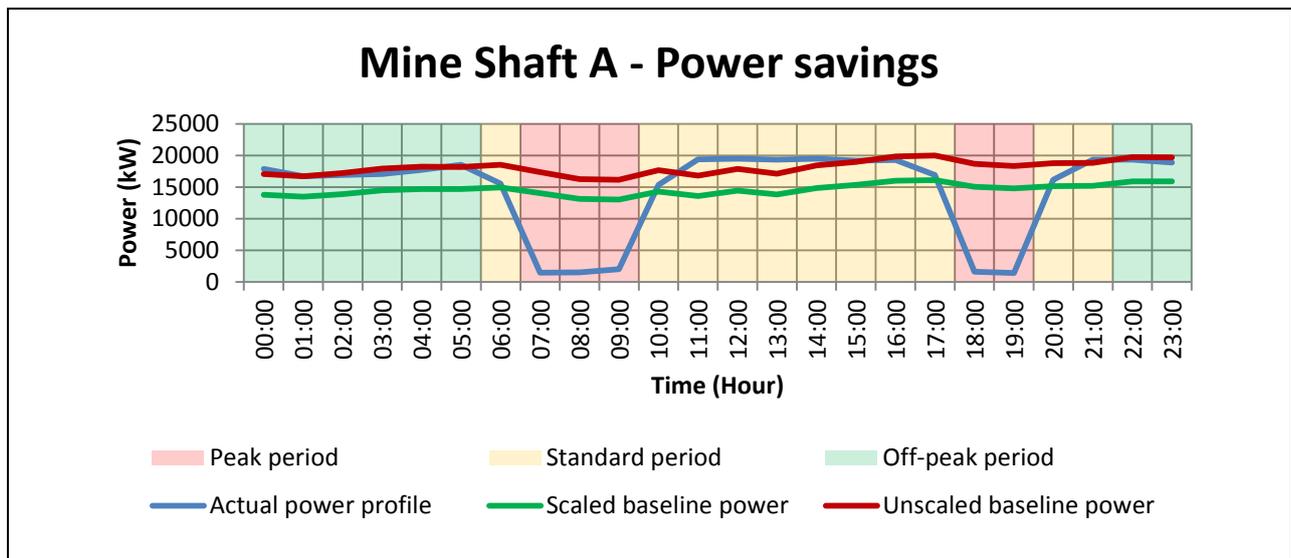


Figure 3-3: Mine Shaft A savings generated

If data loss occurred in any of the data captured for the shafts, data loss periods were disregarded and removed to ensure that accurate running power profiles were generated. Most of the data was collected using automatic logging: a logging interval of two minutes was used. In some cases systems were off-line and operators' logs had to be used. Data for Mine Shaft A was logged using the automatic logging system.

The savings generated can be seen in Figure 3-3. The calculated saving for Mine Shaft A was 12 399 kW load-shifted on average during the morning and evening peak periods. The total load shifted from the peak TOU period to the off-peak and standard TOU periods was 61 997 kW. The financial saving generated per annum totals R18,754,355.21 based on the Megaflex tariffs.

Mine Shaft C results and savings

The dewatering pumps at Mine Shaft C formed a critical part of the operations. As discussed earlier the aim was to completely remove compressed air and move towards a full hydropowered mining shaft. More water would be used than at any other shaft in the complex. Due to large water quantities the pump system was optimised to be able to safely maintain the higher pumping demand.

From the baseline captured no load-shift strategy was visible and the pumps were run as needed averaging 14 135 kW measured over a six week period. The baseline was compiled using data captured from 1 February 2007 to 15 March 2007. The data was averaged over each hour and was plotted for weekdays, Saturdays and Sundays in Figure 3-4.

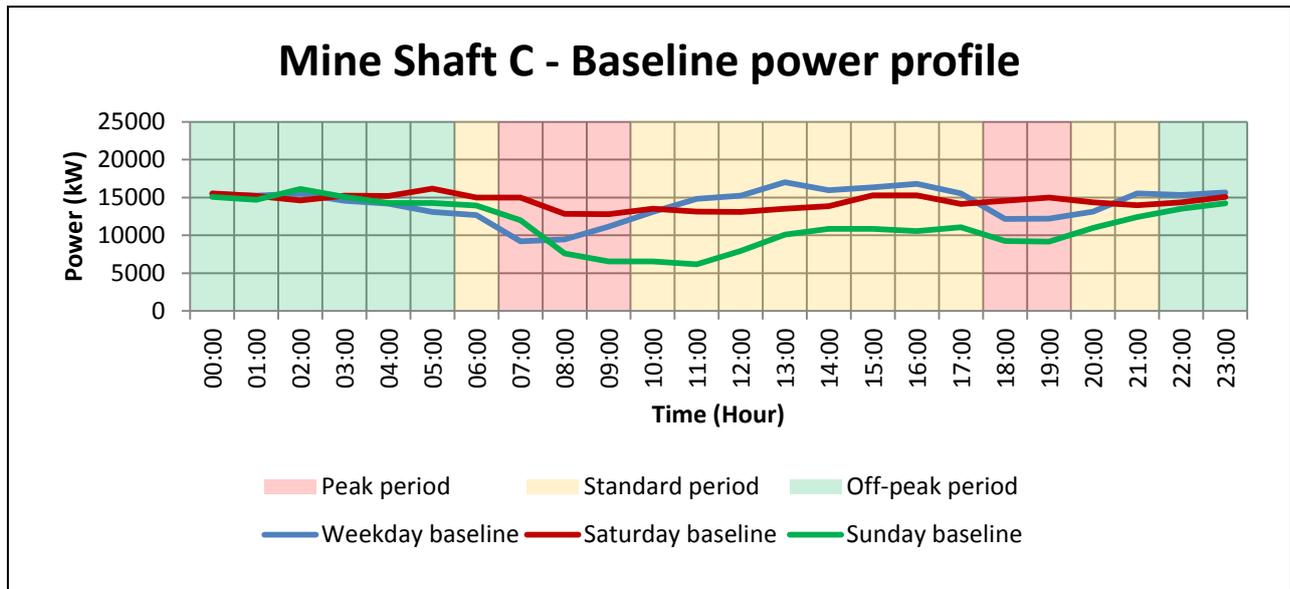


Figure 3-4: Mine Shaft C baseline power profile

The logged data proved to be corrupt due to network issues experienced on surface. Complete pumping stations were invisible on the surface SCADA and alternative data was collected to complete this study. The control room personnel provided hourly logs of pump running statuses. The data provided was dated 3 August 2012 to 25 September 2012. An hourly average running power profile can be seen in Figure 3-5.

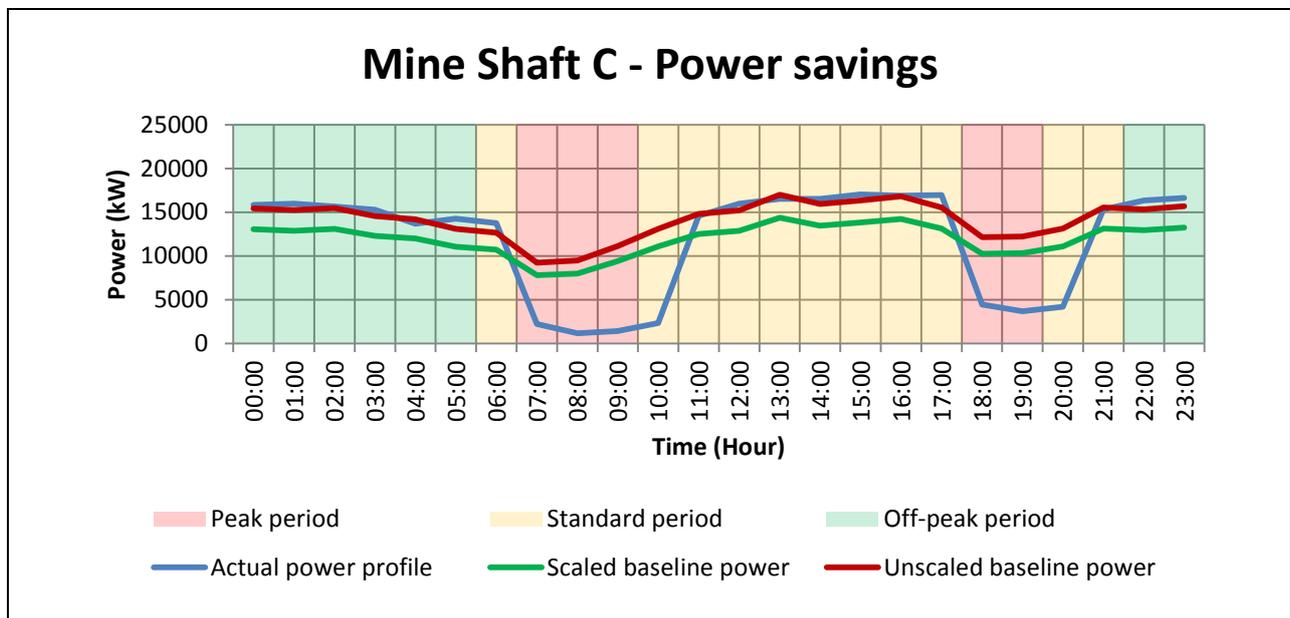


Figure 3-5: Mine Shaft C power savings generated

The saving generated was determined using a similar Microsoft Excel® spreadsheet to the sheet used for Mine Shaft A. The baseline had to be scaled using Solver and resulted in a total load-shift of 32 818 kW. The saving generated during the morning and evening peak TOU periods indicated an average load-shift of 6 564 kW. The financial saving calculated using the Megaflex tariffs was R11,112,756.11.

The actual saving generated may be optimised by reducing the electrical energy usage in the evening peak period by attempting to stop all the pumps. In Figure 3-5 the running kilowatt is averaged at 4 066 kW meaning an optimal running power profile is not yet achieved using a manual load-shift strategy. The system can only be optimised when it is fully automated and controlled without operator intervention; except in emergency situations.

Mine Shaft D results and savings

The baseline for Mine Shaft D to measure the savings on the project was generated using several months' data. Data was captured from June 2008 to September 2008 and was averaged over each hour and plotted to indicate the weekday, Saturday and Sunday profile in Figure 3-6. The baseline power profiles were again verified by independent institutions assigned by Eskom (den Heijer & Grobler, The role of measurement and verification in Eskom integrated demand management's performance contracting initiative, 2011).

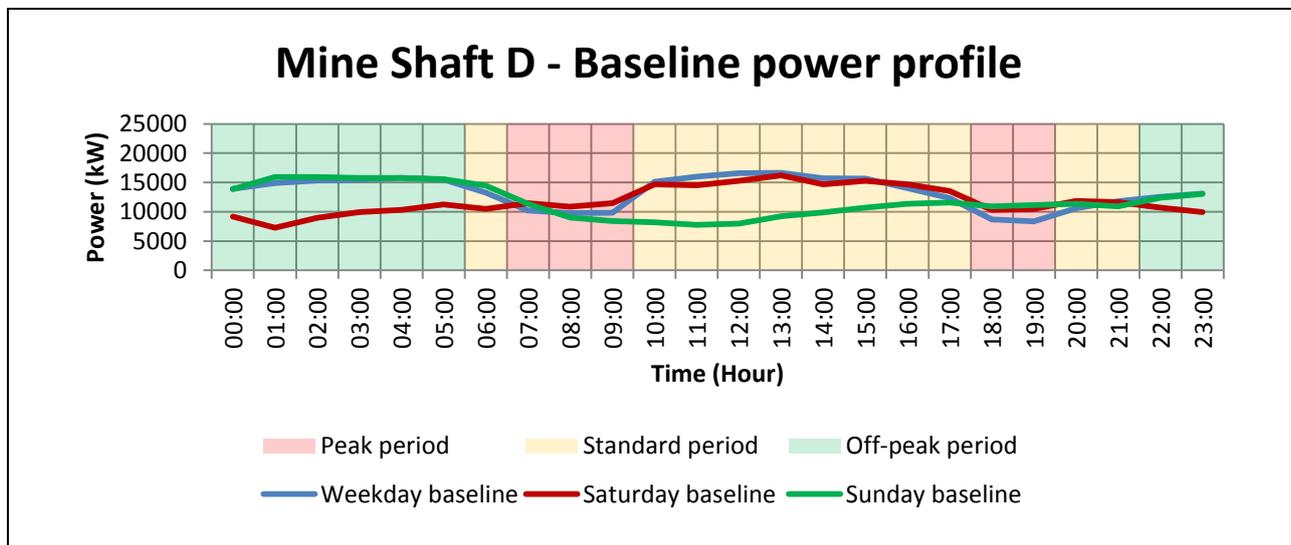


Figure 3-6: Mine Shaft D baseline power profile

The baseline for Mine Shaft D indicates that before the optimisation intervention a partial load-shift (a load-shift strategy was used but not optimised to achieve maximum financial reduction) was visible. The weekday load-shift can be seen in Figure 3-6. The pumping capacity was investigated and a larger load-shift was possible as indicated in Figure 3-7 - where the running power profile and scaled baseline were plotted on the same timescale. Data was collected from 1 January 2012 to 10 August 2012 with data loss experienced during 17 - 20 March 2012, and again during 28 - 31 March 2012.

The savings generated were calculated again using the Microsoft Excel® spreadsheet and resulted in an additional load-shift of 25 995 kW when compared the partial load-shift strategy. The new load-shift strategy generated a saving of 5 199 kW during the morning and evening peak TOU periods (as seen in Figure 3-7). This was also calculated by scaling the baseline using Solver. No data loss was recorded for Mine Shaft D. The financial saving generated was calculated at R7,594,941.60 using Megaflex tariffs.

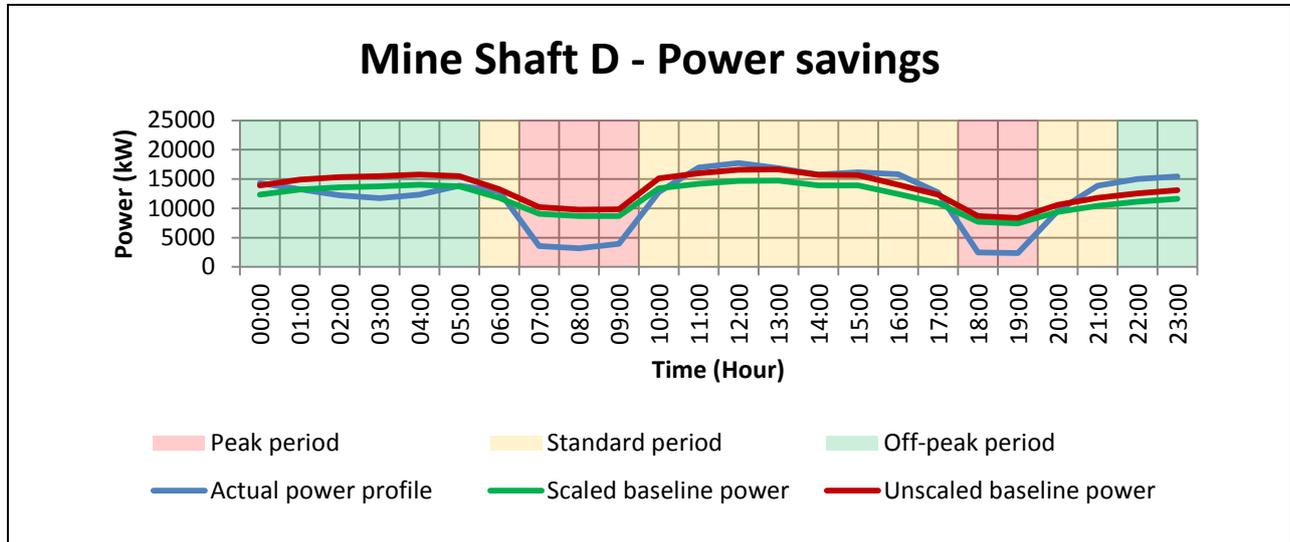


Figure 3-7: Mine Shaft D savings generated

A full load-shift strategy could not be followed on this shaft as 41 Level only has one settler. Due to the life expectancy of the mine it would not be financially viable to install a second settler. On 41 Level the single settler requires a minimum of one pump running at any time of the day⁵. If all pumps were stopped the settler could cause mud particles in the water, thus pump impellers could wear prematurely causing increased pump maintenance costs (Engin & Gur, 2001).

Mine Shaft E results and savings

The baseline used to measure the saving at Mine Shaft E also indicated a partial load-shift strategy and is plotted in Figure 3-8. A full load-shift was possible during 2009, but with the present high gold price old abandoned levels could be mined profitably again (24.com). The higher production demands more service water resulting in fridge plants being used through peak periods to cool enough water to fill the cascading dams in Figure 3-9⁶.

⁵R. Norman, Interviewee, *Engineering Manager Manyano Shaft, Masimthembe Shaft and Celemanzi Shaft*. [Interview]. 27 Jan 2012.

⁶P. Nel, Interviewee, *Electrical Foreman Masimthembe Shaft*. [Interview]. 25 Jul 2012.

The cascading dam system has several small service dams on each level servicing that the respective levels with service water. Each dam has a flotation device that controls the actuated valve on the column, feeding water from the dam above. Should the water level reach 50% or less the actuator opens the valve above, causing water to flow to the lower dam. In turn the upper dam's flotation device would open the next actuator closer to surface. This control strategy cascades through to the 3165 Level cold dam.

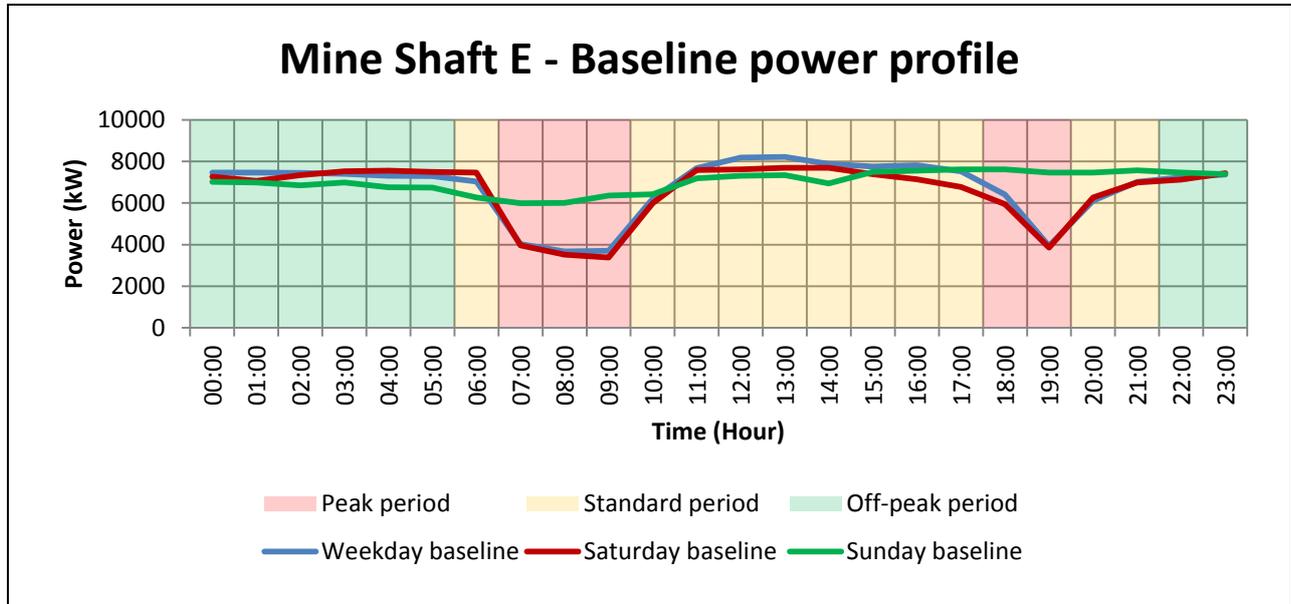


Figure 3-8: Mine Shaft E baseline power profile

The underground pump running statuses were used to compile the baseline for Mine Shaft E and to quantify the savings achieved. The data was taken for three months from 1 March 2007 to 31 May 2007. Weekdays, Saturdays and Sundays were averaged over each hour to form a 24-hour profile and plotted in Figure 3-8.

When the fridge plant was running the surface hot dam reached critical low water levels before the end of the morning and evening peak periods. To keep the dam levels stable and supply enough water to the fridge plant, one pump on 3165 Level and one pump on 23-60 Level were running during the peak periods. The two pumps running during peak TOU periods caused a similar running power profile than for the baseline period.

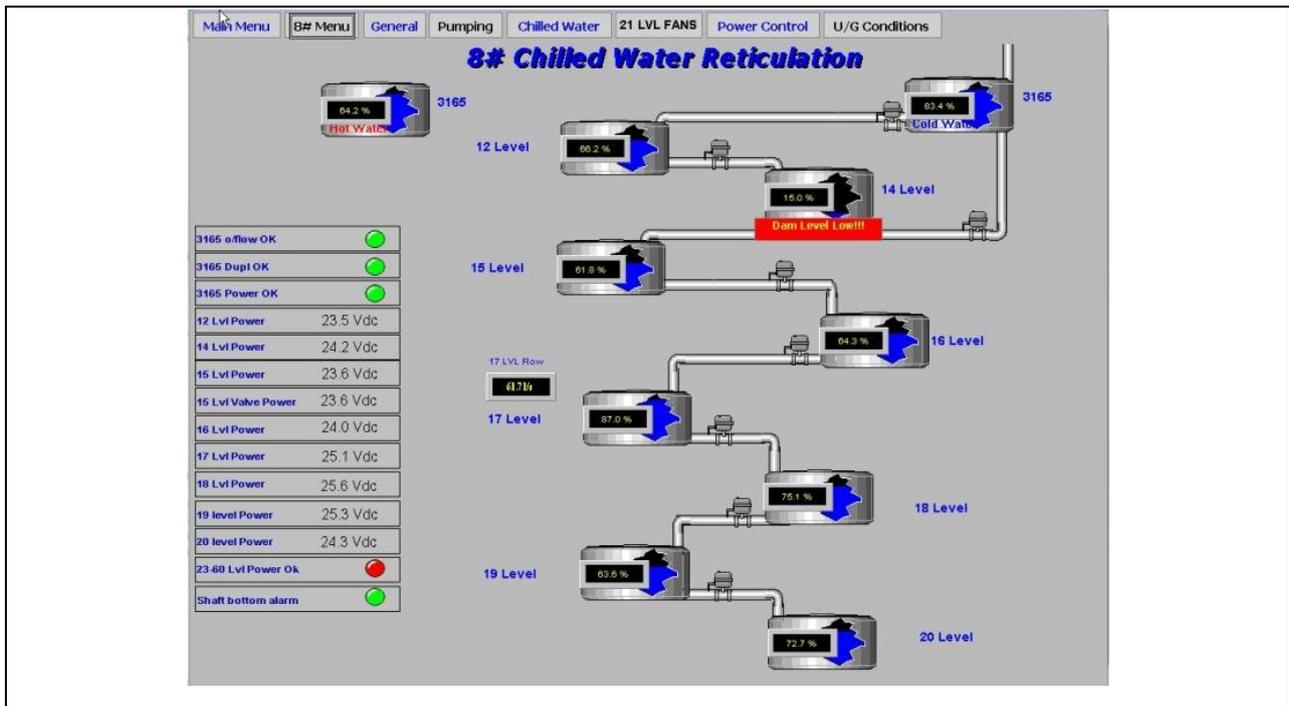


Figure 3-9: Mine Shaft E cascading dam system (service water)

During 2009 the surface fridge plant was not operational and a much larger load-shift was possible⁷. The saving during 2009 indicated a total load of 11 082 kW shifted from the morning and evening peak TOU periods to the standard and off-peak TOU periods. The saving from the load-shift indicated a 2 216 kW saving on average during the morning and evening peak periods. The running power profile for 2009 and scaled baseline were plotted in Figure 3-10.

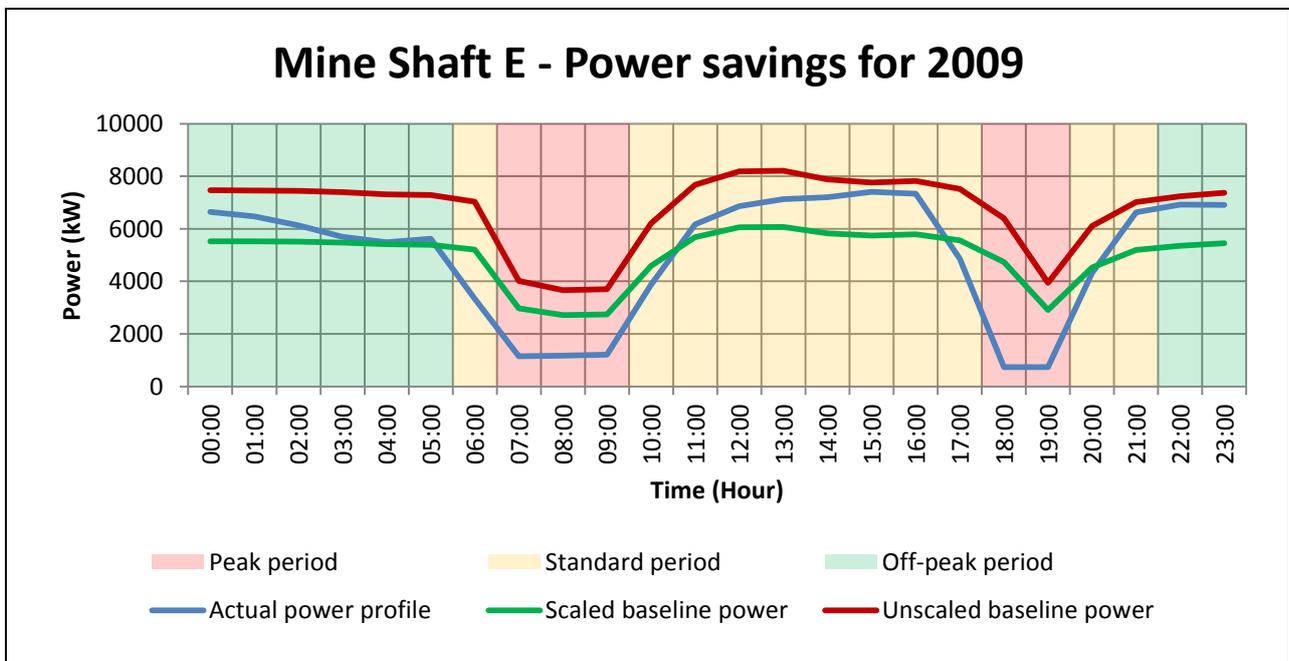


Figure 3-10: Mine Shaft E savings generated for 2009

⁷P. Nel, Interviewee, *Electrical Foreman Masimthembe Shaft*. [Interview]. 25 Jul 2012.

The present running power profile and baseline can be seen in Figure 3-11. No significant saving is visible from this graph. When calculating the saving using Microsoft Excel® and Solver, a total of 846 kW more than the baseline period was used. The higher usage during peak periods indicates an average saving loss of 169 kW. Data was collected from 1 January 2012 to 13 August 2012 to compile a running power profile, with no data loss recorded.

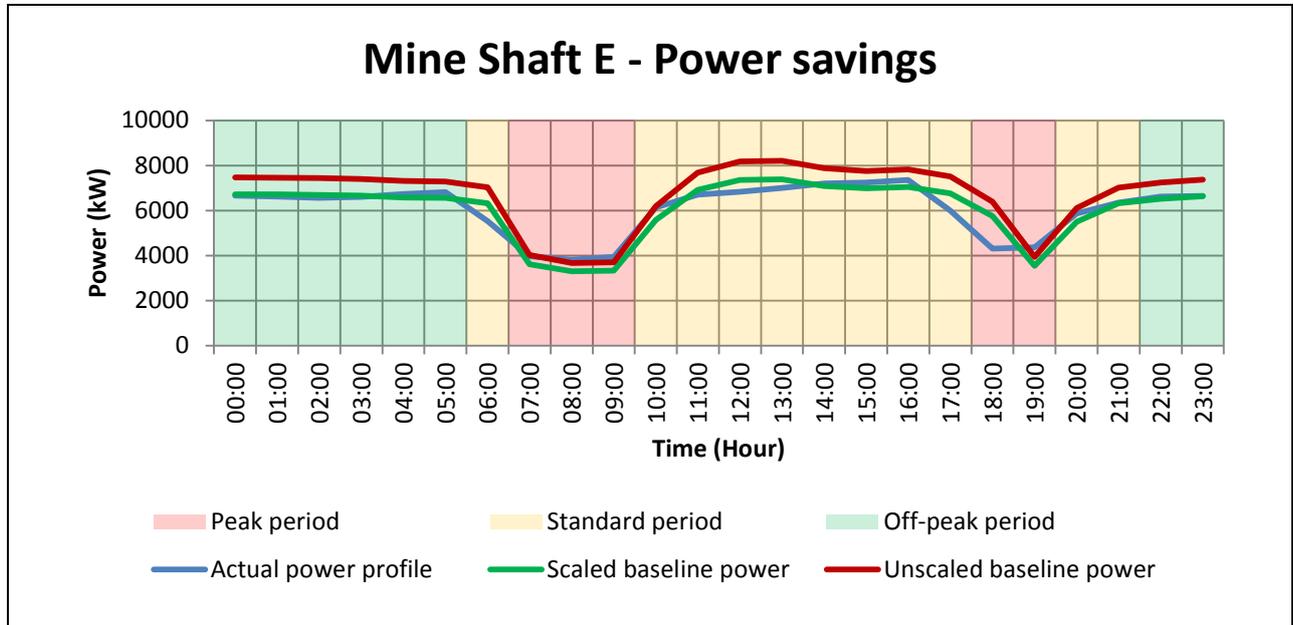


Figure 3-11: Mine Shaft E savings generated

The average power usage when scaling the baseline indicates that the electrical energy shifted to the peak period is 169 kW. Financial savings are still existent from the evening peak and standard TOU periods. This can be seen in Figure 3-12 when the baseline is not scaled. An average electrical energy efficiency of 674 kW can be seen when the actual running power is compared to the baseline power resulting in a financial saving of R1,806,376.53 per annum using Megaflex tariffs.

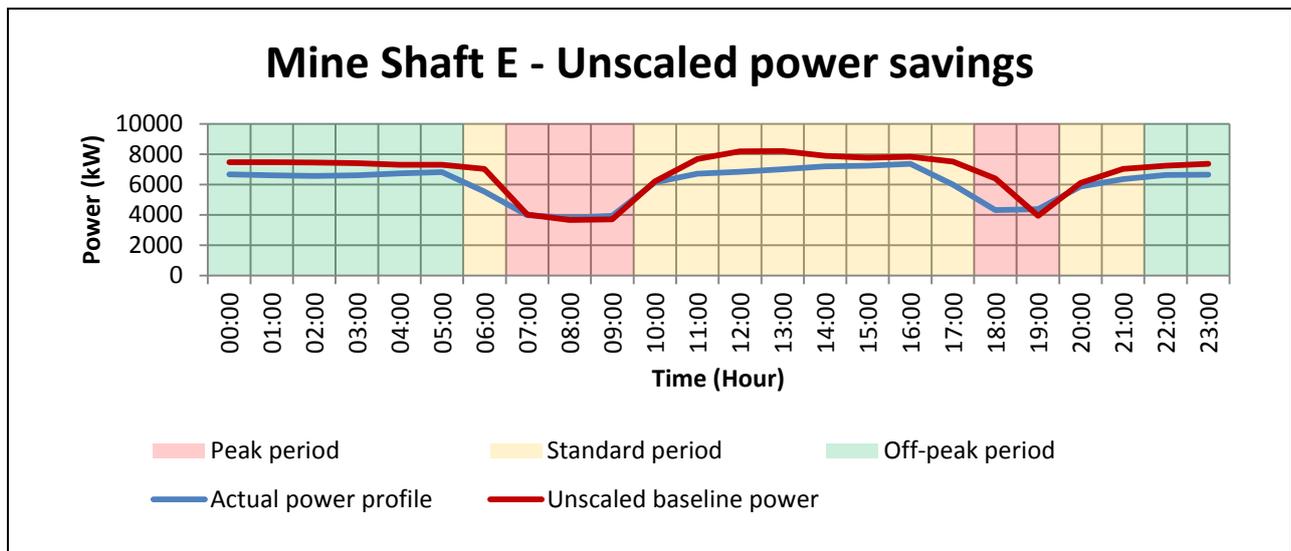


Figure 3-12: Mine Shaft E unscaled baseline and running power

3.3. SIMULATION RESULTS

Simulation scenarios and configuration

A software program was used to simulate the transfer of water between shafts. The influence on each dewatering pump system when water was transferred was also simulated. During the simulations two different pumping procedures were followed. The first procedure (Simulation X) required each shaft to pump its own mine water back to the surface.

The second simulation (Simulation Y) required neighbouring shafts to pump all Mine Shaft A and Mine Shaft B's water back to the surface. The 2-5 Level and 23-60 Level pumping stations to the surface were disabled. All the water used on 1 Sub-vertical Shaft and 2 Sub-vertical Shaft as well as the gravity-fed water from Mine Shaft B was collected on 32 Level and transferred to 23-60 Level.

It was expected that Simulation Y used less electrical energy as water was transferred from 23-60 Level to Mine Shaft C, Mine Shaft D and Mine Shaft E via transfer pumps using the underground pipelines. These transfer pumps use less power than the bigger cascading pumps as there is no head pressure to overcome. This is because the receiving dams on neighbouring shafts are on approximately the same level as the 23-60 Level transfer pumps to neighbouring shafts.

Each simulation was run for one week using actual power data obtained from the mine. To determine the electrical energy usage for the pumping system of the shaft only data from working weekdays was used. The cold water supply for each shaft was closed during off weekends. During working weekends the dam levels were controlled to maintain their present levels. Load-shifting strategies were followed over weekends, but no cost savings were realised.

The simulations are usually run in real-time so that actual operational conditions can be compared with the simulation results. Based on the time constraints placed on the study obligations, the two simulations for each mine shaft had to be completed over a shorter time frame. The time ratio was increased by 500%, where each real-time second represented 500 simulated seconds.

Simulated dam level controls were adjusted until the simulation results reflected actual data collected from each mine's pumping system. Several repetitions were completed to ensure that the simulation of each shaft reflected the actual mining operations. The simulations had to be within acceptable accurate limits before the pumping optimisation could be achieved.

Pump controllers for each group of pumps were connected to the monitoring components of an upstream and downstream control dam. Simulations were studied of the water transfer from the upstream dam through the pump column to the downstream dam, at the rated flow of each pump and power of each electric motor.

The upstream dam is located on the same level as the pumps. The downstream dam is either located on a higher level or underground at the receiving mine shaft. Each pumping station's control level was calculated using the dam level indication of each dam in the pumping station, multiplied by that dam's capacity to get the quantity of water in the dam. The total water quantity in the pumping station was then divided by the maximum capacity to determine the control percentage.

Mine Shaft A simulations

All the water used at Mine Shaft B is gravity-fed to Mine Shaft A via the pipeline located on 31 Level and pumped back to the surface at Mine Shaft A. The pumps at Mine Shaft B were not included in the simulation. These pumps would not change the electrical energy usage in the simulation of the complex and would be used at the same pumping intervals in both scenarios.

Figure 3-13 is a screenshot of the seventh minute, simulated during a morning weekday load-shift period. From this figure it can be seen that a full load-shift was attempted with the control dams located on each pumping station at safe operating levels. The surface dam capacity was simulated at 88.65% to ensure that the fridge plant at Mine Shaft B had enough water to operate at full capacity for the three hours of the morning peak period.

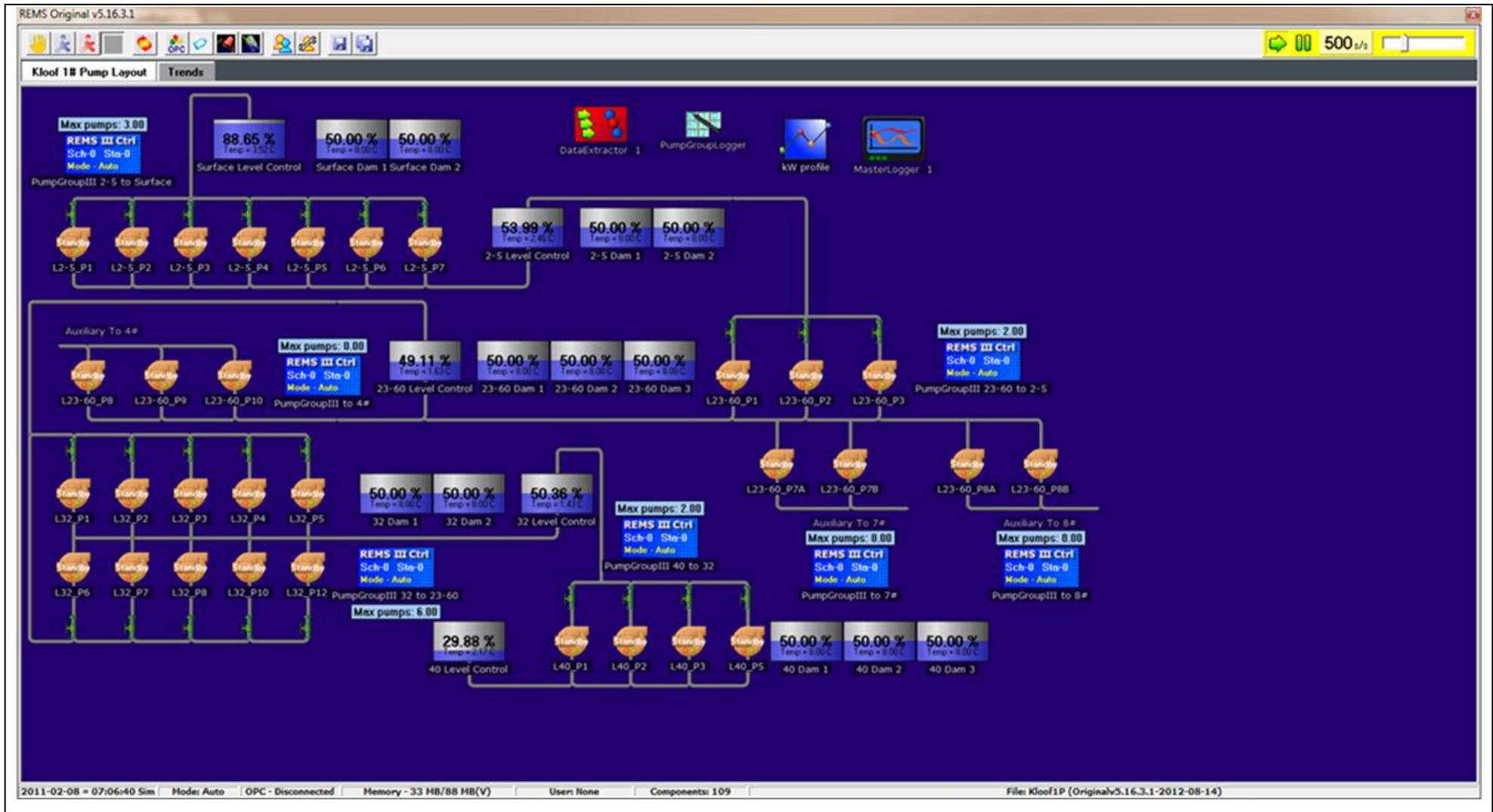


Figure 3-13: Mine Shaft A simulation model (de Lange, 2006; TEMM International, 2012)

The simulated power usage was determined by the sum of the running pumps' installed capacities averaged over each hour. The Mine Shaft A running profile, in terms of power usage for the two different simulations, can be seen in Figure 3-14. The area of each graph between the graph and the x-axis is the total power used over an average 24-hour period.

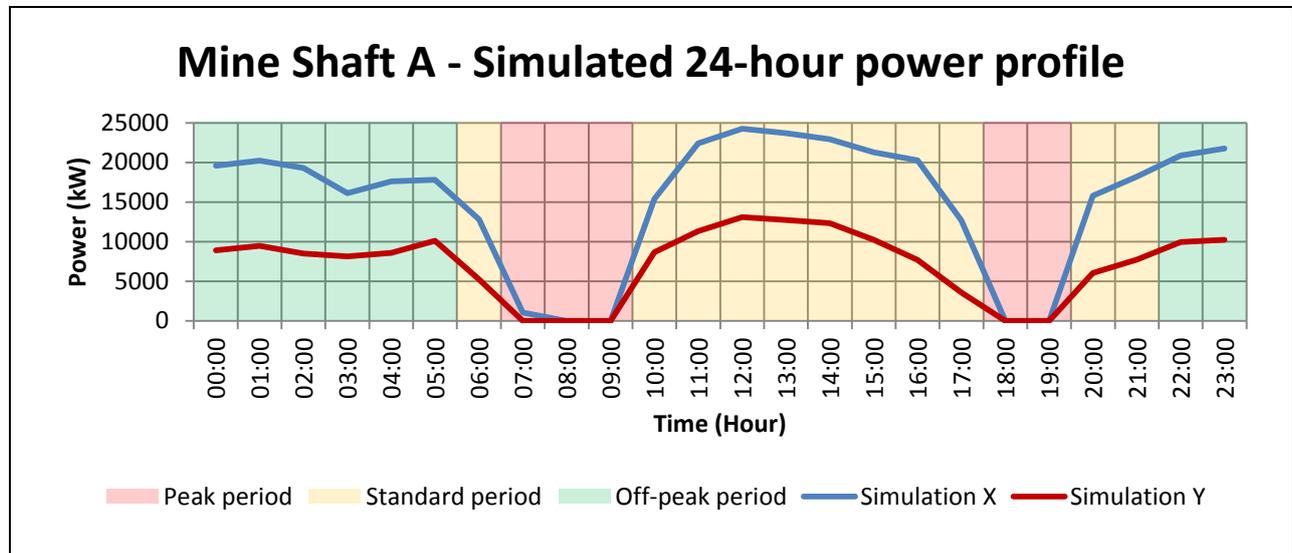


Figure 3-14: Mine Shaft A simulation – Running power profile

During Simulation Y the 2-5 Level pumping station and the three pumps feeding water from 23-60 Level to 2-5 Level were disabled. All the incoming water used on 1 Sub-vertical Shaft, 2 Sub-vertical Shaft as well as the gravity-fed water from Mine Shaft B was transferred to Mine Shaft C, Mine Shaft D and Mine Shaft E using the underground pipelines installed from 23-60 Level pumping station.

When comparing Simulation X with Simulation Y, the simulations indicate that there is a significant difference in electrical energy usage with Simulation X averaging 15 168 kW and Simulation Y averaging 7 192 kW. The simulations indicated that for Mine Shaft A, Simulation Y used 7 975 kW less electrical energy per hour than Simulation X.

The simulations indicated that less electrical energy will be used at Mine Shaft A when transferring water to neighbouring shafts. The expected financial saving for Simulation X was calculated using Eskom's Megaflex tariffs and the calculations resulted in a R18,307,338.75 saving per annum. Simulation Y predicted lower electrical energy consumption and a higher financial saving of R38,068,464.26 per annum.

Mine Shaft C simulations

The water demand of Mine Shaft C is much higher than at the other shafts due to the hydropowered mining equipment used for drilling (Hydro Power Equipment South Africa, 2012). The second simulation for Mine Shaft C had to include results from Simulation Y for Mine Shaft A. Thus, Simulation Y for Mine Shaft C pumped more water to surface than Simulation X to compensate for Mine Shaft A's incoming water. Figure 3-15 shows the simulation model used for Mine Shaft C.

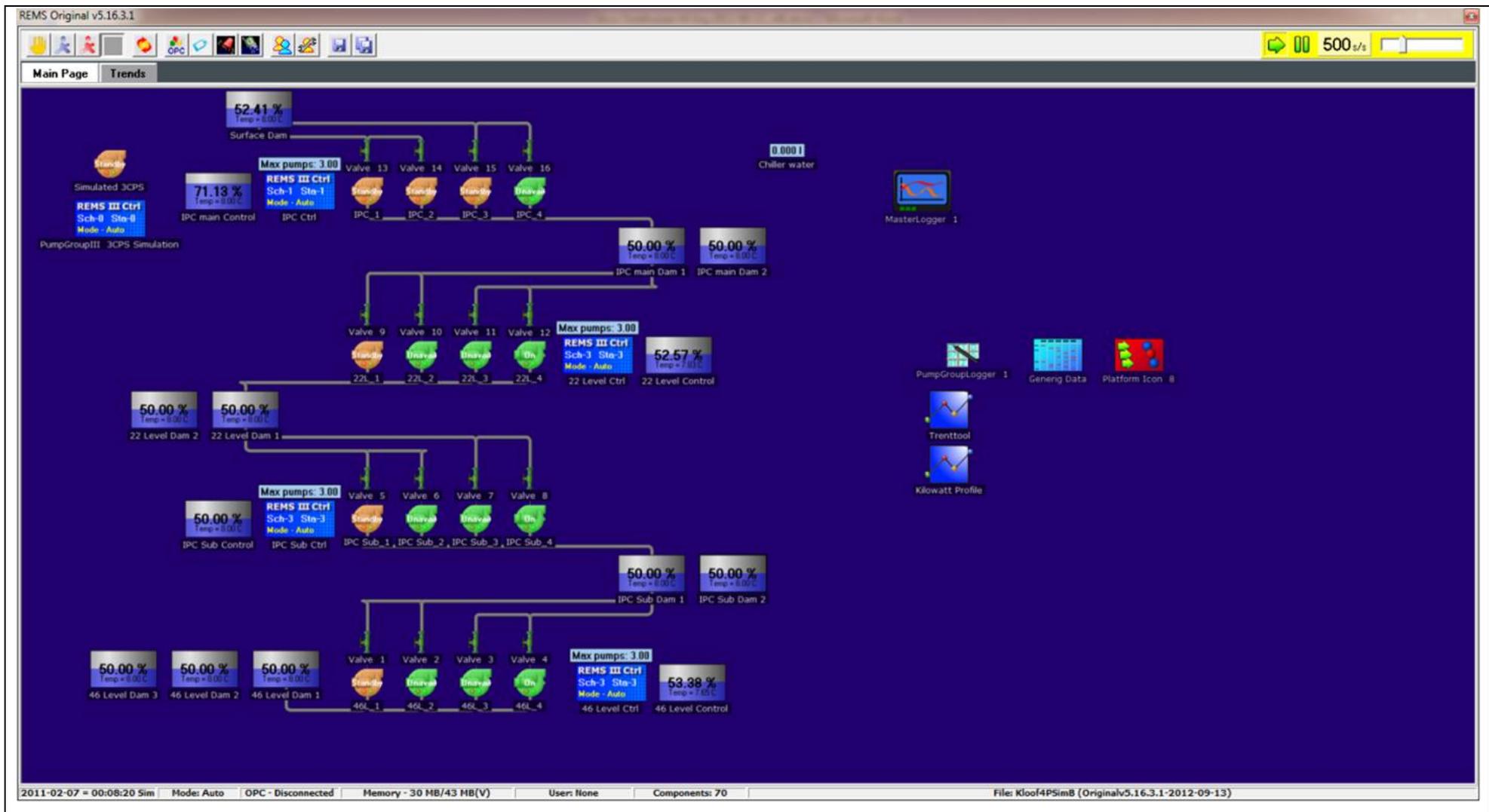


Figure 3-15: Mine Shaft C simulation model (de Lange, 2006; TEMM International, 2012)

Figure 3-16 shows the running power profile for Simulation X and Simulation Y. Simulation Y had a higher average running power profile than Simulation X over a 24-hour period. The higher electrical energy usage was caused by the incoming water on Mine Shaft C’s 22 Level; transferred from Mine Shaft A’s 23-60 Level pumping station.

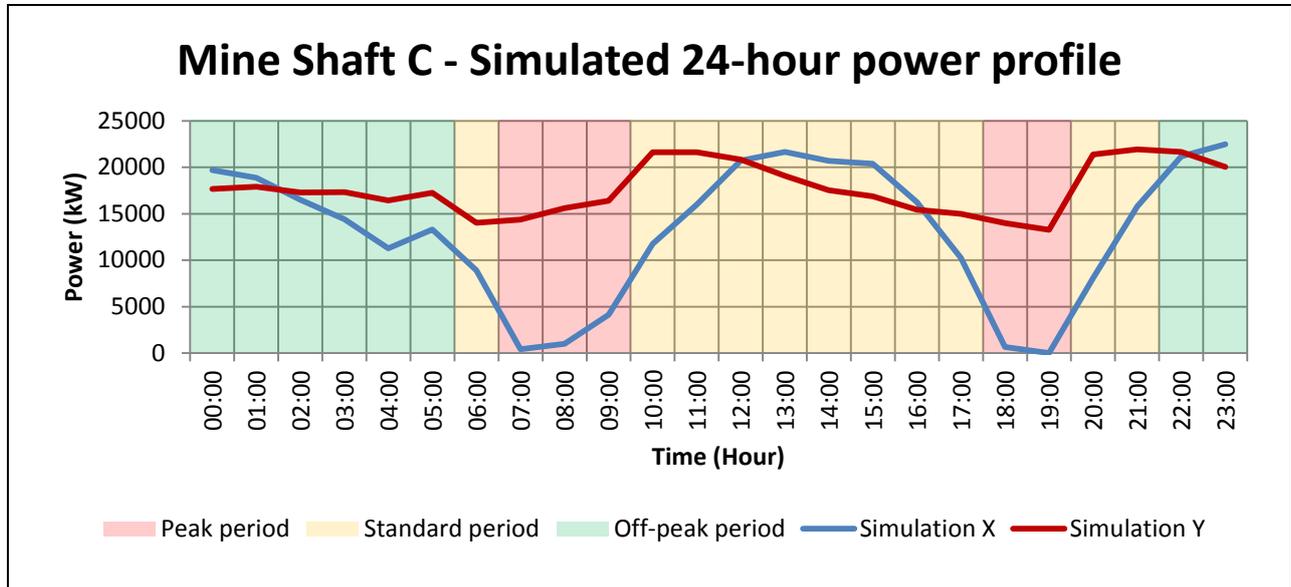


Figure 3-16: Mine Shaft C simulation – Running power profile

The running power profile for weekdays in Simulation Y resulted in an average electrical energy usage of 17 687 kW. This is higher than the 13 099 kW average simulated in Simulation X. The average incoming water from Mine Shaft A at 212 l/s, contributed to an extra 4 589 kW of electrical energy per hour. The extra electrical energy simulated for one week at Mine Shaft C was averaged per hour over 24 hours. Only the weekdays were accounted for in the calculation.

The load-shift that was done in Simulation X during the peak TOU was no longer possible in Simulation Y as there was more water present in the system. A minimum number of running pumps could be stopped during peak periods to prevent flooding of the work areas. Although some pumps were stopped during the peak TOU periods the Mine Shaft C financial savings will not reflect positively when water is transferred from Mine Shaft A as in Simulation Y.

The financial saving was calculated using Eskom’s Megaflex tariffs and the annual expected saving was R8,939,887.69. Simulation Y showed that if Mine Shaft A’s water was pumped out at Mine Shaft C a loss of **R11,520,437.98** would be encountered.

Mine Shaft D simulations

The simulation model for Mine Shaft D can be seen in Figure 3-17. Similar results were encountered in the simulation of Mine Shaft D as in Mine Shaft C. Incoming water from Mine Shaft A resulted in additional electrical energy used in Simulation Y for Mine Shaft C. The incoming water flow was simulated at 121 l/s from Mine Shaft A, resulting in a smaller electrical energy usage increase in Mine Shaft D's Simulation Y than experienced in Mine Shaft C's Simulation Y.

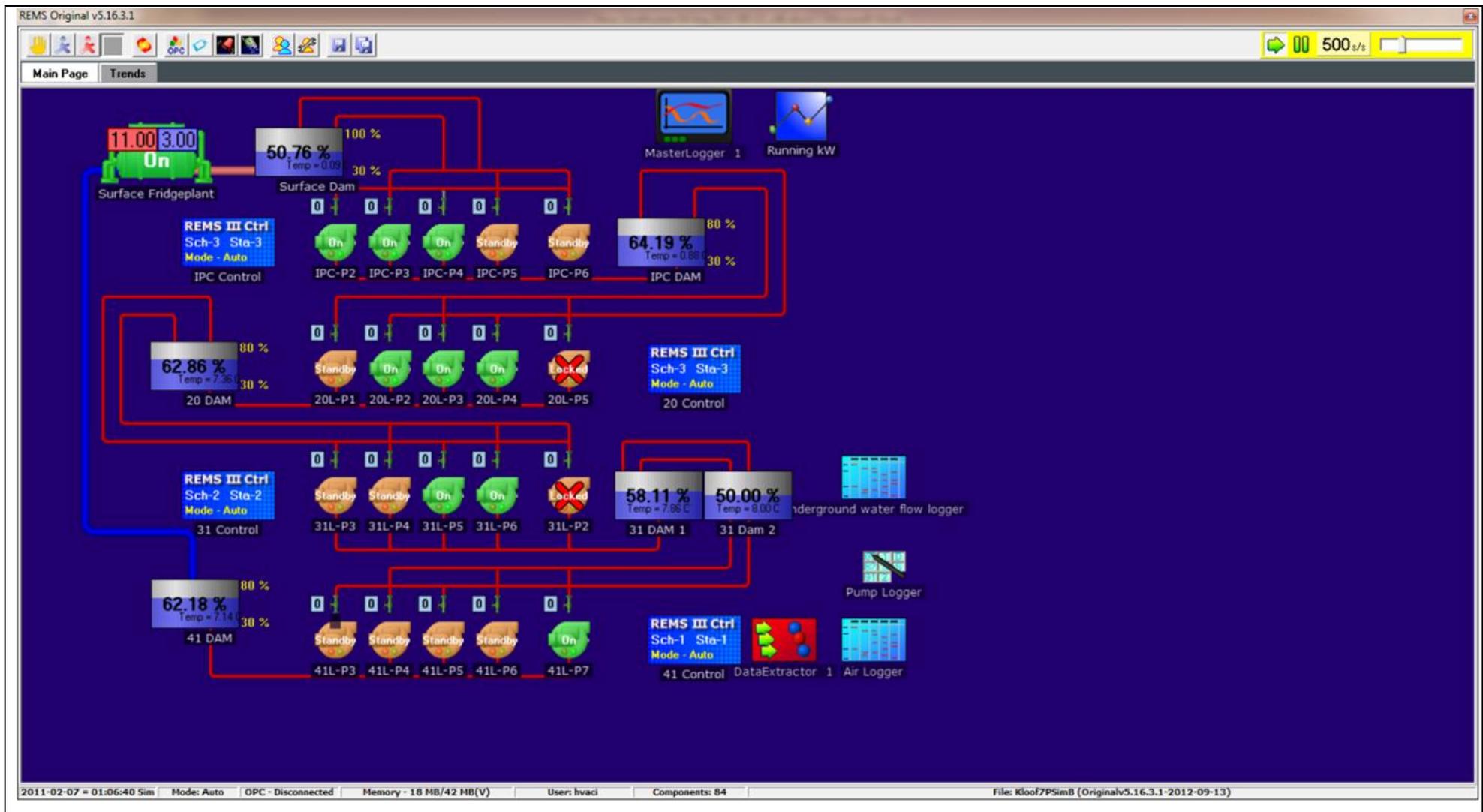


Figure 3-17: Mine Shaft D simulation model (de Lange, 2006; TEMM International, 2012)

The average kilowatt profiles for Simulation X and Simulation Y can be seen in Figure 3-18. Simulation X resulted in an average running kilowatt of 11 980 kW. When compared to Simulation X it can be seen that Simulation Y used more electrical energy to dewater the mine at 14 116 kW. The incoming water caused an electrical energy increase of 2 136 kW during an average simulated weekday.

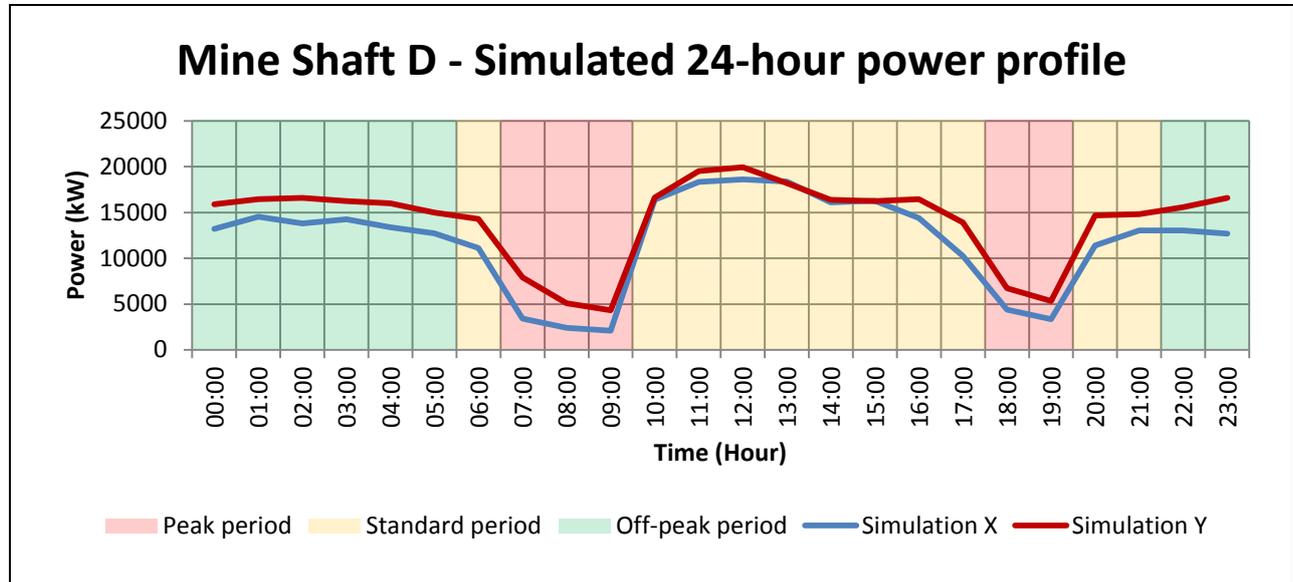


Figure 3-18: Mine Shaft D simulation – Running power profile

Under normal circumstances, a full load-shift is not possible at Mine Shaft D. A minimum of one pump on 41 Level pumping station has to be running at all times. 41 Level only has one settler to separate water and mud and if all the pumps are stopped during peak TOU periods the settler cannot function correctly⁸. Figure 3-18 shows both Simulation X and Simulation Y reflecting a minimum of one pump running during the peak TOU periods on an average 24-hour weekday.

Simulation X for Mine Shaft D resulted in a financial saving of R7,315,540.38 when the saving was calculated using Eskom's Megaflex tariffs. Again a reduced financial saving was generated when incoming water from Mine Shaft A had to be pumped out at Mine Shaft D. Simulation Y resulted in a financial saving of R418,149.32 per annum.

Mine Shaft E simulations

Mine Shaft E has a much smaller pumping capacity and was therefore ranked last amongst the three receiving shafts. The simulation model for Mine Shaft E can be seen in Figure 3-19. The lower pumping priority from Mine Shaft A to Mine Shaft E resulted in less incoming water than the other two shafts. The incoming water was simulated at 12 l/s to Mine Shaft E between 13:00 to 16:00 daily.

⁸R. Norman, Interviewee, *Engineering Manager Manyano Shaft, Masimthembe Shaft and Celemanzi Shaft*. [Interview]. 27 Jan 2012.

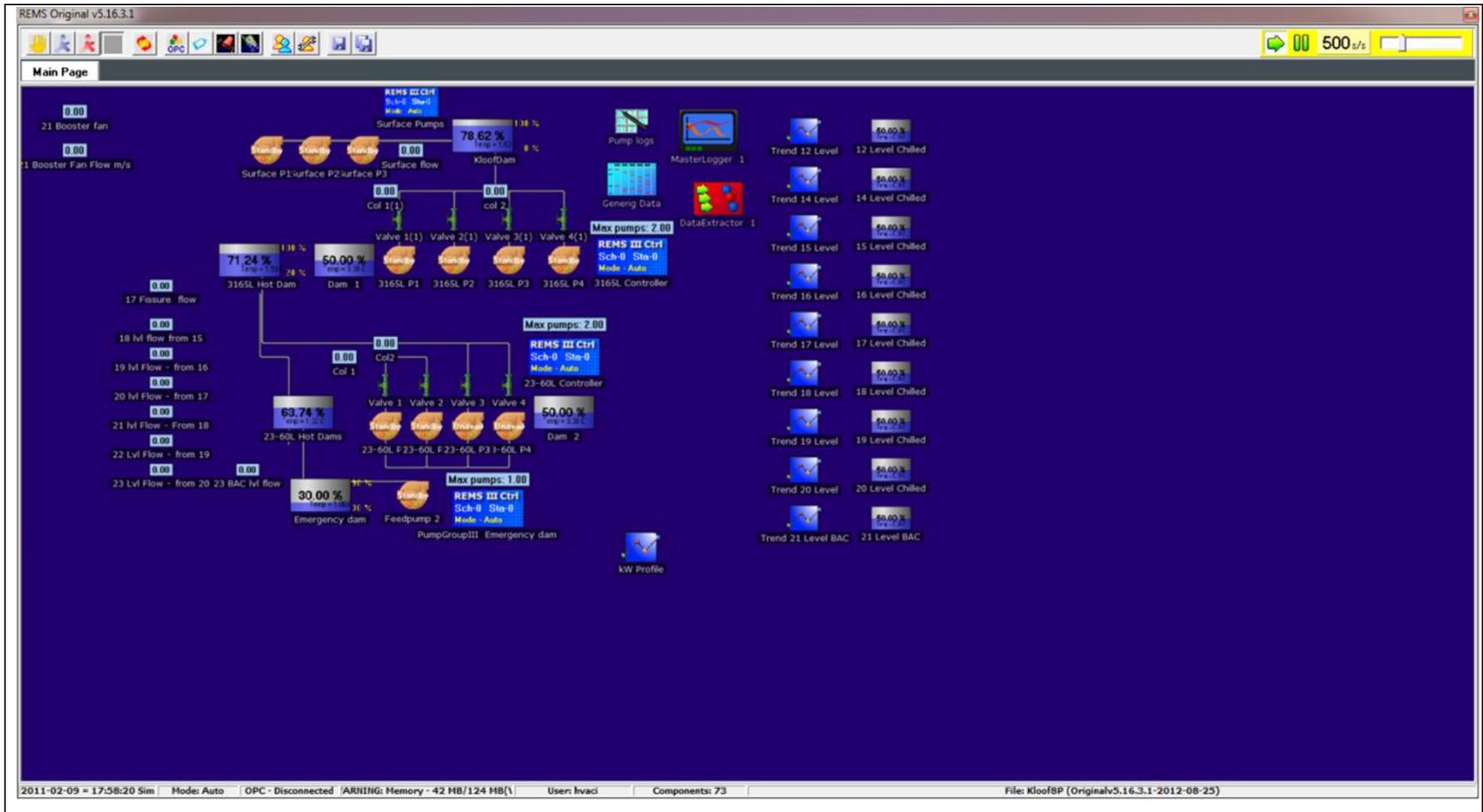


Figure 3-19: Mine Shaft E simulation model (de Lange, 2006; TEMM International, 2012)

The simulated results look similar to previous simulations but the impact was much smaller. Simulation X resulted in an average electrical energy consumption of 6 478 kW. Simulation Y resulted in an average electrical energy consumption of 6 571 kW. The simulation indicated an electrical energy increase of 92 kW in Simulation Y due to increased pumping of water in the system. These running power profiles can be seen in Figure 3-20.

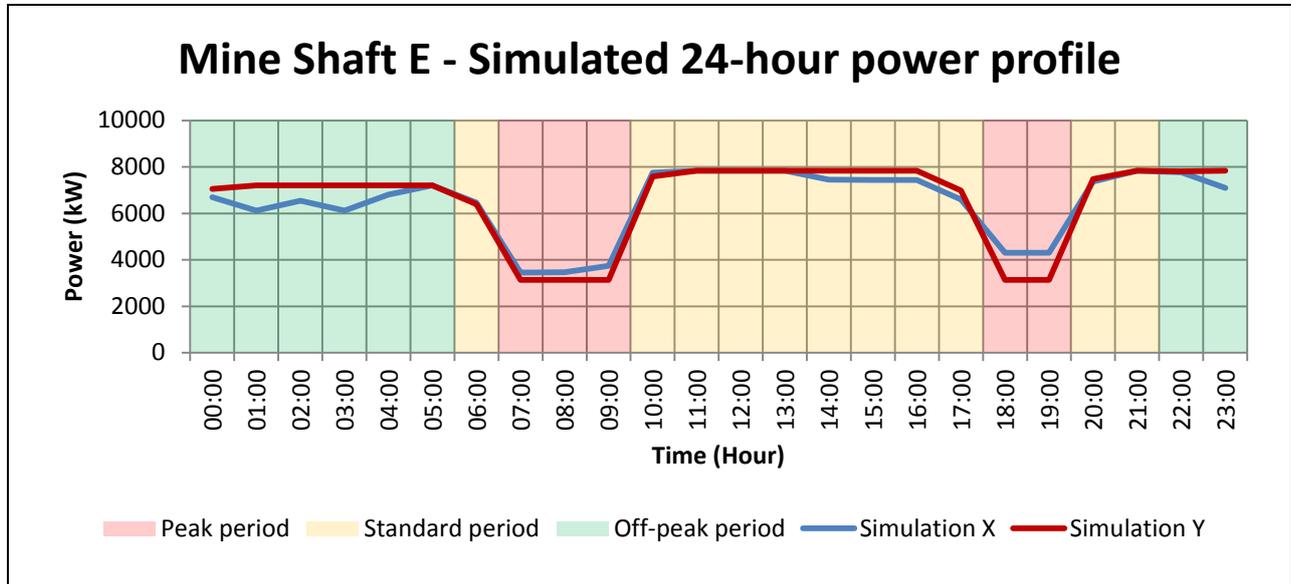


Figure 3-20: Mine Shaft E simulation – Running power profile

Simulation X for Mine Shaft E resulted in a financial saving of R870,195.14 per annum. The saving was calculated again using Eskom’s Megaflex tariffs. Simulation Y had a similar power profile than Simulation X, but the 92 kW difference resulted in a financial saving of R550,453.01 per annum. The incoming water resulted in reduced financial savings for Simulation Y.

3.4. SIMULATION VERIFICATION

The simulated results obtained from Simulation X will be compared to the actual measured power profiles. The actual running power per hour for every shaft was averaged over several working days for the available data. Maximum savings are possible during weekdays due to peak TOU tariffs (Eskom, 2011/12); weekends were not taken into account for this study.

The coefficient of determination (R-squared or R^2) will be used to verify the simulation models. R^2 is used by most statistical practitioners (Renaud & Victoria-Feser, 2010). Although water quantities may vary constantly and pumping strategies are dynamic, R^2 will be sufficient to determine the precision of the model. R^2 is robust and reliable, even when relative small sample sizes are used (Renaud & Victoria-Feser, 2010).

The simulated power profile for each shaft was compared to the actual running power for that shaft by using the coefficient of determination statistical model. The R^2 statistical model takes on a decimal value from 0 to 1, where 0 resulted in 0% confidence in the model and 1 resulted in 100% confidence in the model (Smith, 2012).

R^2 gives an indication of the accuracy and precision. The precision is determined by R^2 . The R^2 of the model was calculated using Microsoft Excel® and an intersection close to 0 would be the most desirable. Accuracy was determined by the intersection on the xy-axis and the inclination angle (Tedeschi, 2006). This combination will ensure maximum accuracy (Tedeschi, 2006).

Each of the simulations was verified using the maximum possible accuracy, but this depended on the location of scattered data points. The precision of each simulation model was indicated on each graph and will be discussed for each shaft individually. To make the verification process easier a linear system was used with the actual running power profile plotted on the x-axis and the simulated power profile on the y-axis.

Mine Shaft A simulation verification

During the testing and simulation stage of Mine Shaft A the main focus was on its intricate pump system. The pumps' installed capacity on each pumping level varied, making optimal control complicated. Mine Shaft A pumps all the incoming water from Mine Shaft B, 1 Sub-vertical Shaft and 2 Sub-vertical Shaft resulting in a present maximum inrush of water on 32 Level at 700 l/s⁹. The flow profile of the incoming water from Mine Shaft B can be seen in Figure 3-21.

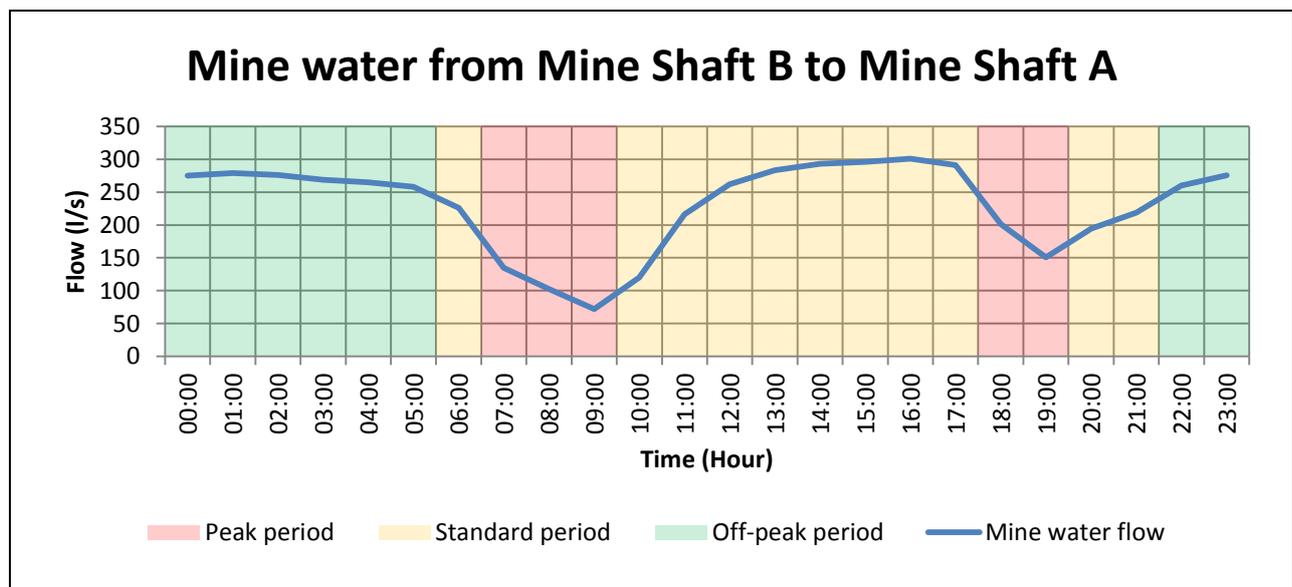


Figure 3-21: Gravity-fed mine water from Mine Shaft B to Mine Shaft A

⁹R. Pretorius, Interviewee, Shaft Engineer, KDC East Thuthukani Shaft. [Interview]. 21 Feb 2012.

The flow rate from Mine Shaft B plotted in Figure 3-21 had to be controlled in order to achieve a full load-shift strategy for Mine Shaft A's pumping system. The valve was never closed completely to prevent water hammers in the column and the controlled flow rate of the water was between 70 and 310 l/s. Data was captured from 20 March 2012 to 7 May 2012 and data loss occurred from 10 - 18 April 2012.

By the time of writing the automation of Mine Shaft A was not complete but a 96% potential saving can be expected between Simulation X and the actual load-shift strategy (Pelzer, Richter, Kleingeld, & van Rensburg, 2009). Once the pumping system is automated the dewatering system is expected to perform similarly to the simulated pumping procedure.

The actual running power profile and simulated power profile correlation can be seen in Figure 3-22. The R^2 value was calculated using Microsoft Excel® and resulted in a 94.03% precision. The simulation resulted in an accurate, sustainable pumping procedure to ensure the maximum financial savings on the electrical energy used for pumping.

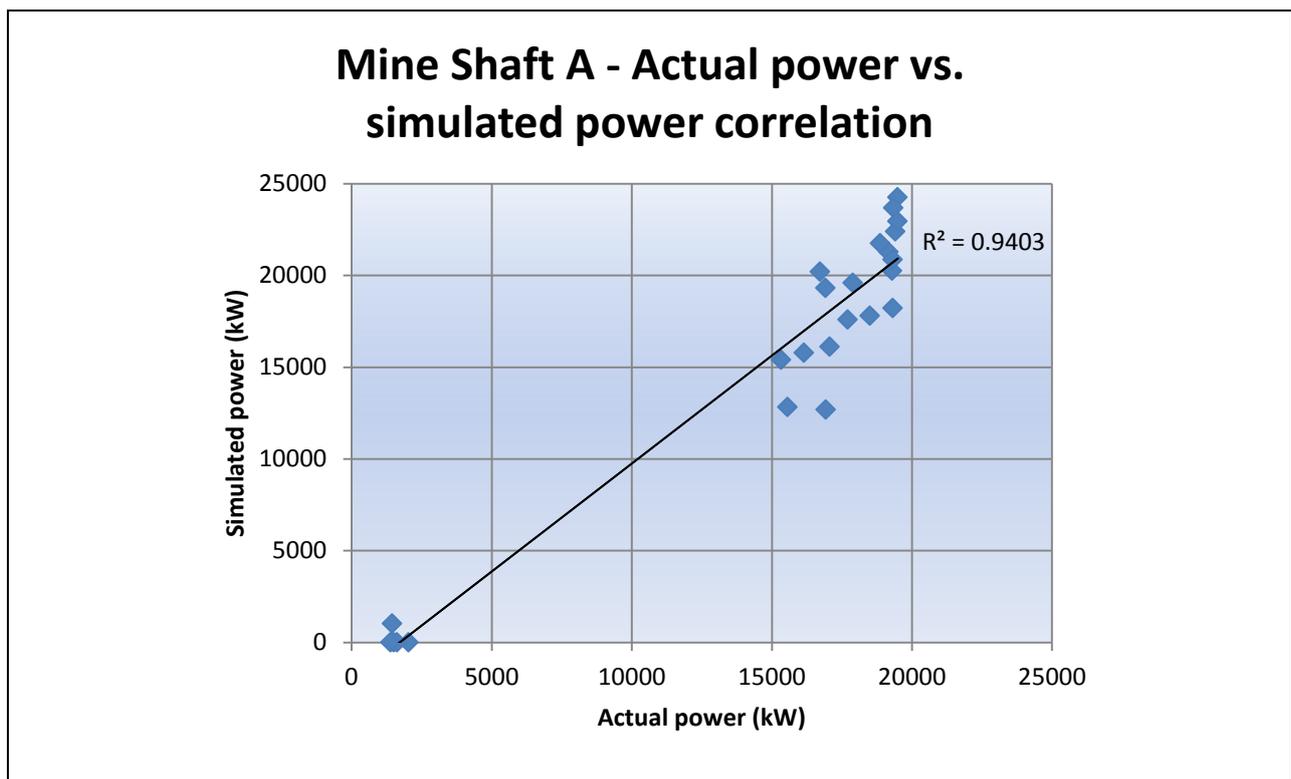


Figure 3-22: Mine Shaft A R^2 verification

The two running power profiles were plotted on the same time axis in Figure 3-23. It is evident that the simulated profile scheduled pumps more effectively, resulting in maximum savings by switching off all the pumps during both the morning and evening peak TOU periods. A larger comeback load can be seen during Eskom's standard time between peak periods but it can be shifted to be recovered during off-peak periods at night.

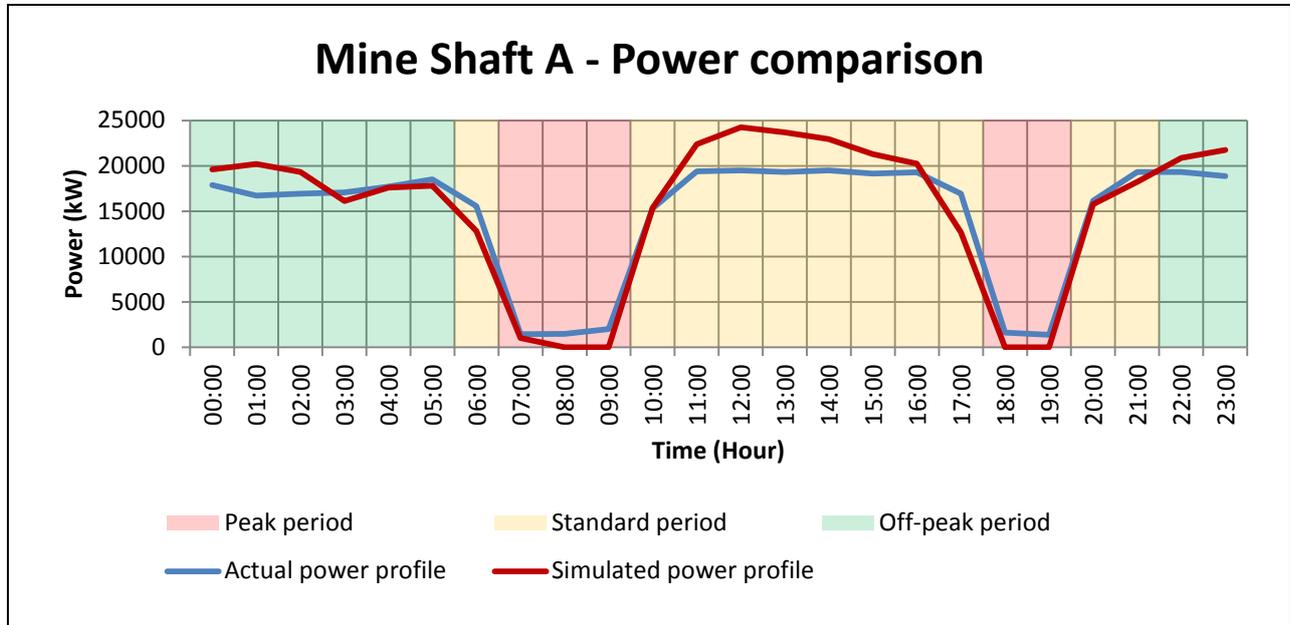


Figure 3-23: Mine Shaft A running power profile compared to simulated power profile

Mine Shaft C simulation verification

The simulated power profile is compared to the actual running power profile in Figure 3-24. Substantial data loss on the automatic logging system was experienced over several months. The running power profile was composed from the operator's logged data collected from the Mine Shaft C control room. The correlation between the actual and simulated profiles resulted in the lowest precision recorded in this dissertation at 72.82%.

The lower correlation can be attributed to two major factors: human inability to prepare the clear-water dams properly to achieve maximum savings; and incorrect logging of pump statuses. The operators log pump running statuses from the mine's SCADA. In some cases, running statuses were not available on the SCADA and operators were forced to phone the pump attendants underground to verify running statuses. The simulation can be optimised when verifiable data becomes available.

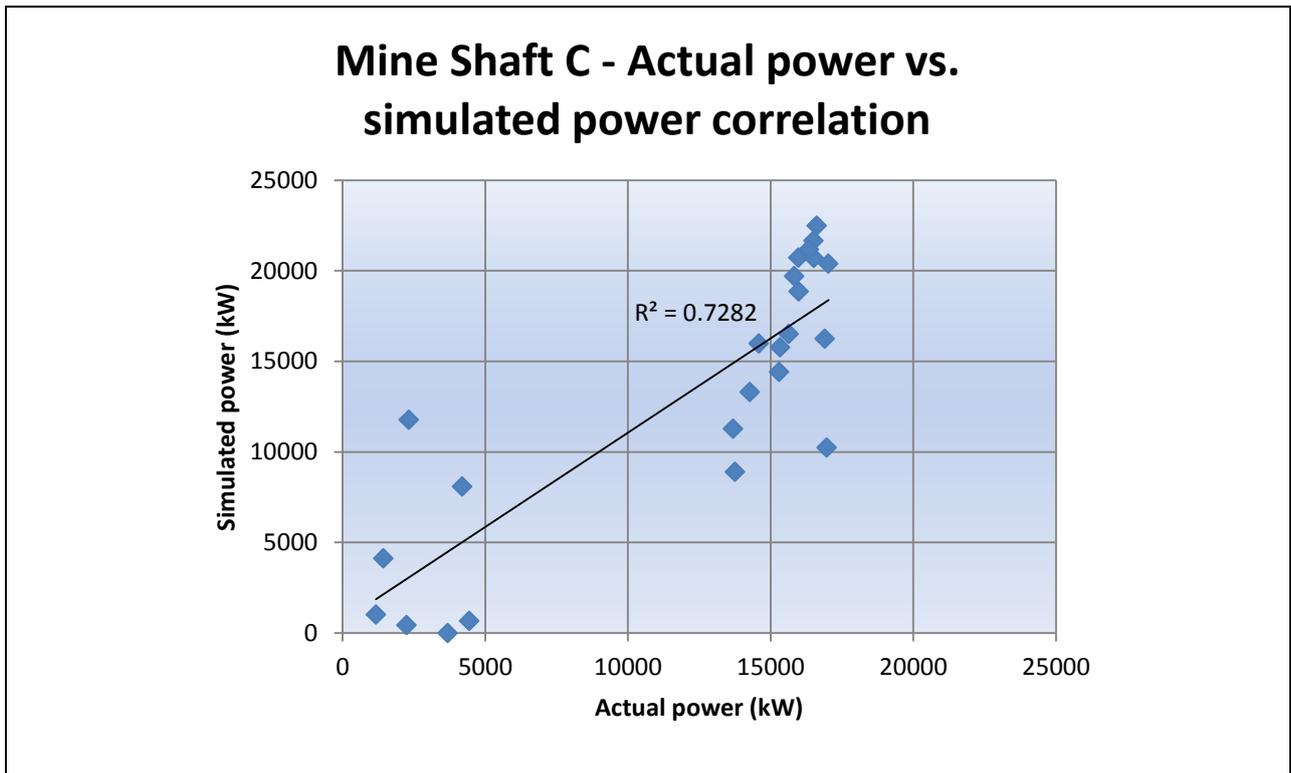


Figure 3-24: Mine Shaft C R^2 verification

Figure 3-25 shows the running power plotted on the same time axis as the simulated power. It can be seen that the simulated power profile follows the actual power profile. The running power was not optimised and less electrical load was shifted out of the morning and the evening peak periods. A much larger comeback load can be seen in the off-peak and standard TOU periods.

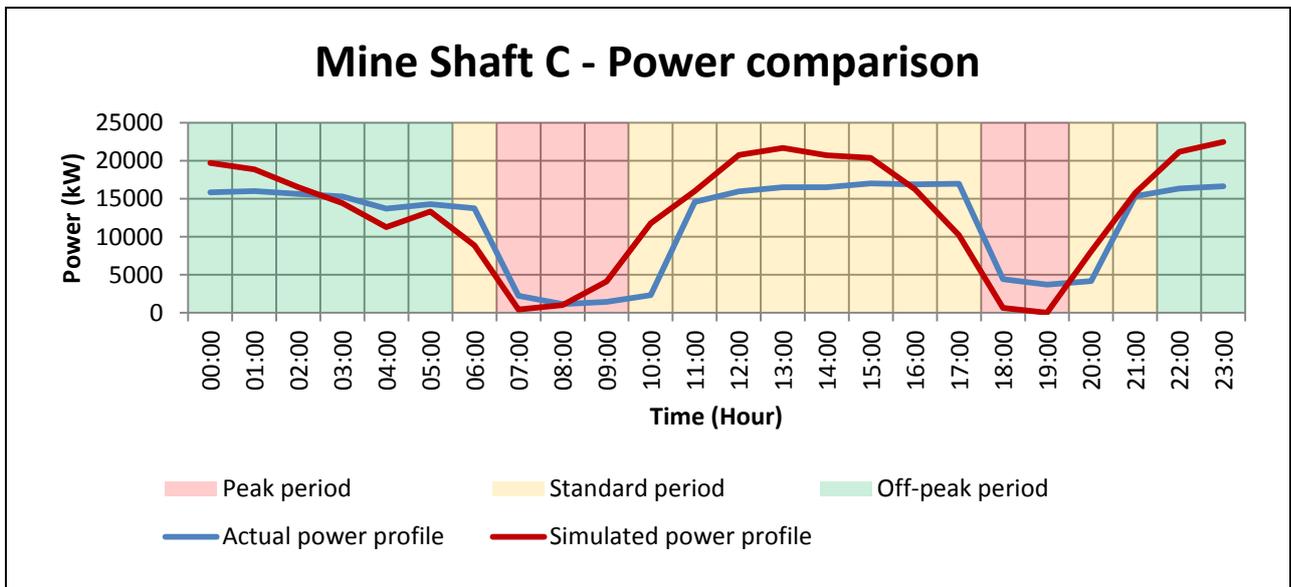


Figure 3-25: Mine Shaft C running power profile compared to simulated power profile

When calculating simulated savings using the spreadsheet in Figure 3-1. It can be seen that the simulated saving resulted in a total load-shift of 43 995 kW. An average saving of 8 799 kW over the morning and evening peak TOU periods was achieved. This optimised simulation resulted in an increased saving of 2 235 kW on average. The savings generated can be seen in Figure 3-26.

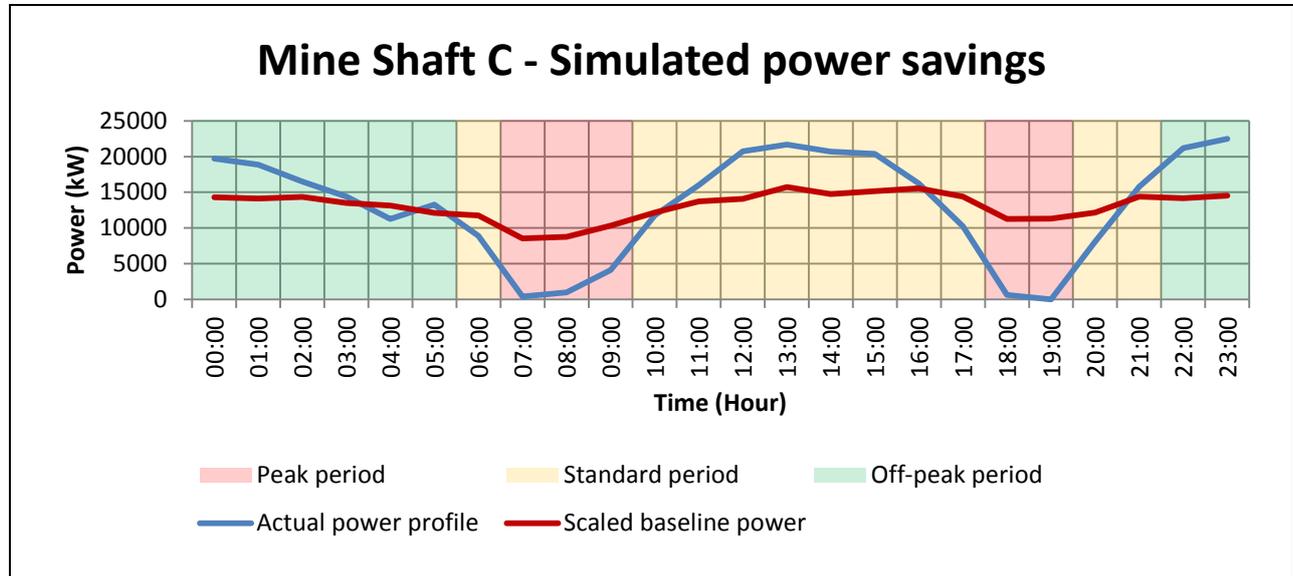


Figure 3-26: Mine Shaft C simulated savings generated

At the time of writing Mine Shaft C was not yet fully automated, but completion was estimated for December 2012. Full automation of the system would enable better control based on measured criteria and not on anticipation of dam levels and human judgement. As seen in the Simulation X an extra 2 MWh saving can be generated when the system is optimised using logical calculations.

Mine Shaft D simulation verification

Mine Shaft D's simulation resulted in a more accurate correlation than Mine Shaft C. Accurate data logged at two-minute intervals could be collected for this study before the simulation was done. The precision can be seen in Figure 3-27. The R^2 calculation resulted in a precision of 89.08% when the actual running kilowatt profile was compared to the simulated kilowatt profile.

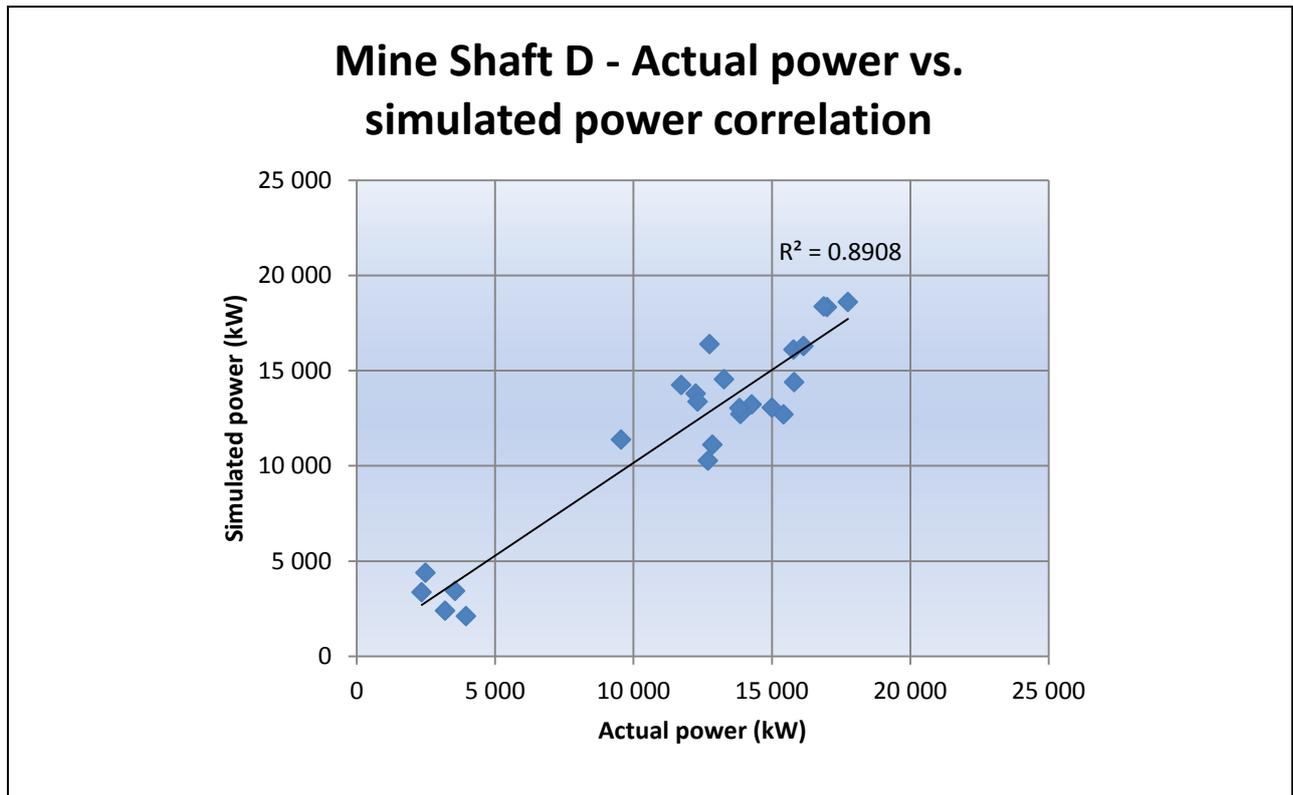


Figure 3-27: Mine Shaft D R^2 verification

The running power profiles are plotted on the same time axis in Figure 3-28. It can be seen again that the simulated power profile follows the actual running power profile. Thus, the savings generated would be similar between the actual power and simulated power. The simulated power profile is plotted in red and the actual power profile is plotted in blue in Figure 3-28.

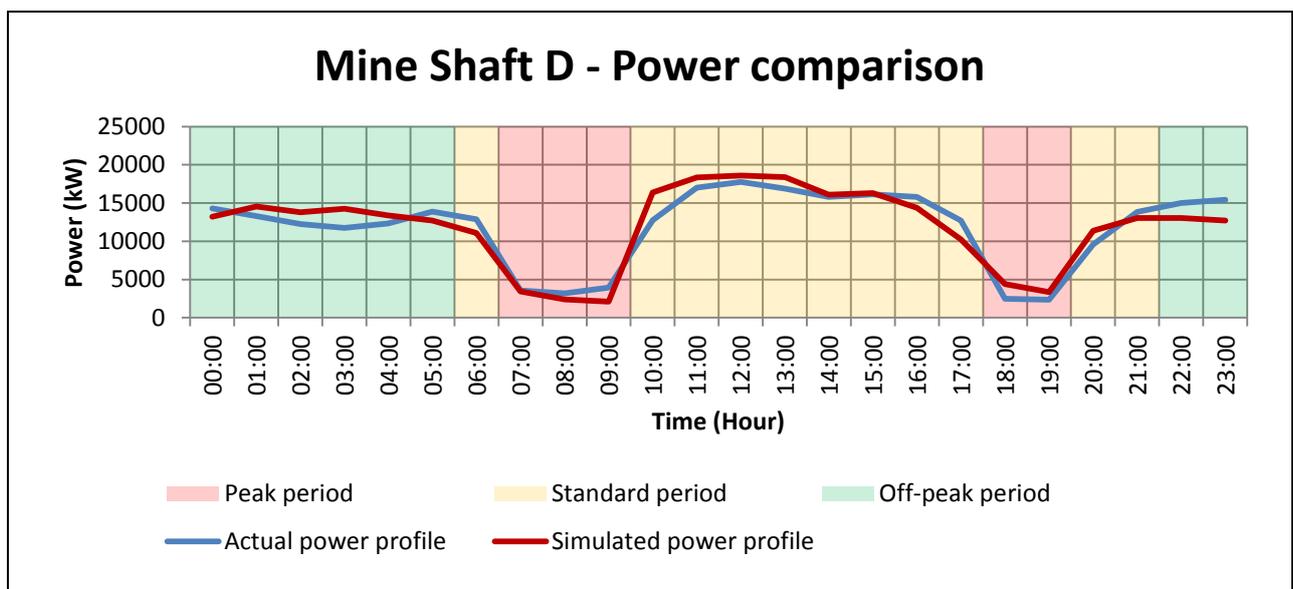


Figure 3-28: Mine Shaft D running power profile compared to simulated power profile

Mine Shaft E simulation verification

No significant saving was generated at Mine Shaft E. The correlation resulted in a precision of 82.06% in Figure 3-29. Mine Shaft E has the smallest pumping capacity in the complex, when compared to the other shafts. The maximum saving for Mine Shaft E was achieved during 2009 and can be seen in Figure 3-10. The saving for 2009 was 2 216 kW but this is no longer feasible due to the use of the surface fridge plant as discussed earlier.

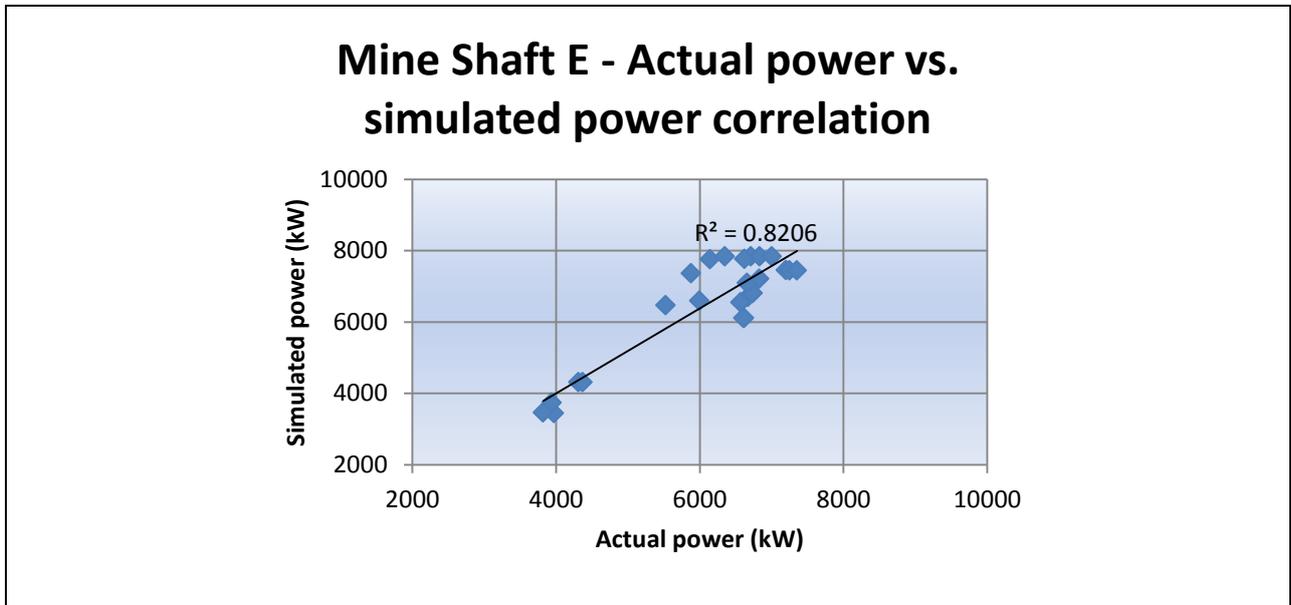


Figure 3-29: Mine Shaft E R² verification

The simulated power profile and actual power profile are plotted in Figure 3-30. The simulated pumping strategy followed the actual running power profile with deviations at the start of the standard TOU period and at the start at the off-peak TOU period. The simulated power profile is plotted in red and the actual power profile in blue.

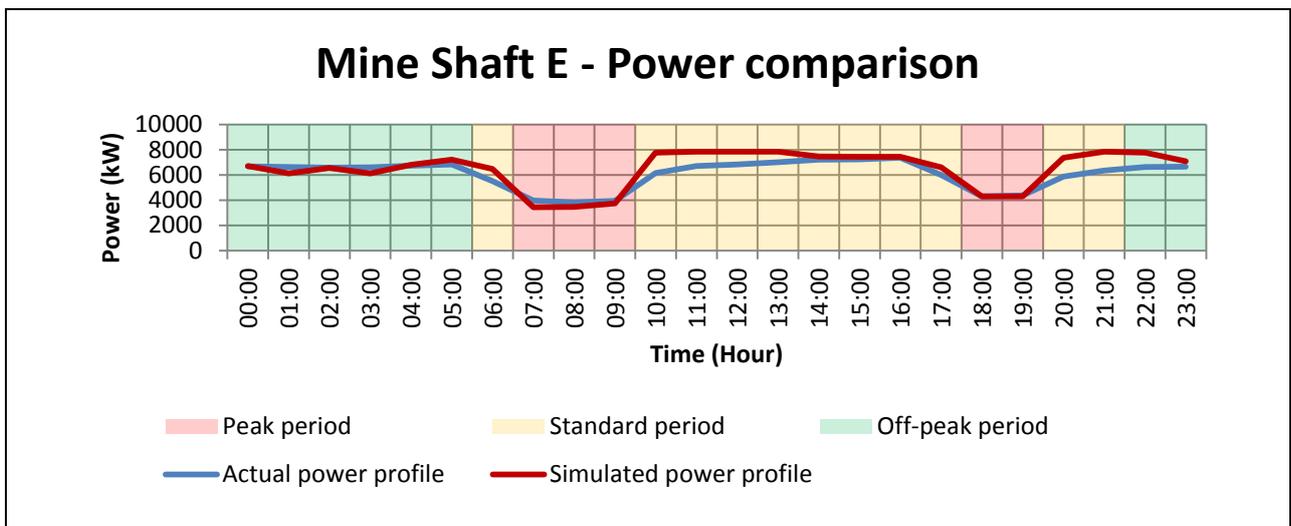


Figure 3-30: Mine Shaft E running power profile compared to simulated power profile

Although water can be pumped to Mine Shaft E from Mine Shaft A it is not desirable as no extra cost savings can be generated during normal pumping operations. When the water quantity is increased this can negatively affect the present electrical energy usage. Maximum pumping will be required to accommodate incoming water over a 24-hour profile instead of maximum savings generated from stopping pumps during peak TOU periods.

3.5. CHAPTER SUMMARY

The results for Simulation X and Simulation Y were discussed for each of the four shafts in the complex. Mine Shaft B was excluded as Mine Shaft A transfers all of Mine Shaft B's water to surface. Simulation X required each shaft to transfer its own water to surface for cooling and reuse. Simulation Y on the other hand required all Mine Shaft A and Mine Shaft B's water to be transferred to neighbouring shafts where it was transferred to surface.

The baselines verified by M&V teams were presented and described for each shaft. Savings on the actual running power were quantified using a load-shifting strategy by scaling of the baseline and financial savings calculated. The running power profiles were compared to the simulated profiles using R^2 to ensure the simulations were reliable. Accuracy predictions from 72% to 94% were achieved for the shafts. The advantages of automatic control over manual control were discussed.

Chapter 4

4. CONCLUSION

4.1. SUMMARY

The continued economic growth has resulted in significant increases in the demand for electricity. To prevent load-shedding, electrical energy demand was reduced during peak periods by introducing DSM and TOU tariffs (Eskom, 2008). The most significant energy users were identified with specific focus on the deep-level gold mines in the mining sector. Materials handling and processing were the highest electricity consumers on gold mines. These essential production processes cannot be affected by DSM interventions.

The supply of compressed air and pumping of water were respectively identified as third and fourth largest consumers where properly scheduled DSM interventions would not affect production of the gold mines directly. Pumping systems were studied to identify optimisation potential based on financial savings and reducing demand on the distribution network during Eskom peak periods (Eskom, 2011/12; Middelberg, Zhang, & Xia, 2009). Load-shifting strategies were introduced by not just optimising a single shaft but a whole mine complex consisting of multiple shafts.

The cascading pump systems were discussed as part of the reticulation systems where water is used for mining, pumped out to surface, treated to neutralise low pH levels and finally cooled to be reused. The best practices were identified to assist with the safe automatic management and control of a pumping station using centrifugal pumps and the pumping columns required for water transfer.

A case study was identified where shafts were interconnected underground and water could be transferred between shafts as required. The upgrade of pump columns and pumping stations was the result of a near-catastrophic column failure and the flooding of the 2 Sub-vertical Shaft bottom. All the mine water used by three sub-vertical shafts had to be transferred to neighbouring shafts where it could be transferred to surface.

The optimisation of a mine complex consisting of multiple shafts required that production would not be compromised. The pumping strategies had to be adapted according to the pumping capacity and storage capability on the receiving shaft. All safety precautions were taken into account to prevent future flooding of any of the shafts in the complex.

Various pumping scenarios were identified and investigated. The rated flows of pipelines between shafts as well as rated flows of pump columns to surface were recorded to ensure the water transfer quantities could be maximised. Due to large underground water resources smaller production shafts could not be decommissioned as their primary function was to dewater the complex.

The optimisation process required automation of the system according to legislation stipulated in the Mine Health and Safety Act (President's office, 1996 (revised 2009); Department of Minerals and Energy, 2008). Various infrastructure upgrades were installed on the underground pumps to monitor and control the cascading pump system. The automated control on the pump system required that the operating status of all the pumps and dams had to be visually displayed on the surface SCADA.

A detailed simulation model for each mine shaft was developed based on a best and worst case scenarios. The first, Simulation X, required each individual shaft to transfer its own mine water to surface without any water transfer from neighbouring shafts. The second, Simulation Y, required all the mine water collected from Mine Shaft A and Mine Shaft B to be transferred to neighbouring shafts where it could be transferred to surface.

Simulation Y resulted in substantial savings by disabling two pumping stations on Mine Shaft A. The power saving generated was shifted to the other shafts. The total power saving, indicated by the simulation to transfer water to surface, resulted in an average of 1.2 MW (2.48%) less electricity used over five weekdays when all the water from Mine Shaft A was transferred to neighbouring shafts. Table 4-1 shows all the shaft's usage figures.

Table 4-1: Predicted average power consumption using simulation models

Shaft	Average power usage Simulation X (kW)	Average power usage Simulation Y (kW)	Power difference between X and Y
Mine Shaft A	15 167.57	7 192.26	52.58%
Mine Shaft C	13 098.56	17 687.24	-25.94%
Mine Shaft D	11 980.09	14 115.83	-15.13%
Mine Shaft E	6 478.25	6 570.73	-1.41%
Total simulated power	46 724.46	45 566.07	-2.48%

Although an average of 1.2 MW total saving over five weekdays can be expected it will not necessarily generate financial savings as pumping procedures must be optimised to pump the minimum water during peak TOU periods. As the load-shift strategy was electrical energy neutral the same quantity of water still has to be pumped every day. Optimising the system would mean to schedule minimum pumping during peak periods and maximum pumping during off-peak periods (Kleingeld, Vosloo, & Swanepoel, 2011; Schoeman, Van Rensburg, & Bolt, 2011; Marais, Kleingeld, & van Rensburg, 2011).

The advantages of automating a pumping system resulted in 96% of the savings predicted being generated. Furthermore, the underground pumping systems could be scheduled to achieve maximum savings based on logical calculations rather than human perception (Pelzer, Richter, Kleingeld, & van Rensburg, 2009). Manual control systems only achieved 60% of the savings predicted (Pelzer, Richter, Kleingeld, & van Rensburg, 2009). Automatic pump systems will prolong the lifecycle of pumps by enabling preventative maintenance rather than corrective maintenance (Pelzer, Richter, Kleingeld, & van Rensburg, 2009).

After simulations were completed, data was collected for each shaft in order to verify the simulations. The verification process required use of Microsoft Excel® to calculate a linear trend in the simulated and actual running power profiles. The actual and simulated profiles were plotted on the x- and y-axis respectively and a vector was calculated to determine R^2 for each simulation (Renaud & Victoria-Feser, 2010; Smith, 2012; Tedeschi, 2006).

The R^2 value (or precision) calculated in each case resulted in an acceptable correlation between the actual and simulated profiles. The profiles were plotted on the same time axis and a correlation between each set of power profile was evident. The correlations for each mine shaft can be seen in Table 4-2.

Table 4-2: Calculated R^2 values between actual and simulated running power profiles

Shaft	R^2
Mine Shaft A	94.03%
Mine Shaft C	72.82%
Mine Shaft D	89.08%
Mine Shaft E	82.06%

From the calculated R^2 values it can be seen that the most reliable correlation was for the simulation of Mine Shaft A. Because this shaft was the main focus of the study, the most time and effort was spent to optimise the simulation. The worst simulation was for Mine Shaft C as no reliable data was accessible due to the fibre-optic backbone and network downtime on the levels. If reliable data was available greater precision could be expected.

The original aim of this study was to optimise a whole complex consisting of multiple mine shafts. During the case study data was measured and the complex was simulated using different pumping procedures. The pumping system was then optimised to achieve maximum financial savings. The results of the optimised complex and simulations can be seen in Table 4-3.

Table 4-3: Financial savings generated using APPENDIX A: MARVIN SAVINGS CALCULATOR

Shaft in complex	Optimised financial savings	Simulation X financial savings	Simulation Y financial savings
Mine Shaft A	R18,754,355.21	R18,307,338.75	R38,068,464.26
Mine Shaft C	R11,112,756.11	R8,939,887.69	-R11,520,437.98
Mine Shaft D	R7,594,941.60	R7,315,540.38	R418,149.32
Mine Shaft E	R1,806,376.53	R,870,195.14	R550,453.01
Total annual savings	R39,268,429.45	R35,432,961.97	R27,516,628.60

The study showed that significant financial savings are possible when optimised power profiles are compared to the baseline power recorded. Best case scenario - Simulation X, where each shaft transfers its own water to surface - resulted in a saving of R35,432,961.97. The worst case scenario - Simulation Y still resulted in a saving of R27,516,628.60 as load-shifting strategies were still used.

Optimum distribution can be expected between Simulation X and Simulation Y by transferring enough water to neighbouring shafts to optimise the load-shift strategy at Mine Shaft A. This optimisation requires switching off all pumps in the peak TOU periods. A full load-shift can only be done when some water is transferred to neighbouring shafts.

The transfer water must be regulated to prevent transfer in peak periods and achieve maximum load-shifting on all the shafts. Figure 4-1 shows the running power used by the transfer pumps as needed during 2012. The optimised model requires the average power used to transfer water from 23-60 Level to Mine Shaft C, Mine Shaft D and Mine Shaft E at 6 652 kW, 1 869 kW and 352 kW respectively.

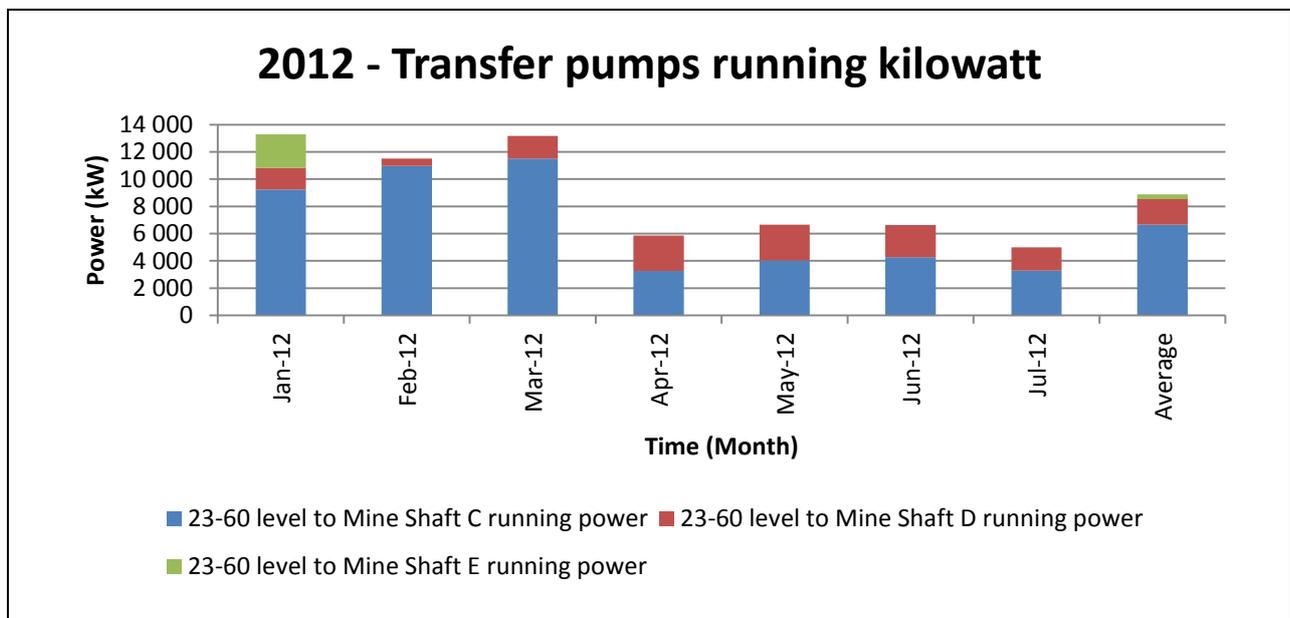


Figure 4-1: Transfer pumps from Mine Shaft A running kilowatt

Thus in 2012, an average of 8.9 MW was used daily for the transfer of water to Mine Shaft C and Mine Shaft D. Incoming water to Mine Shaft C and Mine Shaft D did not have such a large impact as when all the water was transferred. The optimal running strategy required for each shaft was determined and resulted in a financial saving in the complex of R39,268,429.45 annually.

4.2. RECOMMENDATIONS

In the mining sector a lot of electrical energy is wasted on unnecessary pumps running during each day. The biggest challenge is to create awareness amongst the personnel by teaching people a culture of saving and conservation. Further studies may include aptitude tests to determine why no savings culture exists and how to resolve this.

The savings strategies installed must have a running maintenance contract forcing the mines to optimise the process rather than just saving money. At the moment M&V monitors the savings monthly, but the mine is not enforced to maintain the installed infrastructure to ensure that the maximum efficiency could be achieved. DSM maintenance processes can be put in place linked to penalties payable to Eskom.

Compressed air used more energy than pumping in 2011. Future studies may include the impact of converting compressed air machinery to hydropowered or electrical equipment. Compressed air leaks cost the mine millions in wasted electrical energy each year because of extra compressors started to maintain the air pressure needed for drills. Water leaks are maintained better as it may cause flooding of the underground workings, where compressed air leaks are ignored because it is not life threatening.

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6. APPENDIXES

6.1. APPENDIX A: MARVIN SAVINGS CALCULATOR

Table 6-1: Annual savings calculated using MARVIN

Hour of day	Baseline	Optimised	Summer Tariff				Winter Tariff			
			Tariff	Summer Tariff Weekday	Summer Tariff Saturday	Summer Tariff Sunday	Tariff	Winter Tariff Weekday	Winter Tariff Saturday	Winter Tariff Sunday
1	17072	20936	21.87	21.87	21.87	21.87	25.39	25.39	25.39	
2	16716	20580	31.27	21.87	21.87	21.87	25.39	25.39	25.39	
3	17212	21076	51.04	21.87	21.87	21.87	25.39	25.39	25.39	
4	17930	21794		21.87	21.87	21.87	25.39	25.39	25.39	
5	18216	22080		21.87	21.87	21.87	25.39	25.39	25.39	
6	18181	22045		21.87	21.87	21.87	25.39	25.39	25.39	
7	18509	22373		31.27	21.87	21.87	47.52	25.39	25.39	
8	17386	8886		51.04	31.27	21.87	182.83	47.52	25.39	
9	16256	7756		51.04	31.27	21.87	182.83	47.52	25.39	
10	16130	7630		51.04	31.27	21.87	182.83	47.52	25.39	
11	17686	17686		31.27	31.27	21.87	47.52	47.52	25.39	
12	16828	16828		31.27	31.27	21.87	47.52	47.52	25.39	
13	17867	17867		31.27	21.87	21.87	47.52	25.39	25.39	
14	17128	17128		31.27	21.87	21.87	47.52	25.39	25.39	
15	18405	18405		31.27	21.87	21.87	47.52	25.39	25.39	
16	18991	18991		31.27	21.87	21.87	47.52	25.39	25.39	
17	19828	19828		31.27	21.87	21.87	47.52	25.39	25.39	
18	19981	19981		31.27	21.87	21.87	47.52	25.39	25.39	
19	18656	10156		51.04	31.27	21.87	182.83	47.52	25.39	
20	18314	9814		51.04	31.27	21.87	182.83	47.52	25.39	
21	18795	22659		31.27	21.87	21.87	47.52	25.39	25.39	
22	18802	22666		31.27	21.87	21.87	47.52	25.39	25.39	
23	19730	23594		21.87	21.87	21.87	25.39	25.39	25.39	
24	19681	23545		21.87	21.87	21.87	25.39	25.39	25.39	
Total										
MW energy efficiency			0	Summer Tariff			Winter Tariff			
MW shifted in Morning			8 500	Summer Tariff Weekday	Summer Tariff Saturday	Summer Tariff Sunday	Winter Tariff Weekday	Winter Tariff Saturday	Winter Tariff Sunday	
MW shifted in Evening			8 500							
Network demand			-3 864							
Load factor			0.91							
Total load-shift			42500							
Total comeback load			-42500							
Total				R 11 308	-R 1 321	-R 3 718	Total	R 64 347	R 1 327	-R 4 316
Avg Daily Savings				R 7 357			Avg Daily Savings	R 45 535		
Summer Savings				R 2 114 541	-R 58 120	-R 159 870	Winter Savings	R 4 118 204	R 18 576	-R 60 428
Total Summer Savings				R 1 896 551			Total Winter Savings	R 4 076 351		
Total Active Energy savings				R 5 972 903						

6.2. APPENDIX B: SHAFT ENGINEER'S SLIDESHOW – PUMPING STRATEGIES

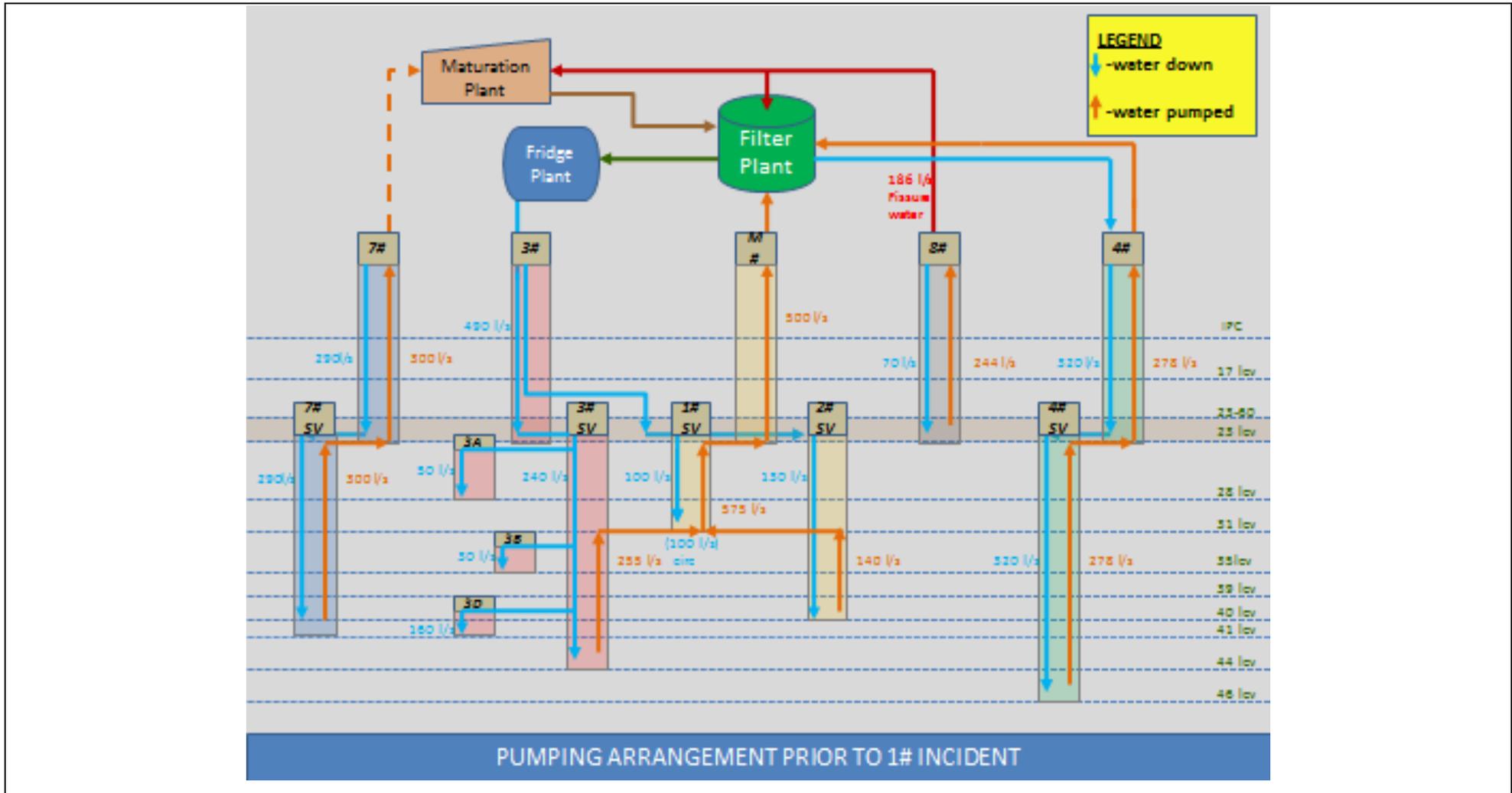


Figure 6-1: Pumping procedures before the 2010 column failure at Mine Shaft A

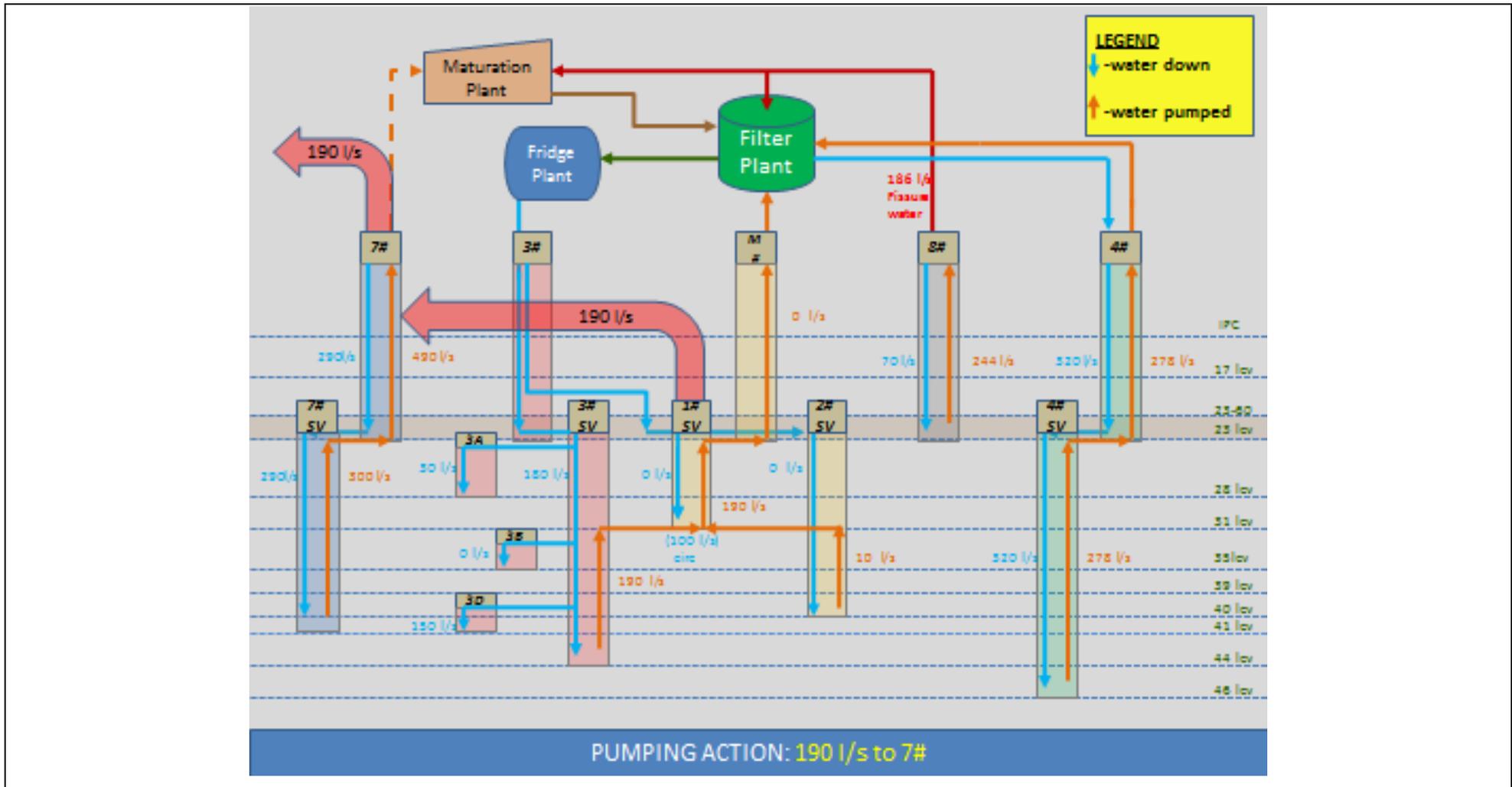


Figure 6-2: Water transferred to Mine Shaft D

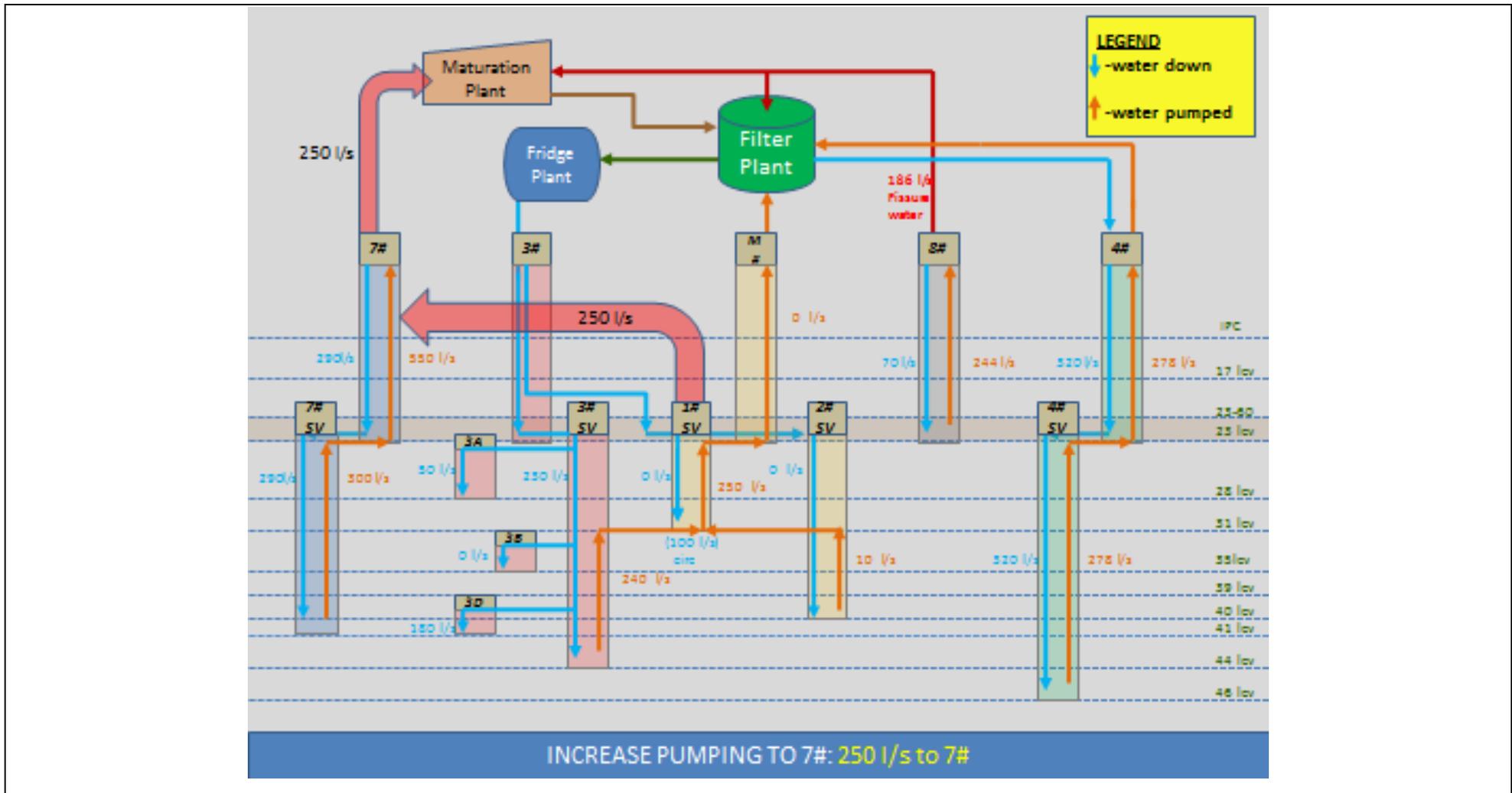


Figure 6-3: Water transferred to Mine Shaft D upgraded to 250 l/s

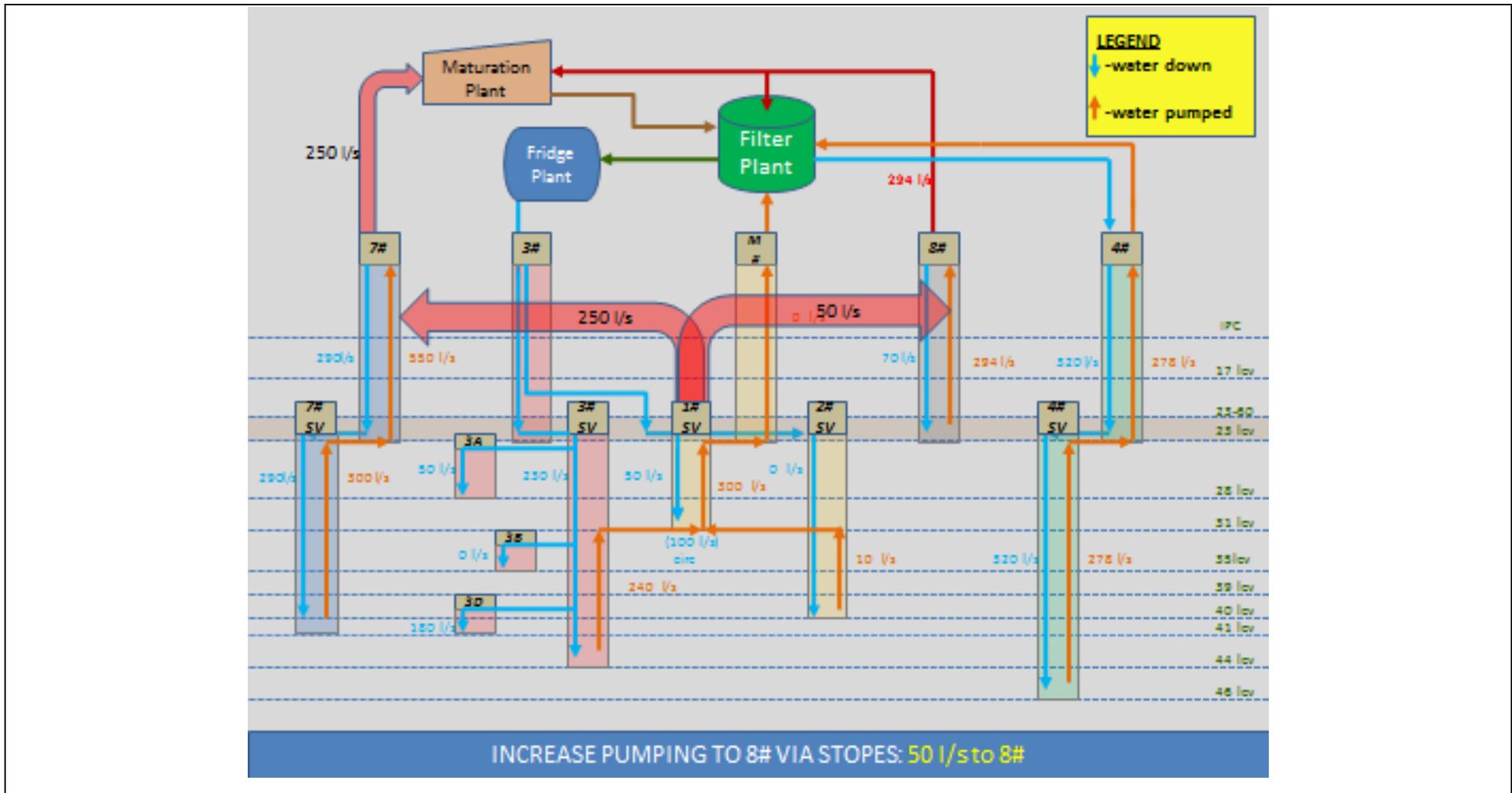


Figure 6-4: Water transferred to Mine Shaft D and Mine Shaft E

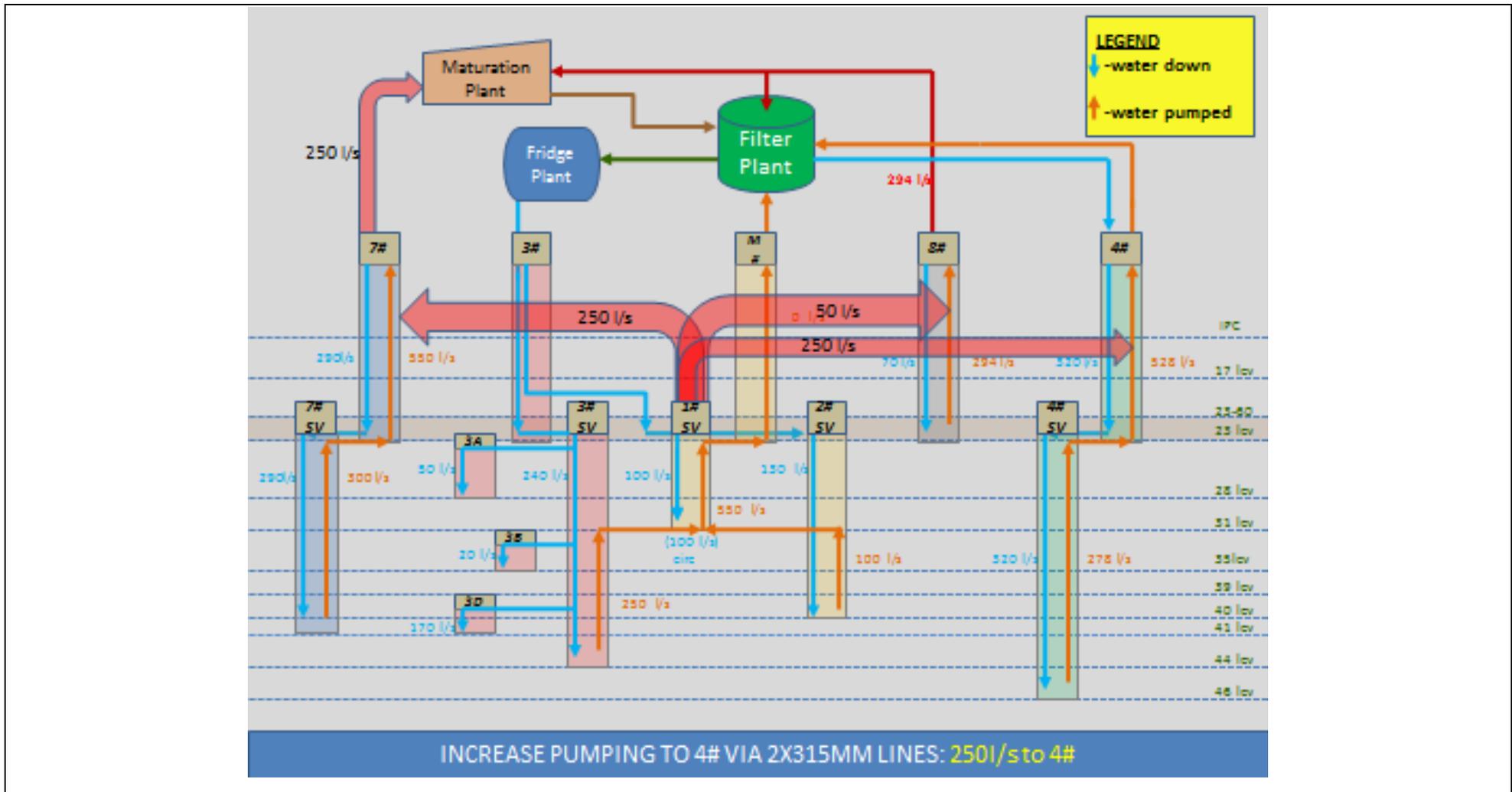


Figure 6-5: Water transferred to Mine Shaft C, Mine Shaft D and Mine Shaft E

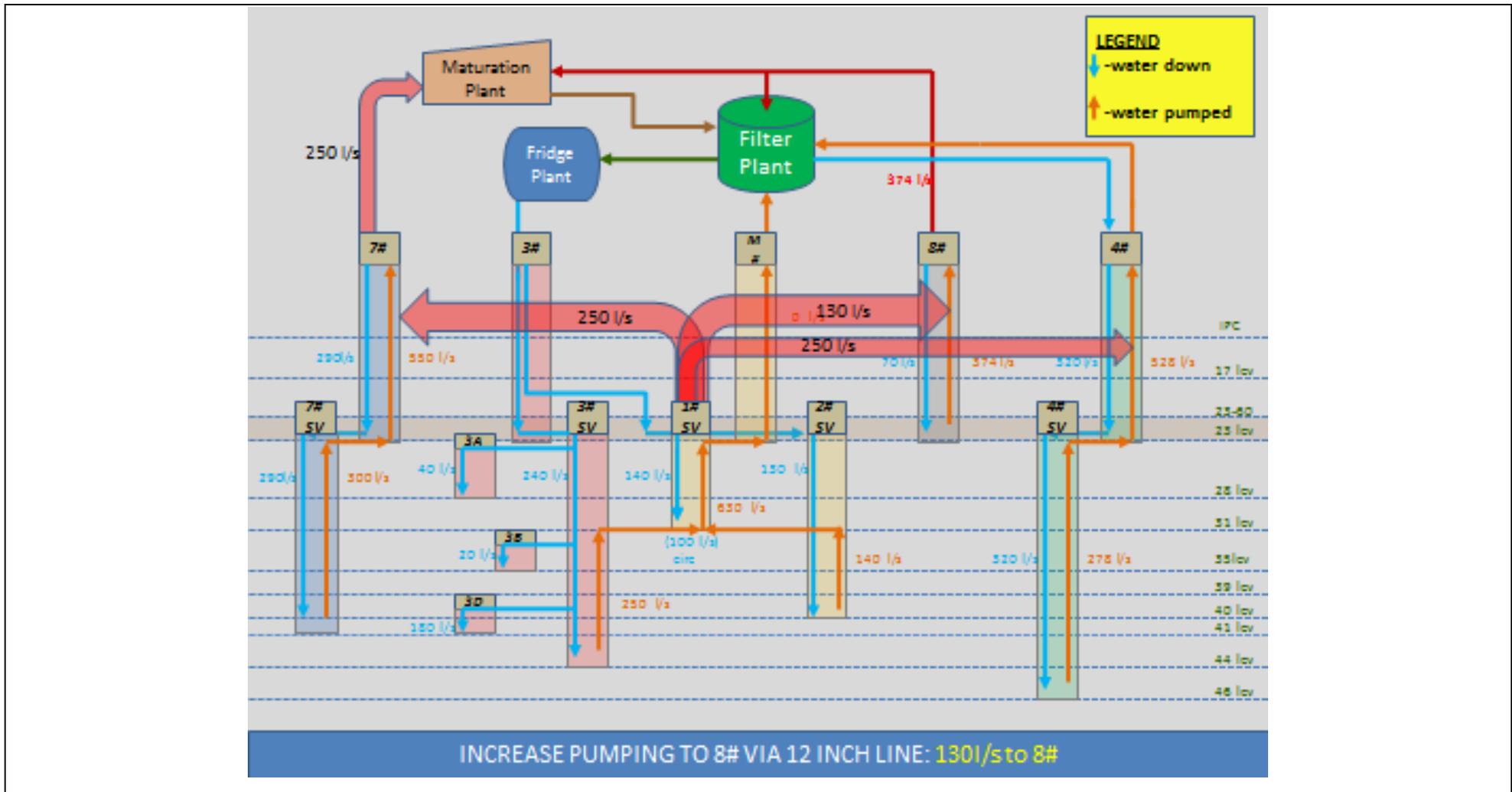


Figure 6-6: Water transferred to Mine Shaft E upgraded to 130 l/s

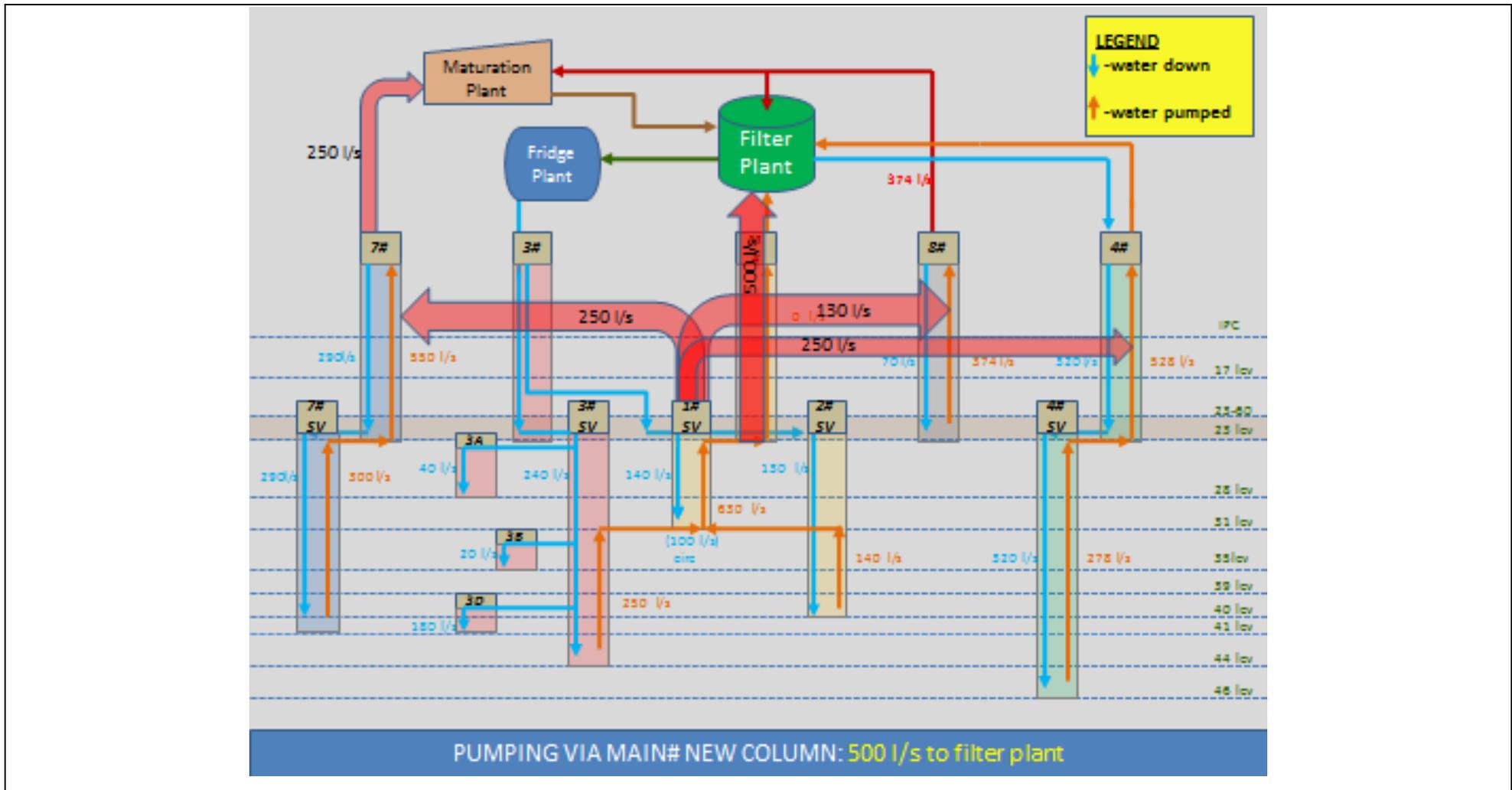


Figure 6-7: Mine Shaft A water transfer to surface restored at a flow of 500 l/s

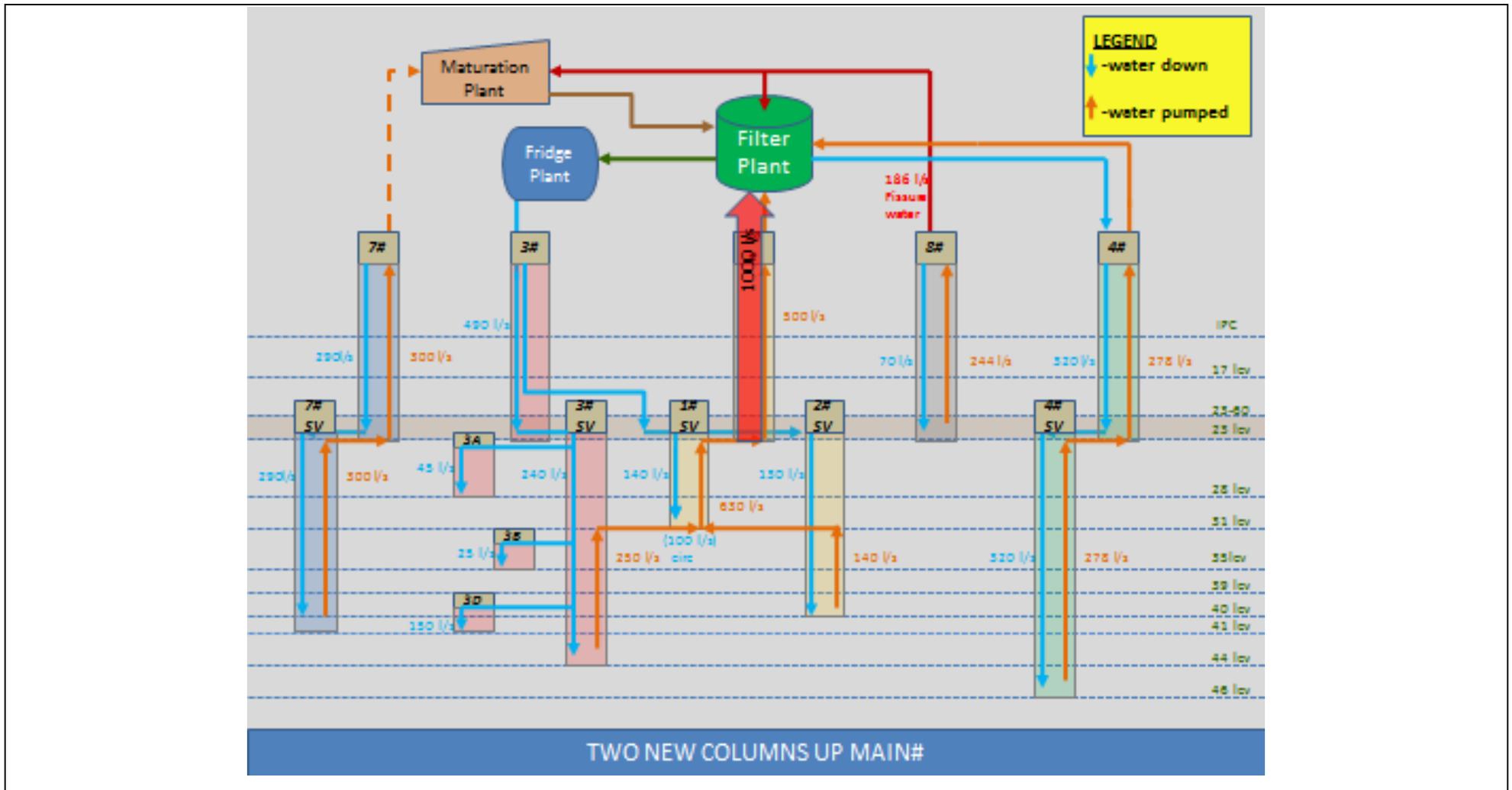


Figure 6-8: Mine Shaft A water transfer to surface upgraded to a flow rate of 1 000 l/s