A NEW MINIMUM COST MODEL FOR WATER RETICULATION SYSTEMS ON DEEP MINES

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ABSTRACT

Title: A new minimum cost model for water reticulation systems on deep mines
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In the past, electricity in South Africa was taken for granted. This situation suddenly changed in January 2008, when the electricity supply system threatened to collapse. Energy efficiency was suddenly brought to the fore when steep tariff increases and consumption penalties were enforced on consumers.

The mining sector is affected most severely. The expected tariff increments, together with consumption penalties, will drastically increase production costs. A number of mines will be forced to reduce production or even close in order to avoid these high costs. This will have a negative effect on the South African economy that relies heavily on mining to earn foreign exchange.

In deep level mining, water reticulation is one of the primary consumers of electricity. The refrigeration plants, together with the underground water supply and underground dewatering systems are integrated to form a complete water reticulation system. This system uses up to 41.9% of the total energy consumption on a typical gold mine. It is used to extract hot water from the mine, refrigerate it and distribute the cold water back to underground mining levels. Work has been done on individual elements of dewatering and refrigeration systems to reduce electricity costs. However, no results could be found of an integrated control solution for all aspects of mine water reticulation.

In this study novel techniques were developed to integrate, simulate, optimise and control all elements involved in the water reticulation system. This enables quick assessment of the effect of individual components on the complete system. By integrating all elements into a single system, components can now be optimally controlled without adversely affecting other parts of the system.

These techniques were applied on Kopanang and Tshepong water reticulation systems. The results concluded that over and above conventional demand side management (DSM) initiatives, additional savings could be realised.

An additional outcome was to develop generic models to evaluate and optimise any deep level mine dewatering system. These models were applied on a number of mine dewatering systems. By using these new techniques on only two mines, the average load was reduced by 2.3 MW, which realises annual savings of more than R 3-million (2008 tariffs).

The new models should be applied on all deep level mines to optimise energy consumption on their water reticulation systems. The mining sector can save more than R 20-million annually at 2008 tariffs. It is also suggested that this application be applied to other sectors, such as large water distribution installations.

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SAMEVATTING

Titel: ‘n Unieke besparingsmodel vir waterretikulasiestelsels in diep myne.
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Promotor: Prof. M. Kleingeld
Graad: *Philosophiae Doctor* in Ingenieurswese (Elektries)

Elektrisiteit is in die verlede in Suid-Afrika as ‘n gegewe beskou. In Januarie 2008 het die situasie egter drasties verander toe Suid-Afrika se elektrisiteitsvoorsieningstelsel gedreig het om plat te val. Effektiewe energieverbruik is skerp onder almal se aandag gebring met strawwe tariefverhogings en boetes wat op verbruikers ingestel is.

Die verhoogde tariewe en energieverbruikboetes beïnvloed die mynwese nadelig, aangesien dit verhoogde produksiekostes teweegbring. Baie myne sal gedwing word om produksie te verlaag of om te sluit, omdat hulle nie die verhoogde tariewe sal kan bekostig nie. Dit sal op sy beurt ‘n negatiewe effek op die Suid-Afrikaanse ekonomie hê, omdat die land swaar steun op mynbou ten einde buitelandse valuta te verdien.

Waterretikulasiestelsels in diep myne is een van die primêre verbruikers van elektrisiteit. Hierdie stelsels pomp warm water uit die myn, verkoel dit en versprei die verkoelde water terug na die ondergrondse vlakke. Navorsing is gedoen op beide individuele ontwateringselemente en verkoelingstelsels op myne om elektrisiteitskostes te verlaag. Geen studie is egter gevind van ‘n geïntegreerde kontrolestelsel vir alle elemente van waterbesparing op myne nie.

In hierdie studie is nuwe tegnieke ontwikkel om alle elemente wat betrokke is by die waterretikulasiestelsels te integreer, dan te simuleer, optimaliseer en laastens te beheer. Dit sal lei tot die vinnige evaluering van die effek van die individuele komponente op die stelsel as ‘n geheel. Wanneer al die elemente geïntegreer word in ‘n enkele stelsel, kan die komponente optimaal beheer word sonder om ander dele van die stelsel te beïnvloed.

Hierdie tegnieke is toegepas op Kopanang en Tshepong myne se waterretikulasiestelsels. Die resultate het getoon dat addisionele besparings teweeggebring kan word, bo en behalwe die “demand side management” (DSM) inisiatiewe.

‘n Verdere uitkoms van die studie is ook die ontwikkeling van generiese modelle om enige ontwateringstelsels in diep myne te evalueer en te optimaliseer. Die modelle is gebruik op verskeie mynontwateringstelsels. Toepassing van hierdie nuwe tegnieke op slegs twee myne het gelei tot ‘n besparing van 2.3 MW, wat ‘n jaarlikse besparing van R 3 miljoen tot gevolg het (2008-tariewe).

Hierdie model moet geïmplementeer word op alle diep myne om energieverbruik in waterstelsels te optimaliseer. Deur die model te implementeer, kan die mynwese tot R 20-miljoen per jaar bespaar (2008-tariewe). ‘n Verdere voorstel is om hierdie model ook vir groot waterverspreidingsaanlegte te gebruik.

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It is a pleasure to thank the many people who made this thesis possible:

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- Finally, and most importantly, I would like to thank the almighty God, for it is under his grace that we live, learn and flourish.

- Everything was done to acknowledge sources of information and references to published works. However, should the reader notice any omission, please inform me for rectification.

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ABBREVIATIONS

ΔT : change in temperature of the fluid
˚C : Celsius
3-CPS : Three chamber pipe system
AC : Alternating current
BAC : Bulk air coolers
Btu : British thermal units
c/kWh : cent per kilowatt hour
c_p : specific heat capacity for water
COP : Coefficient of performance
DSM : Demand side management
ECS : Energy conservation scheme
EE : Energy efficiency
ED : Energy dissipater
EIA : Energy information administration
ELCON : Electricity Consumers Resource Council
ESCo : Energy Service Company
ESCos : Energy Service Companies
GM : General Manager
H : Head
HVAC : Heating, ventilation and air-conditioning
HT : High tension
IEP : Integrated energy planning
kg/MWh : kilograms per Megawatt hour
km : kilometer

kVA : kilovolt-Ampere

kW : kilowatt

kWh : kilowatt-hour

kl : kilo litre

L : Level

m : meter

m/T : mass flow rate

M&V : Measurements and verification

Ml : Megalitre

MPa : Mega Pascal

MVA : Megavolt Ampere

MW : Megawatt

MWh : Megawatt hour

NPSH : Net Pressure Suction Head

Pa : Pascal

PLC : Programmable logic controller

PDV : Pump discharge valve

q : heat transfer rate

Qty : Quantity

R/kWh : Rand per kilowatt hour

RTP : Real-time pricing

RTU : Remote terminal unit

R^2 : Coefficient of determination

REMS : Real-time Energy Management System

RSA : Republic of South Africa

SCADA : Supervisory control and data acquisition

SHE	:	Safety health environment
SF	:	Suction Filter
SPV	:	Shock prevention valve
SV	:	Suction valve
TOU	:	Time of use
t	:	Ton
VAT	:	Value Added Tax
VUMA	:	Ventilation of Underground Mine Atmospheres

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CHAPTER 1: Introduction and background

This chapter presents background on the current electricity situation in South Africa and introduces all the components that are integrated to form a complete water reticulation system. Some of the water management, efficiency models and monitoring systems presently on the market are also discussed. The outcome of this chapter highlights the need for a simplified simulation and automation system that could be used to integrate a water reticulation system.

1.1 Demand Side Management (DSM) in South African mining

1.1.1 South African economic and electricity demand growth

The need to conserve energy has become one of the fundamental issues of the 21st century. The time of abundant energy being readily available is over [1],[2]. Growing populations and economies have led to an increased demand for energy, particularly electrical energy [3].

According to figures released by South Africa Info [4] in 2005, the annual economic growth rate averaged 3.5% from September 1999 to June 2005. The South African economy is also very energy intensive [5] and therefore the electricity demand is expected to increase by 1,200 MW per year [6].

It was forecast that the existing power generation capacity of South Africa will be insufficient to meet this rising demand [7]. This was verified when the national electricity grid threatened to collapse in January 2008. Unscheduled maintenance required that some electricity generators be taken off-line. The 8% South African reserve supply margin was inefficient to buffer the increasing demand and as a result Eskom introduced national power shedding [8].

1.1.2 South African electricity demand

Eskom, the producer of 60% of the electricity in Africa [9], conducted investigations into the massive increase in electricity demand [10]. The outcome of this investigation indicated that the power demand profile followed certain predictable trends.

During weekdays the demand is much higher than Saturdays, Sundays and public holidays. Figure 1 illustrates the demand during a typical working weekday. This figure highlights the importance of **time of day** in maximum daily demand peaks.

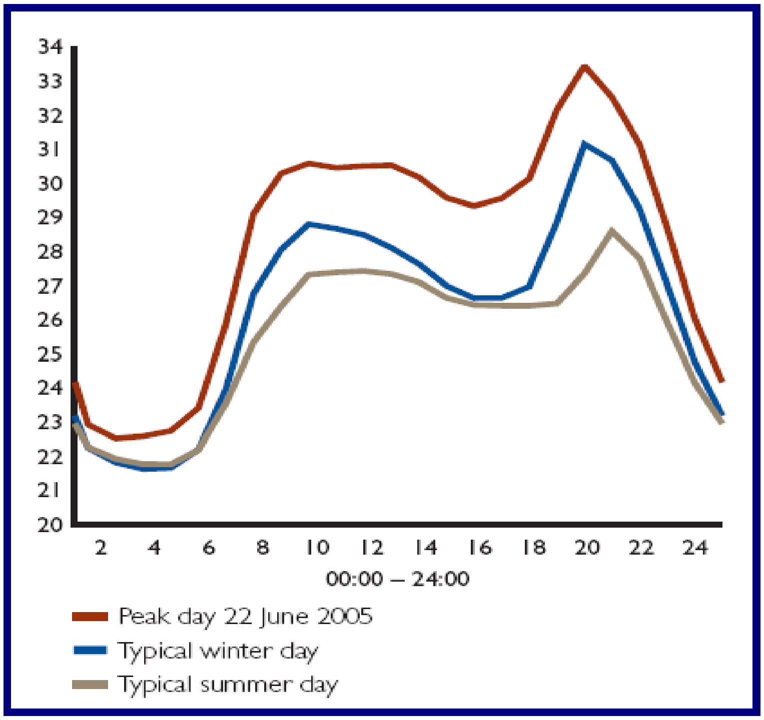


Figure 1: Daily electricity demand [11]

During a typical week day the electrical demand increases between 07:00 and 10:00 and again between 18:00 and 20:00 [12]. It can also be seen from the figure that the maximum demand during the evening peaks is much larger than the morning peaks. The morning peak times, however, last longer.

1.1.3 **Time-of-use pricing**

To encourage clients to consume less energy in peak demand periods, Eskom introduced time-of-use pricing tariffs. These structures result in increased tariffs during the high peak periods and lower tariffs during low peak periods [13].

One such tariff is Mega Flex**.** This time-of-usage tariff was developed for urban, industrial and mining customers with a Notified Maximum Demand from 1 MVA. This tariff consists of three different time pricing periods, namely peak, standard and off-peak [14], shown in Figure 2.

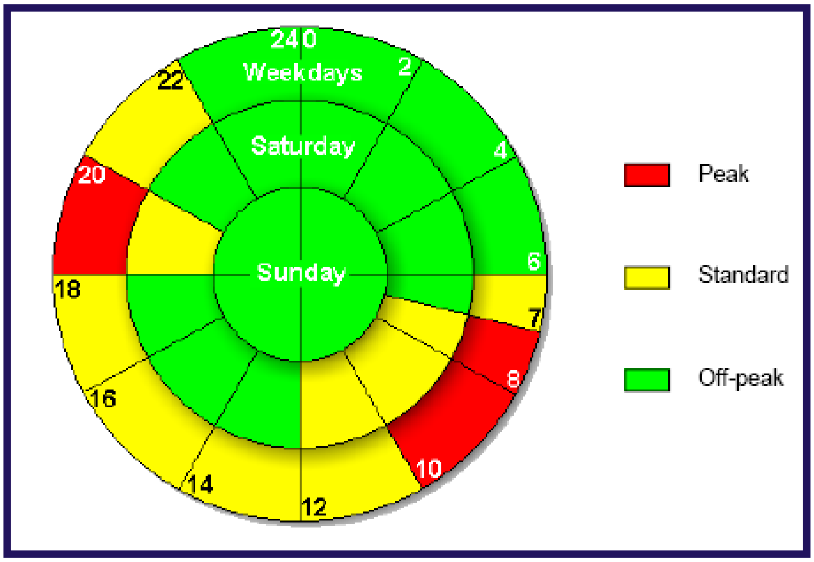


Figure 2: Mega Flex - Variable pricing chart

From Figure 2 it can be seen that peak times, coloured in red, are from 07:00 – 10:00 and 18:00 – 20:00. The off-peak times, coloured in green, are from 22:00 – 06:00. In the off-peak times electricity costs are much cheaper than the standard or peak times.

In June 2008, the main electricity utility of South Africa, Eskom, was granted a 27.5% tariff increase to expand their overburdened generating plants. The new 2008/2009 tariffs are shown in Table 1 [14]. Similar increases are also expected for the next five years.

Table 1: Mega Flex – energy usage tariffs (2008/2009)

High-demand season (June – August)		Low-demand season (September – May)
74,21c + VAT = **84,60c/kWh**	**Peak**	21,06c + VAT = **24,01c/kWh**
19,62c + VAT = **22,37c/kWh**	**Standard**	13,07c + VAT = **14,90c/kWh**
10,97c + VAT = **12,16c/kWh**	**Off-peak**	9,26c + VAT = **10,56c/kWh**

From Table 1 it can be seen that the pricing structure differs significantly between winter and summer periods. The reason for this is that the demand for electricity is much higher during winter (June, July and August) than in summer (September – May).

1.1.4 Demand side management

To enhance reaction to the variable electricity pricing systems, Eskom introduced the DSM (demand side management) programme in 1992 [15]. This programme sponsors projects that successfully respond to the variable pricing structure. It also entails actions that manipulate or control the times and quantity of energy consumed by the user. These actions result in either reducing energy demand during peak time periods or reducing overall energy consumption.

DSM intervention mechanisms can generally be broken down into four categories. These categories are load shifting (Figure 3), strategic load growth (Figure 4), energy efficiency (Figure 5) and peak clipping (Figure 6).

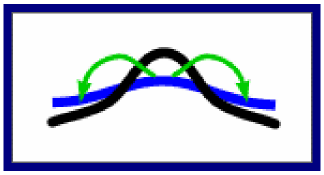


Figure 3: Load shifting

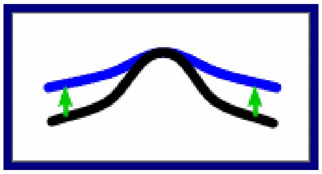


Figure 4: Strategic load growth

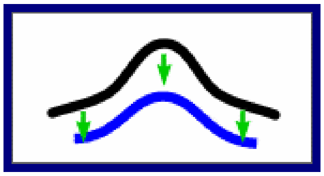


Figure 5: Energy efficiency

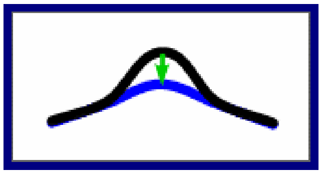


Figure 6: Peak clipping

- **Load shifting [16]** involves the revising of the time at which a customer uses electricity. This is achieved with the aid of price-based incentives, such as time-of-use (TOU) tariffs and real-time pricing (RTP).
- **Strategic load growth** is used by utilities that have surplus power. Additional electricity sales are created with regard to the time of the day.
- **Energy-efficiency [15]** involves conversion to more efficient end-use technologies and practices. This is beneficial for both the customer and the utility.

- **Peak clipping [17]** allows a utility to cut the power to a portion of the customer's site for a limited period. The customer is compensated for this interruption.

1.1.5 Energy conservation scheme (ECS)

The main focus of the variable pricing structure and DSM programme was not to reduce the national electricity consumption, but to rather force the client to use the same amount of electricity in a different time period. However, after the national generation capacity was unable to supply the South African demand, this focus changed to energy efficiency (EE). Unfortunately time is limited and a more drastic measure than DSM has to be taken.

Eskom is presently engaging plans to implement its energy conservation strategy in the first quarter of 2009. The plan is to determine how much energy users consume over a period of one year. Penalties will then be imposed on clients who consume energy in excess of a predetermined agreed-on figure [18]**.**

The penalty system will be divided into three windows. The first is when an end-user uses between 100% and 101% of its allocated energy. In this case the user would pay R 2.80/kWh. If an end-user consumes anything more than 101% and less than 110% of its allocated energy supply, the cost would increase to R 4.50/kWh. For any electricity consumption more than 110% of the allocated energy supply, the penalty will increase to R 9.00/kWh [19].

The reason for the steep fines is due to the fact that South Africa does not have enough capacity for the next five years. To ensure economic growth, a reliable source of energy must be made available to the industry. By applying these profound penalties, Eskom expects to instigate a culture of energy saving.

1.1.6 South African mining

One of the sectors that are influenced most severely by the recent Eskom tariff increases is the mining sector. To prevent blackouts, the mining sector was forced to operate between 90% and 95% of their normal electricity consumption [20]. This has a negative effect on the South African economy, which relies heavily on mining to earn foreign exchange.

The South African mining industry is also a large electricity consumer. Mining in South Africa consumes 17.6% of all electricity generated [21], as shown in Figure 7. It can also be seen from the figure that municipalities and townships are the largest consumers during evening and morning peak demand times. Changing the power profile of thousands of households will have the same effect as changing the power profile of a typical mine.

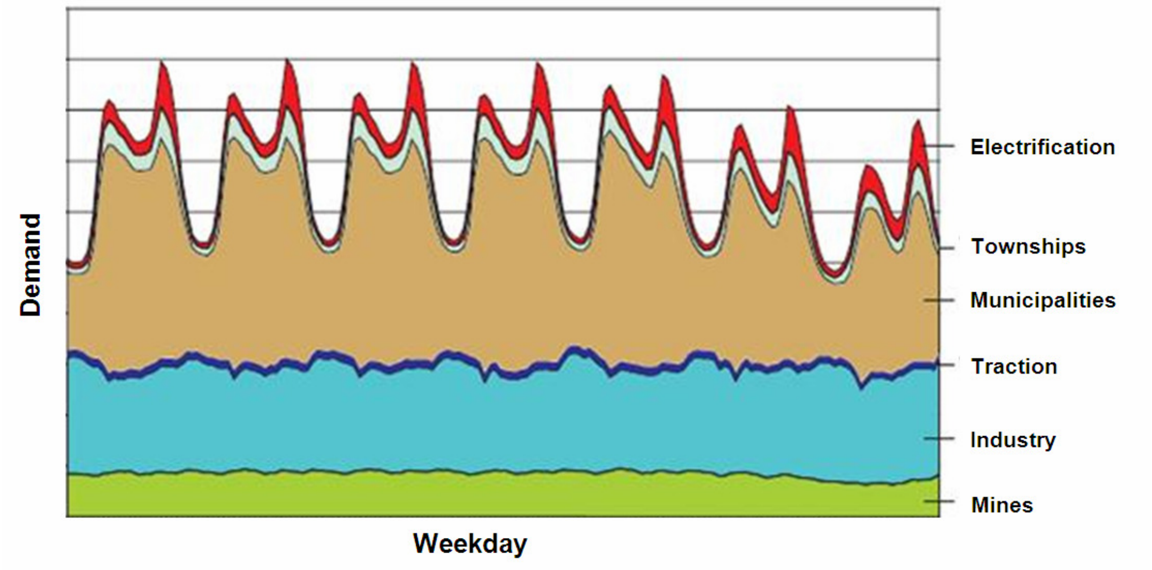


Figure 7: Weekly Total electricity demand (%)

Gold has been an important driver of the South African economy. The country supplies 12% of the global gold output [22]. Within South Africa, the gold mines are also the single greatest users of electricity across all mining sectors. The amount of electricity used for gold mining is almost as much as the electricity used by all the other mining sectors combined.

One of the major day-to-day challenges South African deep mines face is the high underground temperatures that are encountered. Temperatures increase dramatically as the mining depth increases. This causes great difficulty to create and maintain comfortable working conditions for both humans and machines [23].

Therefore, deep level mines require unique cooling methods. If cost, reliability and safety are taken into consideration, the best cooling technique has been shown to be large refrigeration plants [23]. These plants use large amounts of water as a cooling medium, which is transported to underground working levels. The refrigeration plants, together with the underground water supply and underground dewatering systems are integrated to form a complete water reticulation system. This system uses up to 41.9% of the total energy consumption on a typical gold mine [16].

1.2 Mine water reticulation

As discussed in the previous section, refrigeration plants are used to reduce the water temperatures that are fed underground for cooling purposes. These plants are usually located on surface. However, due to the extreme depths of some mines, refrigeration plants are installed underground. The water that feeds the refrigeration plants is usually water that is pumped from underground. However, water can also be purchased from local water-councils, should low system water volumes create operational difficulties.

Figure 8 shows a typical refrigeration layout of a mine.

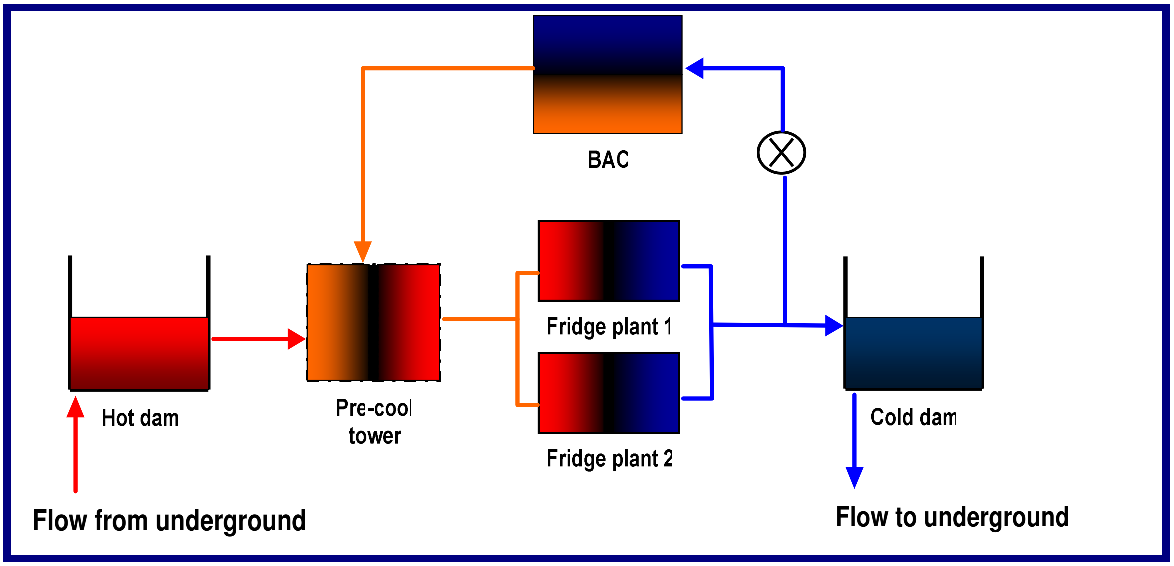


Figure 8: Typical refrigeration of a mine

Hot water is pumped from underground to the surface hot dam at a temperature of 25℃ – 30℃. This water is then pre-cooled through the cooling towers to an outlet temperature of 15℃ –20℃. The cooling towers use ambient air to cool down the hot underground water. After passing through the cooling towers the water is fed into the refrigeration plants where further cooling takes place to the desired outlet temperature, which is usually about 3℃.

A percentage of the cold water supplied by the refrigeration plants is then passed through the bulk air cooler (BAC). A major part of the cold water flows to the cold dam, supplying cold water to various underground levels. The main purpose of the BAC is to cool the ventilation air, which flows through to the mineshafts. The water is heated as it passes through the BAC, but is still colder than the underground water. The water from the BAC is still able to decrease the temperature of the warm water coming from the pre-cool tower.

For each mine the refrigeration plants are required to supply a required reduction in water temperature - ΔT. This temperature is determined by considering the underground working conditions. In many of the cases the installed refrigeration capacity is over-designed to accommodate future mine developments [23].

Some deep level mines reach depths of up to 4 000 m below surface. Due to these depths, the water fed underground creates extreme high pressures. The shaft column pressure must be reduced before water is used for services or cooling as seen in Figure 9.

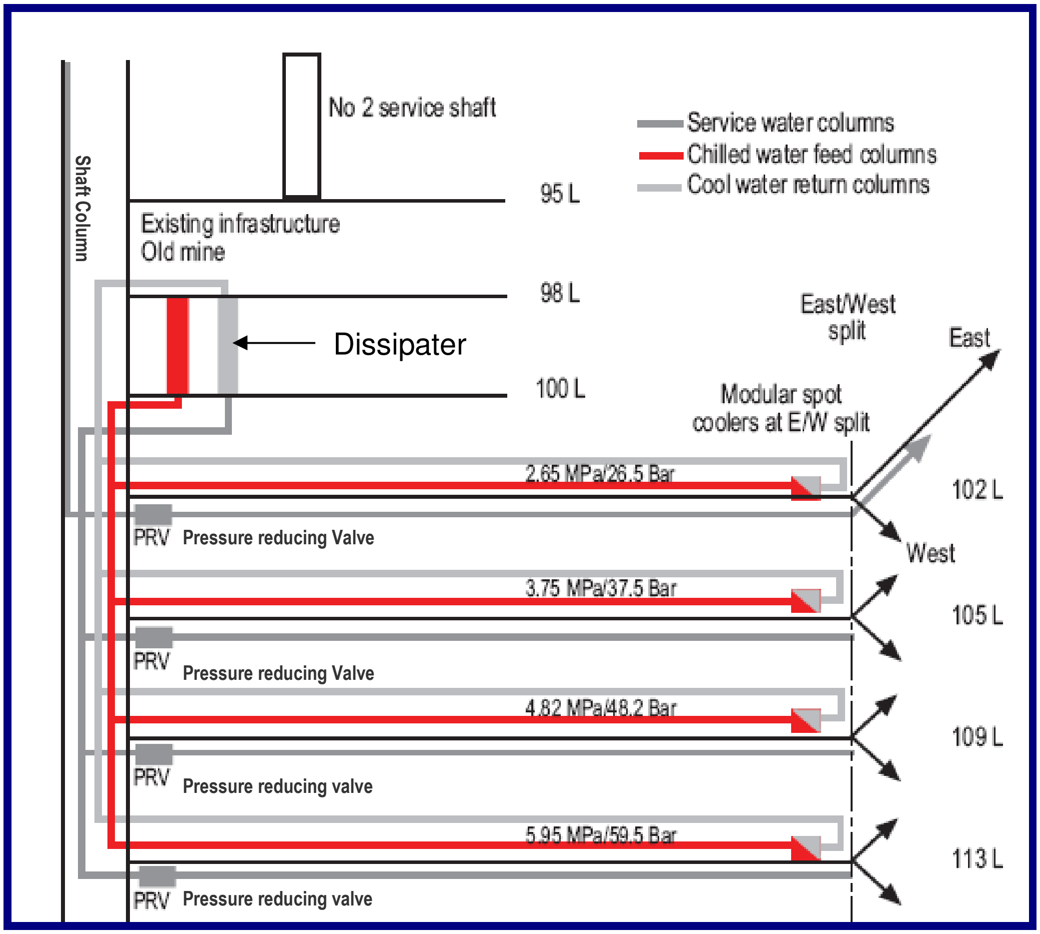


Figure 9: Mine water layout of the “New Mine” at Elandsrand [24]

A dissipater or pressure-reducing valve is installed on each main column and level pipe to reduce the downstream pressure of the water fed to the mining sections. To reduce the high column pressure, the pressure reducing valves convert the gravitational potential energy into thermal energy. This result in an increase in the underground temperature and therefore a more efficient solution is required.

The three chamber pipe system (3-CPS) and turbine-pump configurations are alternatives to the inefficient dissipater. These configurations make use of the mechanical energy generated by the high static water to deliver usable shaft work. This work can be used to pump water out of the mine. For more details about these systems refer to Appendix A.

After the cold water has been used for either drilling, cleaning (sweeping) or for further cooling operations, such as in cooling cars and spot coolers, it is channelled from the various levels into underground settlers (Figure 10).

Figure 10: Underground settler

Natural underground water or fissure water that seeps from the rock surfaces, adds to the service water entering the settlers. These settlers are used to separate mud particles from the water after it has been used in the mining operation.

The water flows towards the settlers in channels containing flocculent, which increases the density of the mud particles in the water. This causes the mud to sink to the bottom. For this reaction to be effective, the pH level of the water must be maintained between 3 and 7, depending on the type of flocculent used [25]. To meet this requirement, lime is usually added to the water before it enters the settler [26].

The clear, clean water at the surface of the settler is then channelled to the underground clear water dam. This water is then pumped back to the surface by means of the dewatering system. The dewatering system is a necessary and very complex system that must be controlled efficiently. It is used to prevent flooding and to maintain adequate water levels to ensure proper functioning of the cooling process.

The dewatering system supplies underground hot water to a number of refrigeration plants and cooling towers on the surface [26]. Underground refrigeration plants have been constructed and installed in certain deep level mines [23]. A basic layout of a typical underground pumping system at a deep level gold mine is shown in Figure 11.

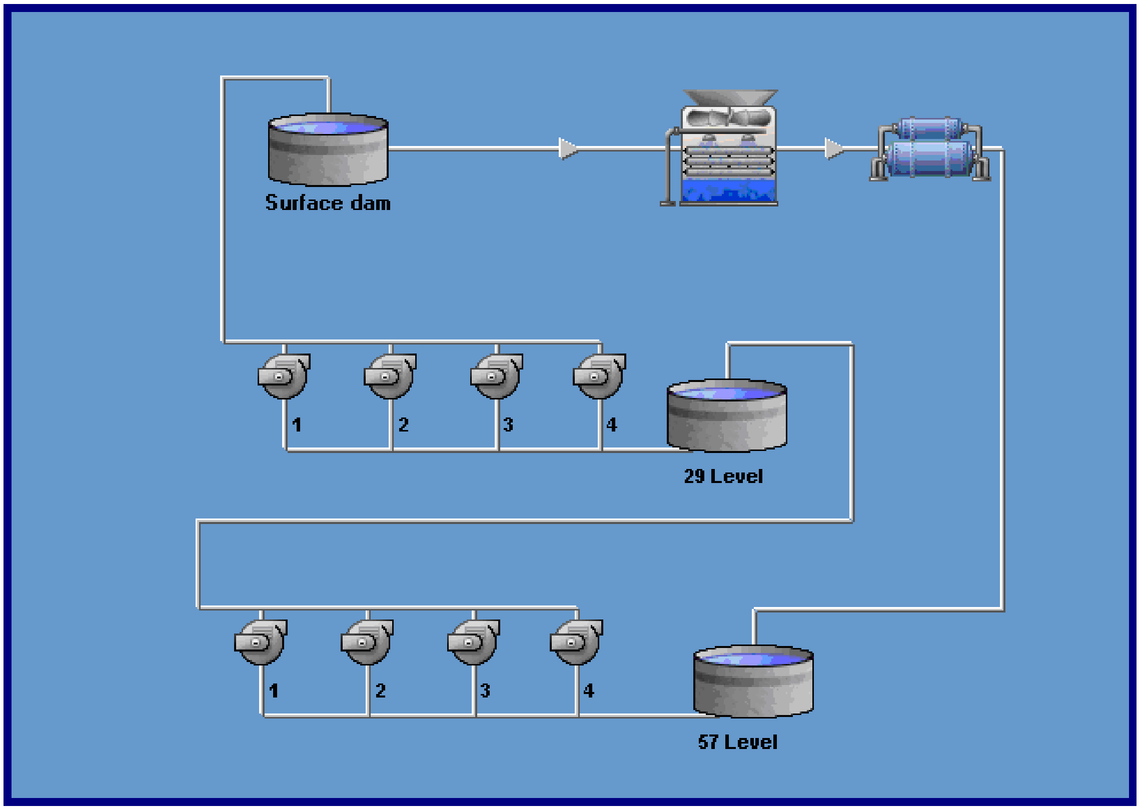


Figure 11: Basic layout of a typical underground pumping system at a gold mine

From Figure 11 it can be seen that multiple pumping levels are possible. This is usually the case for deep level mines. Goldfields Kloof 7 Shaft reaches a depth of more than 3 000 m below the surface and makes use of five cascaded pumping stations [27]. The water is pumped from one pumping station into an upper level dam. This process is repeated until the water reaches the surface or is re-used somewhere in mid-shaft as service water. When the water reaches the surface it flows into the refrigeration plant to be cooled.

The typical closed loop water reticulation process described above is illustrated in Figure 12. If the total volume of the water cycle decreases, it is replenished by adding external water from a local water supplier.

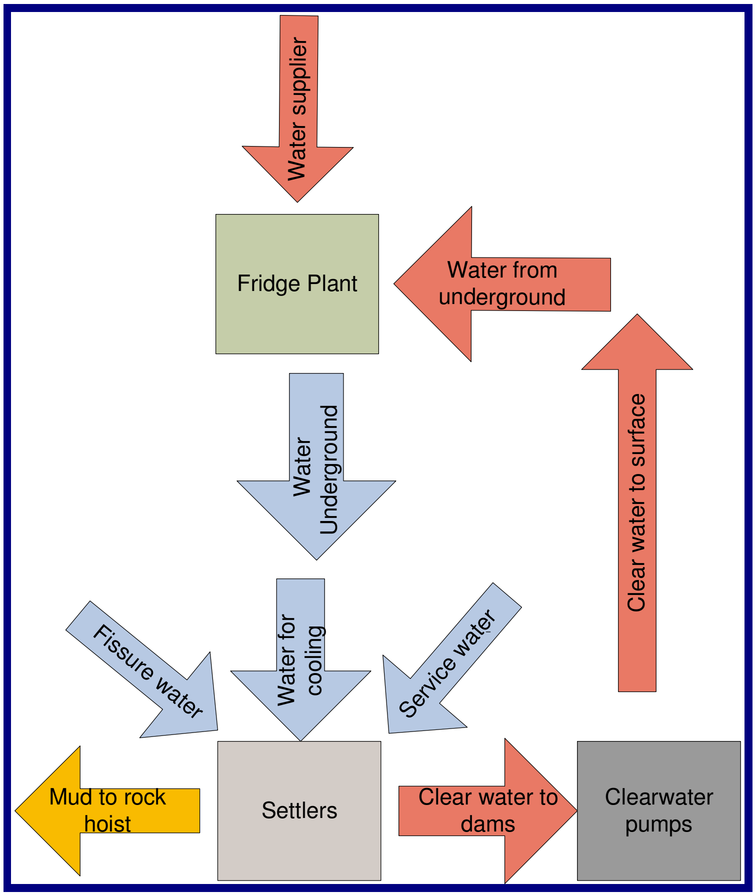


Figure 12: Mine water cycle

1.3 Existing monitoring, management and efficiency measurements

1.3.1 Overview of existing systems

Increases in electricity costs in South Africa and the pressure to reduce pollution worldwide has increased the need for energy efficiency and energy management systems. However, not all control systems focus on energy alone. Some of the software discussed in this section will only focus on the management of water distribution systems. A number of techniques and models to determine efficiencies are also discussed.

In this section, systems concentrating on water reticulation and energy management will be evaluated and compared. The requirements for a complete computerised mine water reticulation system, as well as a mine dewatering efficiency model will be discussed.

Table 2 gives an overview of systems presently being used to control, simulate or determine the efficiency of water distribution systems. These systems will be discussed in the sections that follow. The various properties of each system are categorised.

Table 2: Water control, management and simulation systems

System	Simulation	Optimisation	Load Shifting	Energy efficiency	Reduce running cost	Control	Automated Operation	Monitor	Water refrigeration	Water Pumping
Motor current monitoring				●				●		●
TAS Online		●		●				●		●
Rajan pump performance model				●				●		
A guide to improve energy efficiency		●		●						
Underground Pump Operator						●		●		●
PLC Programming						●	●		●	●
Adroit						●	●	●	●	●
Wonderware Intouch						●	●	●	●	●
WinCC						●	●	●	●	●
VUMA	●	●	●		●				●	
U.S. Patent No.6366889 by Zalloom	●	●	●		●					●
U.S. Patent No. 6178362 by Woolard et al.	●	●	●		●					●
H2ONET Scheduler		●	●		●	●				●
RTP ControlTM by Honeywell Inc			●		●	●	●			
SA Patent No. 2004/1172 by Temm Int (Pty) Ltd.			●			●		●		●
Real-time energy management system (REMS) for Pumps	●	●	●		●	●	●	●		●
Real-time energy management system (REMS) for Fridge plants	●	●	●		●	●	●	●	●	

1.3.2 Pump condition monitoring and efficiency models

1.3.2.1 Overview of pump monitoring and efficiency models

Because most underground dewatering pumps consume large amounts of electricity, monitoring a pumping system is important. Figure 13 shows the long-term benefit obtained by regular maintenance on a pumping system. It is also made clear from the graph that the outcome of the unmaintained pumping system eventually is replacement.

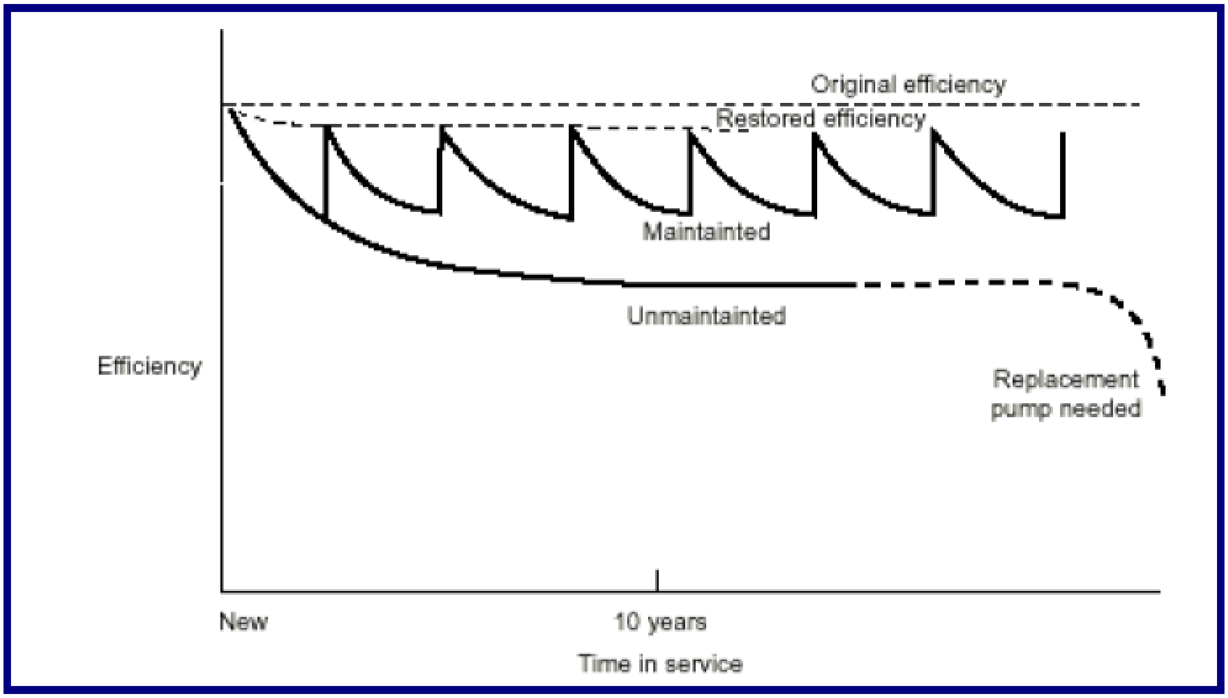


Figure 13: Maintenance on pump efficiency [28]

There is no agreed figure on how much efficiency a pump will lose if not maintained. However, according to studies conducted in the United Kingdom the following facts were prominent [28]:

- Most of the loss occurs in the first few years of life.
- After about ten years the loss starts to level out.
- The overall drop in efficiency for an unmaintained pump can be up to 15%.
- 85% of the lifetime cost of a pump is for its energy consumption.
- An un-maintained pump can fail catastrophically after 20 years' service.

The pump maintenance and efficiency models presently on the market range from simple monitoring to complex calculations. In this section an overview of some of these systems will be discussed.

1.3.2.2 Manual motor current monitoring

Electrical current is related to the pump power consumption. The current drawn by the motor will give a good indication of the efficiency of the pumping system. Because underground mine dewatering pumps pump at an enormous fixed static head and constant flow, any changes in current should be closely monitored to identify inefficient operations. A current monitoring system can therefore be used to detect any possible problems that may exist in a pump. The amperage drawn by each motor is logged on an hourly basis, and if any changes are identified, an investigation is launched.

Figure 14 shows the effect of deterioration on the pump characteristics.

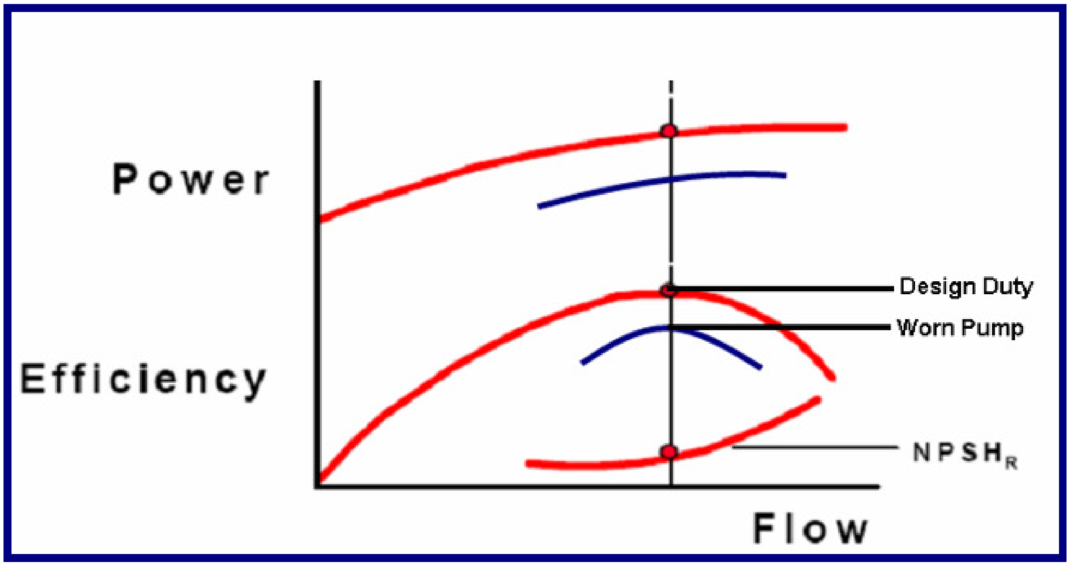


Figure 14: Effect of deterioration on pump characteristics

In the figure it can be seen that if the power of a motor driving the pump reduces, the efficiency also decreases. Therefore monitoring the motor current on a daily basis is good practice. However, the system is only limited to the efficiency of a single pump, and the overall efficiency of the dewatering system cannot be monitored.

1.3.2.3 Tas Online [29]

Tas Online's PumpMonitor® system quantifies real-time and lifetime efficiency cost of a pump. This monitoring system can also predict the most cost-effective time to replace or refurbish a pump and therefore aids in scheduling maintenance. This system also gives early identification of potential equipment failure and problems. Therefore worn pump accessories can be replaced before permanent damage is caused to the pump. This will reduce the lifetime cost of the pumps.

The information provided by this system can also assist in load shifting projects by identifying the most efficient pump. During the Eskom evening peak periods the less efficient pumps will be switched off first. Therefore the more efficient pumping combinations can be operated during the peak periods.

This system can only assist in energy management and is by no means a real-time energy management system. It does not focus on the efficiency of the dewatering system, but only on that of the individual pumps. It also does not take any water efficiency into consideration.

1.3.2.4 Optimising energy efficiencies in industry [30]

Two pump performance models were developed by Rajan [30]. The one model monitors the performance from the design characteristics of the pump. In this approach the theoretical pump performance is interpolated from the input data, like flow rate and head. By using these inputs the efficiency of a pump can be calculated.

In the second model from Rajan, the model was developed to monitor the performance of the pump as a function of time. This is based on the concept that the performance of the pump deteriorates with time. If the performance deteriorates faster, the pump should be investigated for possible problems or be overhauled.

Both these models focus on the performance of a specific pump and not a system. Therefore the effect of poor water management will not be identified.

1.3.2.5 "A guide for improved energy efficiency, reliability & profitability" [31]

"A guide for improved energy efficiency, reliability and profitability" discusses a few steps to improve efficiencies. This book lists a few symptoms of inefficient pumping systems. Some of these symptoms include existence of bypass lines and throttled valves. Solutions, such as variable speed drives, are also discussed. This guide therefore focuses on industrial applications and not necessarily mine dewatering (see Appendix A). Water efficiencies are also not calculated.

1.3.3 Industrial simulation and control

1.3.3.1 Overview of industrial simulation and control

A number of control and simulation software packages are available on the market. Some of them are very complex. In this section a few systems will be discussed and the need for a simplistic control system highlighted.

1.3.3.2 Traditional mine dewater and refrigeration management

Traditionally, underground pump stations and refrigeration have been controlled by pump operators. Usually a team of three operators, depending on the amount and condition of the pumps or refrigeration plants, are assigned to an underground pump station. At the time of writing the average salary of an operator was R 5 000 per month.

The pump operator is required to control the underground dam level between specific levels by using his own discretion. A mechanical level float is usually installed on each dam and has to be monitored by the operator. Figure 15 shows the typical dam level trend and pump status of an underground pump station, which is manually controlled. This figure demonstrates that the pumps are started and stopped with no consideration of the variable pricing structures.

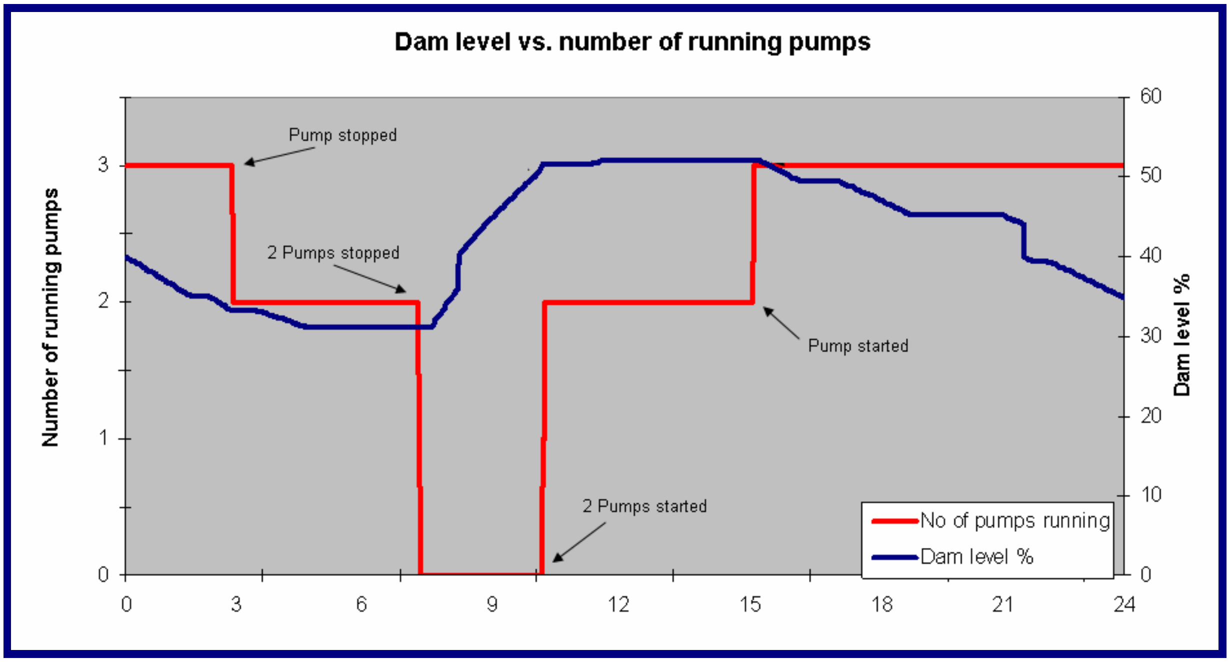
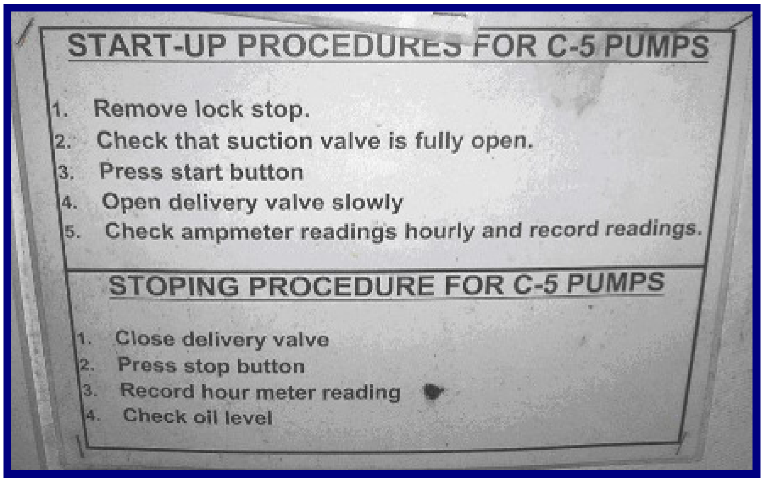


Figure 15: Typical control philosophy of underground pump operators

When a pump is started or stopped by an operator, it has to be done according to guidelines formulated for the specific pumping system. Figure 16 shows a picture explaining these procedures at the underground pump station of Masimong Gold Mine.



START-UP PROCEDURES FOR C-5 PUMPS

1. Remove lock stop.
2. Check that suction valve is fully open.
3. Press start button
4. Open delivery valve slowly
5. Check ampmeter readings hourly and record readings.

STOPING PROCEDURE FOR C-5 PUMPS

1. Close delivery valve
2. Press stop button
3. Record hour meter reading
4. Check oil level

Figure 16: Start-up and stopping procedures for C-5 pumps [32]

The operators are also required to take hourly runtime readings, bearing temperatures, dam levels and amperage readings. This information is used by the mining personnel to identify potential problems with either the pump or the motor.

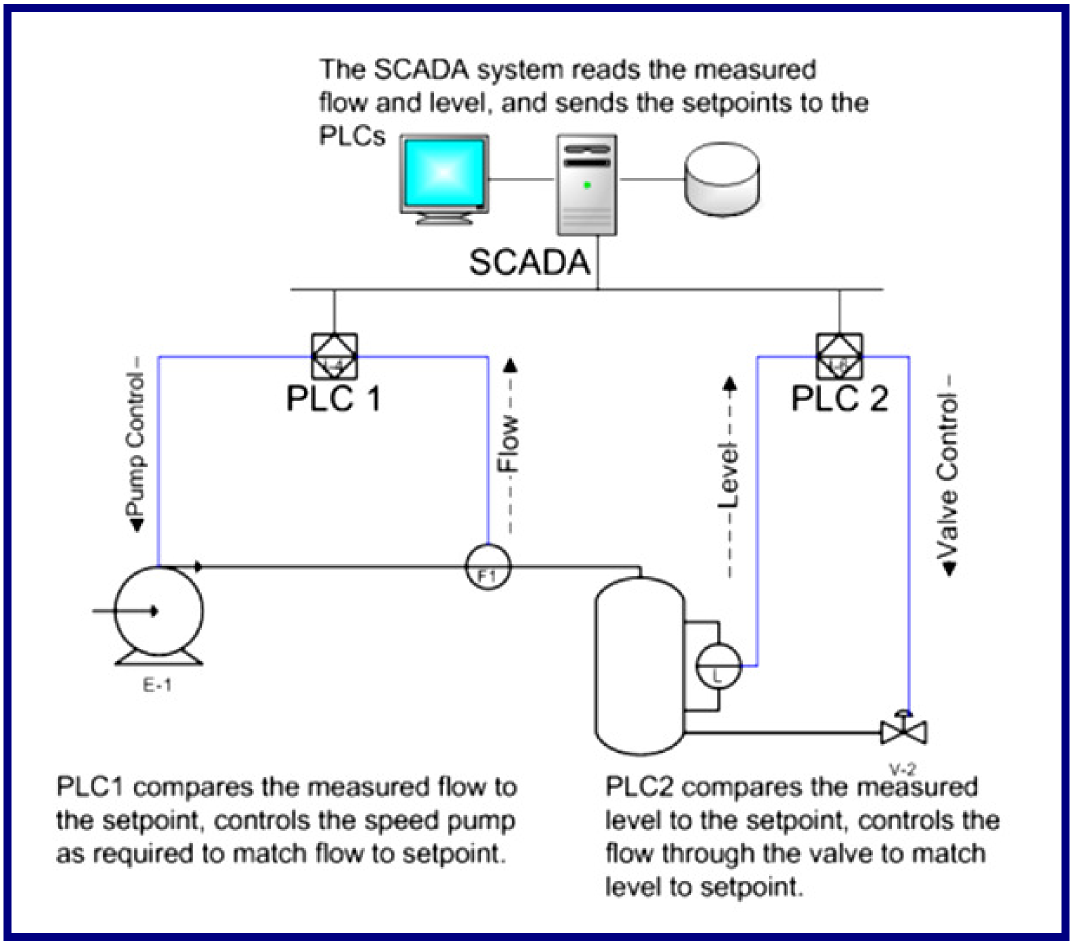
The same type of control is done on the refrigeration systems. However, the operator is usually not allowed to stop or start any machines. His primary function is to monitor the system temperatures and dam levels. If for some reason the system needs to be stopped, the operator should contact the relevant artisan to assist him.

The manual pump and refrigeration control is one of the most primitive control strategies. By using this method only minimum electricity cost is being achieved. Due to poor operator skills and technical knowledge, the operation is usually not very effective in terms of energy savings. Pump, motor and refrigeration maintenance is also usually poorly managed and money is wasted due to the inefficiencies.

1.3.3.3 SCADA packages

A supervisory control and data acquisition (SCADA) refers to centralised systems that can monitor and control multiple systems or components from a remote computer station. This remote server is usually situated hundreds of metres from the mine. Most of the control actions are performed automatically by remote terminal units (RTUs) or by programmable logic controllers (PLCs). These units and controllers are usually located close to the controlled equipment.

The SCADA system displays the appropriate information from the field PLCs and RTUs on the monitoring display at the site of the main server. Basic input selections on the field equipment can be done from the remote server. A PLC for example, may control the flow of cooling water through part of the refrigeration process. The SCADA system will allow operators at the remote station to alter some of these set points. A typical setpoint is, disable/enable alarm conditions for high temperatures or loss in flow. These setpoints and flow measurements can also be displayed and recorded. Figure 17 shows such a configuration.


The SCADA system reads the measured flow and level, and sends the setpoints to the PLCs

PLC1 compares the measured flow to the setpoint, controls the speed pump as required to match flow to setpoint.

PLC2 compares the measured level to the setpoint, controls the flow through the valve to match level to setpoint.

Figure 17: Typical PLC and SCADA layouts

SCADA packages allow the user to develop a programme by means of control algorithms. This will allow the SCADA to be used to control refrigeration or pump systems. However, programming of SCADA is difficult and requires highly skilled and experienced personnel to programme such a system.

It is impossible for a SCADA system to control an integrated water reticulation system. SCADA systems also do not have the functionality to perform simulations or complex calculations.

SCADAs do not allow for optimisation. This means that load shift by means of SCADA programming will lead to serious problems, such as pump cycling or inappropriate dam levels. Common SCADAs found are Adroid [33], Wonderware Intouch [34] and WinCC [35].

1.3.3.4 PLC Programming

Common Programmable Logic Controllers (PLCs) like the Siemens, Allen Bradley, and Modicon have been used in the past to control refrigeration systems and pumping stations. These controllers, however, have limited memory space. The controllers are also too small and cannot allow any form of database capabilities, therefore simulations and complex models cannot be executed by the PLC.

1.3.3.5 VUMA [36]

Coolflow® is the registered name of the mine water-network modelling tool of VUMA (Ventilation of Underground Mine Atmospheres). This programme allows the user to simulate water-cooling systems.

Applications of Coolflow® include the simulation of chilled water dams, the effects of chilled water in production zones, and the prediction of network system losses quantified per component. This tool lends itself to a wide range of uses in the South African mining environment. One of its successes was the simulation of the refrigeration system at

Mponeng Mine. This system uses ice instead of water to cool down underground conditions.

Coolflow® focuses only on simulations and can supply valuable system information. The system software can, however, not be used as an automatic controller. Since this system is very complex, highly trained and qualified personnel are required to formulate meaningful results using this tool.

1.3.3.6 U.S. Patent No.6366889 by Zalloom [37] and U.S. Patent No. 6178362 by Woolard et al.

U.S. patents No. 6366889 and No. 6178362 claim that they have the ability to optimise energy costs in heating ventilation and air-conditioning (HVAC) systems in mines, buildings and industries. The main focus of this system is to identify operational and costing errors, by assisting the user in analysing energy consumption trends.

One of the features of these systems is the ability to connect to the real-time data by making use of internet-based communication capabilities.

These systems, however, lack the following:

- The simulation tools are not continuous and only give a once-off result and answer.
- Automated control.

1.3.3.7 U.S. Patent No. 5963458 by Cascia et al [38]

This patent makes use of a digital controller that calculates an optimal set point for a single component in a heating, cooling or hoisting system. This set point is calculated in real-time and, if followed, energy consumption will be optimised.

The shortcomings of this system are:

- It does not allow load shift.
- It cannot be used to control multiple components in an integrated system.

1.3.3.8 Municipal water distribution systems

A number of commercial municipal water distribution systems are available. These systems claim to optimise and minimise electrical costs. However, these systems cannot always be applied to mining systems. Significant differences exist between municipal water distributions systems and mine water reticulation. Due to the following elements, different strategies for municipal and mine water reticulation are needed:

- Municipal water reservoirs are larger than underground storage dams in mines. Therefore the mining environment requires more frequent pump cycles and has a greater requirement to reduce pump cycling than the municipal systems.
- The static head of a mine-dewatering pump has a much bigger influence on the total head than that of municipal systems. Municipal systems focus on the distribution of water over large horizontal distances, while the mining environment focuses more on vertical heights.
- Municipal systems focus on water distribution and water quality. In the mining environment water distribution systems have additional requirements, which include integrating with cooling and ventilation systems.

1.3.3.9 H2ONET [39]

This software helps identify the best combination of network improvements that will meet the hydraulic design and performance criteria at minimum cost. It has been developed for the municipal water distribution system. This system is by no means real-time and the operating schedule is only calculated on a daily basis.

1.3.3.10 RTP ControlTM by Honeywell Inc. [40]

This system is commonly used in the commercial and industrial systems and makes use of load shift to optimise electricity tariff costs. It makes use of the heat capacity of large size dams to shift load during the peak periods. Applications for the system include refrigeration plants and water heating. This system, however, does not allow automatic control.

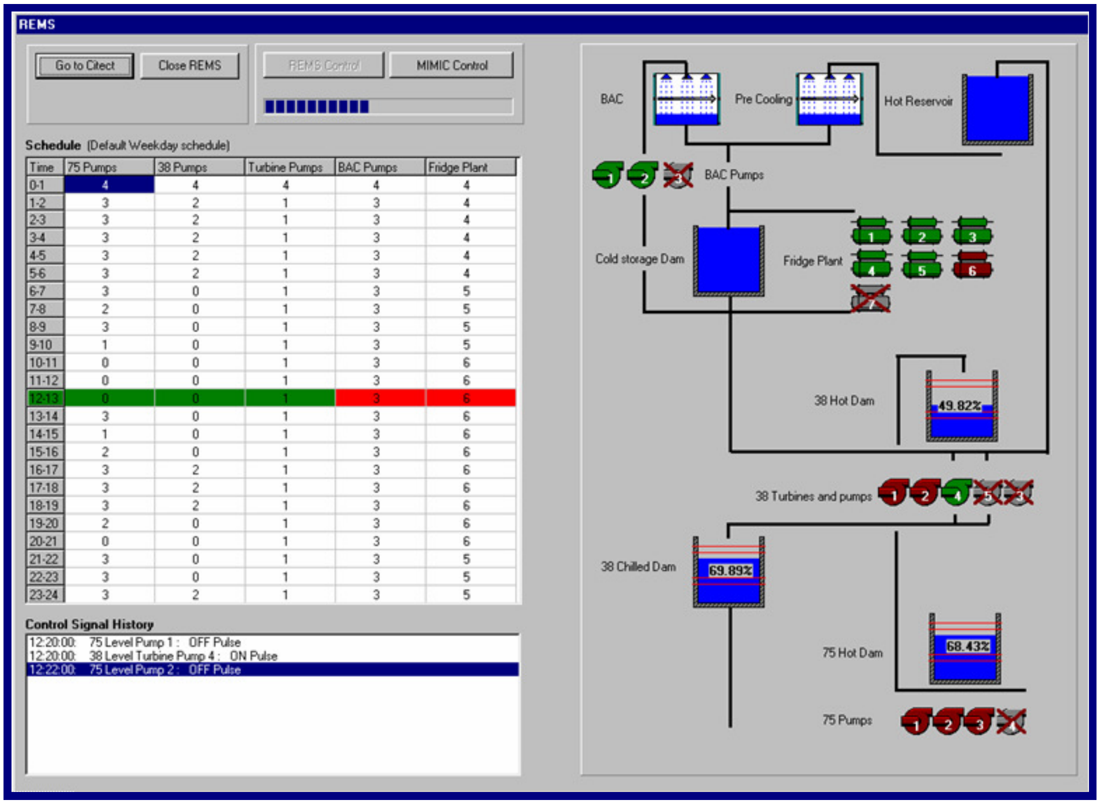
1.3.3.11 SA Patent No. 2004/1172 by Temm International (Pty) Ltd. [41]

This patented system has the ability to control the components of an HVAC system to minimise running costs. The system uses real-time pricing structure to develop a schedule for the following day. This patent also includes software tools that could control the individual components of the HVAC system.

The manufacturer patent claims the following:

- A control system that schedules HVAC equipment 24 hours in advance. It optimises the total energy cost of an installation. The optimisation is based on predicted loads and energy prices over a 24-hour period.
- The control system can be easily implemented.
- The control system is compatible with any existing control or monitoring system.
- The control system does not change the set points of the HVAC system but primarily uses the inherent storage capacity in the system to shift electrical load.
- The control system can be used for HVAC systems of underground mines, commercial buildings and industries.

Figure 18 shows a screenshot of the patented software.



Schedule (Default Weekday schedule)

Time	75 Pumps	38 Pumps	Turbine Pumps	BAC Pumps	Fridge Plant
0-1	4	4	4	4	4
1-2	3	2	1	3	4
2-3	3	2	1	3	4
3-4	3	2	1	3	4
4-5	3	2	1	3	4
5-6	3	2	1	3	4
6-7	3	0	1	3	5
7-8	2	0	1	3	5
8-9	3	0	1	3	5
9-10	1	0	1	3	5
10-11	0	0	1	3	6
11-12	0	0	1	3	6
12-13	0	0	1	3	6
13-14	3	0	1	3	6
14-15	1	0	1	3	6
15-16	2	0	1	3	6
16-17	3	2	1	3	6
17-18	3	2	1	3	6
18-19	3	2	1	3	6
19-20	2	0	1	3	6
20-21	0	0	1	3	6
21-22	3	0	1	3	5
22-23	3	0	1	3	5
23-24	3	2	1	3	5

Control Signal History

```
12:20:00:   75 Level Pump 1 :   OFF Pulse
12:20:00:   38 Level Turbine Pump 4 :   ON Pulse
12:22:00:   75 Level Pump 2 :   OFF Pulse
```

Figure 18: SA Patent No. 2004/1172 software

Disadvantages of this patented system are the following:

- The daily schedule is calculated by software that is not part of the patented intervention.
- Operation not fully automated.
- Control is not done in real-time.
- Can only function on a Citrix SCADA.

1.3.3.12 REMS Pumps [42]

The Real-time Energy Manangment System (REMS) for Pumps was developed by Temm International (Pty) Ltd. This system is an upgrade of their patent (SA Patent No. 2004/1172), discussed in the previous section.

This system is capable of shifting load and realising electrical running cost reduction. A number of case studies were done on South African deep level mines. The system claims to have proved the following:

- It introduced simulation of a real-time situation for the purpose of optimisation.
- It was used to predict and investigate the potential of all the projects it was involved in.
- It achieved success in terms of load shift and running cost reductions.
- The introduction of automation into the control of the water pumping system was successful and yielded positive results.
- The REMS interface proved to be easily intuitive, well developed and contributed to the service performed by the control room operators.

REMS Pumps however focuses only on the dewatering components such as underground pumps. This system does not fulfil the requirements to integrate all components involved in the water reticulation systems.

1.3.3.13 REMS Fridge plants [42]

The Real-time Energy Manangment System (REMS) for refrigeration plants was also developed by Temm International (Pty) Ltd. System properties are very similar to that of REMS Pumps. This system however focuses only on the refrigeration system. It has no interaction with other systems like the underground water level supply or dewatering systems. The decision making process will therefore not consider components outside the refrigeration system.

1.4 Research objectives

In the previous section models and guidelines were discussed that could identify inefficient pumping. Most of these models focus on individual pump efficiencies, rather than the complete system efficiency. There are also numerous differences between conventional pumping like municipal water distributions and mine dewatering. This highlights the need for a model that could identify inefficient mine dewatering systems.

This chapter also discussed a number of different systems and techniques to simulate and control mine dewatering and refrigeration systems. However, none of these systems fulfil the need to simulate, optimise and control a complete mine water reticulation system.

This study will further develop the REMS systems so that it will be able to simulate, optimise and control all elements of mine water reticulation. This will ensure that additional savings and benefits for the mine will be identified and realised.

Each chapter has its own introduction, conclusion and list of references. By making use of this structure, each chapter can be read independently. The introduction explains what can be expected from the specific chapter and the conclusion summarises the outcome of the chapter. An overview of each chapter will now be given.

Chapter 1

In this chapter the worldwide, and more specific, the South African energy demand situation was discussed. This chapter introduced the components involved in the water reticulation system of a typical mine. All these components are integrated to form a complete water reticulation system. Some of the water management, efficiency models and monitoring systems presently on the market were also discussed. The outcome of this chapter highlighted the need for a simplified simulation and automation system that could be used to integrate a water reticulation system.

Chapter 2

There are a number of water reticulation systems in South Africa. To do a detailed investigation to identify inefficient operations on all of them is time- and resource-consuming. Simplified models were developed to identify inefficient electricity and water consumption systems. After these systems are identified, they can be inserted into optimisation models that could assist in increasing system efficiency.

Chapter 3

Chapter 2 identified Beatrix 1 Shaft pump station to be inefficient. An investigation into the inefficiency was launched and the dewater optimisation efficiency model was applied. Water wastages on Kopanang Mine were also reduced by implementing the newly developed underground level water valve controller.

Chapter 4

Demand side management projects have been done on a number of refrigeration and dewatering systems, but have never been integrated to optimise cost savings. This chapter will discuss new techniques and simulations to integrate and optimise a complete water reticulation system.

Chapter 5

To evaluate the effect of an integrated control strategy on a complete water reticulation system, the strategy in Chapter 4 was implemented on two mines. At Kopanang the dewatering, turbine-pumps and refrigeration systems were integrated, and at Tshepong mine the 3-CPS, dewatering and refrigeration systems were integrated.

Chapter 6

This chapter concludes the complete thesis and ends with several suggestions for further work in this field.

1.5 Contributions of this study

The contributions of this study are summarised as follows:

New efficiency model for water reticulation systems

- In the mining environment there is a need to assess the efficiency of water reticulation and compare it with similar systems.
- No model was found that could satisfy the need for a quick and easy way to determine the efficiency of the mine water reticulation system.

- Unique models were developed to assess the efficiency of mine water reticulation systems, without conducting a detailed study.
- With easy accessible data, the water reticulation systems in South African mines can now be prioritised according to efficiencies.

Innovative cost optimisation model for mine water reticulation

- Traditionally electrical energy was cheap and savings that could have been realised were not considered.
- Now that electricity costs have increased, guidelines are needed that could identify system inefficiencies.
- The model that was developed to identify cost savings opportunities on complete water reticulation systems is unique.
- By using this model, savings can be generated immediately, without having to install additional infrastructure.
- For a mine with a lifetime of more than 36 months, the model also focuses on the feasibility of installing infrastructure that could realise long-term benefits.

Individual water reticulation components were integrated

- Previously DSM was only implemented on individual water reticulation components.
- The overall effect of DSM was never determined.
- This study broadened the focus of DSM on the complete water reticulation system.
- Components were integrated to form a complete water reticulation system.
- New technologies like the three pipe chamber systems (3-CPS), and turbine-pump configurations were integrated with the dewatering stations, refrigeration plants and service water components

An integrated simulation of the complete mine water reticulation was developed

- No documentation regarding a complete mine water reticulation simulation was found.
- Systems such as the 3-CPS and turbine-pump configurations had to be included in the simulations.
- Service water from the underground cold water dam into the underground mining levels was modelled to complete the simulation cycle.

Automated software control solution

- DSM focused on specific components and no complete automation control solution was conducted.
- No commercially available automated software control solution to realise cost savings on the complete water reticulation system could be found.
- A new software solution (incorporating the new control algorithms and strategy) was developed.
- This solution identified cost saving potentials in the water reticulation systems in a fully automated and sustainable manner.
- This solution was implemented on case study mines to demonstrate its effectiveness.

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CHAPTER 2: New efficiency calculation and cost optimisation models for mine water reticulation systems

There are a number of water reticulation systems in South Africa. To perform a detailed investigation to identify inefficient operations on all of them is time- and resource-consuming. Therefore simplified models are developed to identify inefficient electricity and water consumption systems. After these systems are identified, it could be inserted into optimisation models that could assist in increasing system efficiency.

2.1 Introduction

Studies have concluded that South African mines consume greater amounts of energy per kilogram gold produced than mines in other countries [43]. One of the reasons for this is the extensive depth of the gold mines in South Africa. The relatively cheap energy costs of the past contributed to this situation.

In this chapter new models will be developed which will assist the mine in calculating the efficiency of its dewatering system. The first model will focus on the energy required to extract water from the mine. The second model will determine the average electricity costs to operate the pumping system. The third model focuses on the water efficiency. Each of these models is independent and represents a specific condition. One of the aims is to keep the model as simple as possible, so that unskilled mining personnel can use it. A further aim was to ensure that the input parameters could be easily obtained.

No model could be found that only focuses on the optimisation of mine dewatering. Due to the great depths of mine dewatering systems, the optimisation strategies differ from ordinary pumping systems. Therefore models were developed to guide the mine through a few important steps to improve the electrical costs on the mine water reticulation system.

2.2 Mine dewatering energy consumption

The water balance table of a mine (Appendix A) should be updated regularly. This should be done to detect any pattern changes. If changes are detected, the cause should be determined immediately, as this could result in lost revenue or even fatalities.

Data from a water balance table can be used to determine the energy consumption of a typical mine dewatering system. These results can be used to calculate the efficiency of the dewatering system. The dewatering system must be analysed in detail before a model can be developed. This will improve the accuracy of the model and eliminate false assumptions.

The quickest and easiest way to determine the daily theoretical energy consumption of a dewatering system is to make use of the following energy calculation [44]:

$$E_{ps} = M \times g \times H \qquad (2\text{-}1)$$

Where:

E_{ps} = daily energy used to extract water from the pump station (J)
M = mass of water pumped (kg)
g = gravity acceleration constant (9.81m/s^2)
H = total head of the pumping station (m)

To convert the above equation to kWh [44]:

$$\begin{aligned} kWh &= 1000W \times 3600s \\ &= 3.6MJ \end{aligned} \qquad (2\text{-}2)$$

The depth of a typical gold mine pump station varies from 600 to 1 000 m. Due to the extreme depths of some of these pumping stations, the static head is the significant factor for pump design. For a typical pumping station with a differential elevation of 800 m, a flow rate of 250 l/s, a steel pipe diameter of 300 mm and a pipe length of 1000 m, the total dynamic head is 840 m. Therefore, to obtain the total head, the static head may be increased by between 5% and 10% to account for all the friction losses without sacrificing too much accuracy [45].

The most accurate way to calculate the energy consumption is by installing a power-logging device on each motor. This device can log the power consumed at any specific time of day. However, due to the high cost of such a device, other methods can be considered and employed.

Another method is to calculate the estimated power from the voltage and amperage readings. Usually only one phase's voltage and amperage reading is displayed, so it is assumed that the three-phase circuit is balanced. A three-phase power system is balanced if the line amperage and voltages for each phase is equal. Most of the motors that drive the dewatering pumps have these instruments installed, which are used mainly for protection purposes. By using equation 2-3 accurate pump power consumption can be determined [46].

$$P = \sqrt{3} V_L I_L \cos\phi \qquad (2\text{-}3)$$

Where:

P = power consumed by the pump (W)
V_L= line voltage (V)
I_L= line current (A)
Cos Ø = load power factor

The daily energy consumption can be determined by multiplying the power consumed (P) and the amount of running time during a specific day. According to law, the mine is required to keep a monthly log of the number of running pumps during each day. To accomplish this, the pump operators must fill in a pump log sheet for each day. This sheet can be used to calculate the amount of hours a specific pump was running during a specific day.

The total energy consumed by a typical pump station is given by:

$$E_{real\ ps} = \sum_{i}^{no\ of\ pumps} (P_i \times h_i) \qquad (2\text{-}4)$$

Where:

$E_{real\ ps}$ = real energy consumption of the pump station
P_i = power consumption of pump i
h_i = number of hours pump i was running during the day

If no current or voltage metering is installed, an accurate alternative is to simply use the rated power of each motor. By using this method, a small amount of accuracy is sacrificed. However, this solution will still give an acceptable indication of the actual energy consumption, due to the fixed static head of the system. The equation below shows how the rated energy consumption can be obtained.

$$E_{rated\ ps} = \sum_{i}^{no\ of\ pumps} (\mathrm{Pr}_i \times h_i) \qquad (2\text{-}5)$$

Where:

$E_{rated\ ps}$ = rated energy consumption of the pump station

Pr_i = rated power consumption of pump i

After the actual energy consumption (either equation 2-4 or 2-5) and theoretical energy consumption (equation 2-1) on the mine pumping stations have been calculated, the efficiency can be determined using equation (2-6).

$$eff_{ps} = \frac{E_{ps}}{E_{real\ ps}\ or\ E_{rated\ ps}} \text{ x } 100\% \qquad (2\text{-}6)$$

This equation can also be used to identify inefficient pumping stations. To calculate the efficiency of the dewatering system, equation (2-7) can be used:

$$eff_{system} = \frac{1}{N}\sum_{i}^{N}\left(\frac{E_{ps}}{E_{real\ ps\ i}}\right)\ \% \qquad (2\text{-}7)$$

Where:

eff_{system} = efficiency of the dewatering system

i = pump station number

N = number of pump stations

The calculation steps above are summarised in Figure 19.

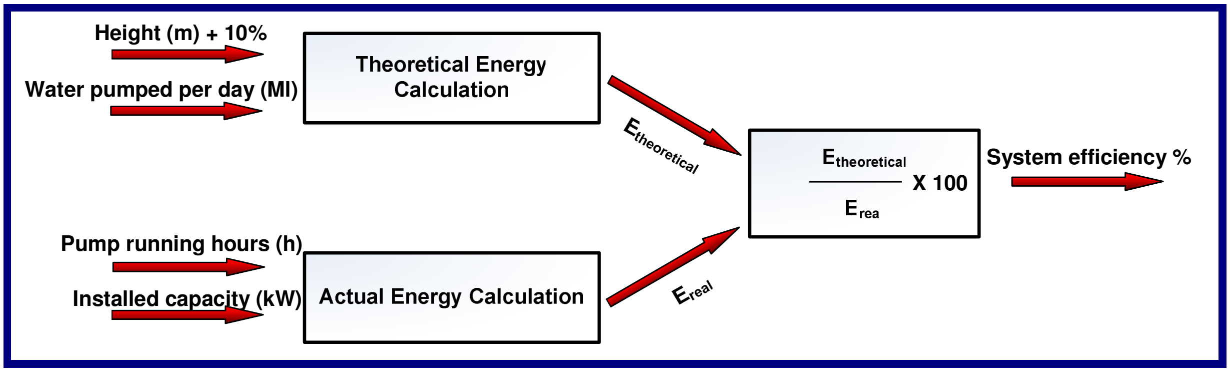

Figure 19: Dewatering efficiency model

This dewatering efficiency model was applied to 11 different mine dewatering systems. The results are shown in Figure 20.

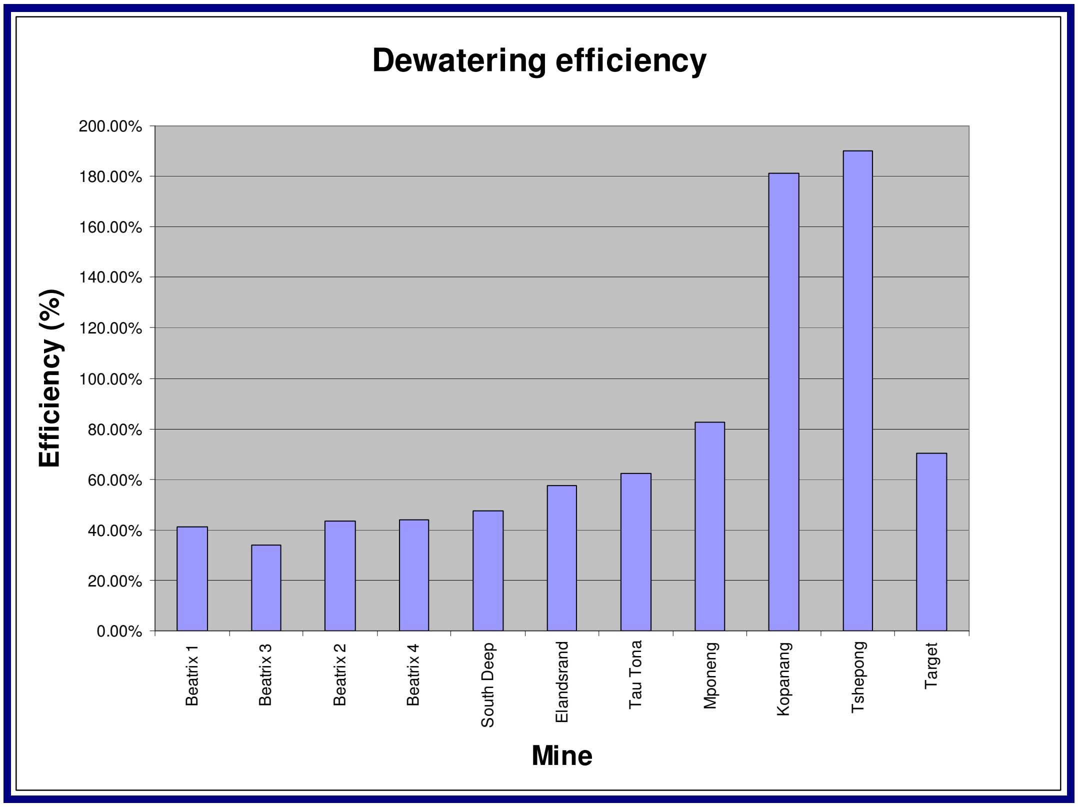

Figure 20: Dewatering efficiency

The efficiencies show a significant variance from mine to mine. Kopanang and Tshepong mines make use of energy sources other than electricity to pump water from the shafts.

Therefore the electrical dewatering efficiency can be as high as 190%. These alternative energy sources include turbine-pumps and 3-CPS systems.

Mponeng mine, compared to the other mines, are relatively young. Therefore its pumping stations are in good condition. Tau Tona, also an AngloGold Ashanti mine has very good maintenance procedures in place. The AngloGold Ashanti pumps are tested and evaluated on a monthly basis. This is also reflected in the dewatering efficiency chart.

From Figure 20 it can also be seen that Goldfields' Beatrix 3 Shaft has the lowest efficiency. This mine has a temporary pump station and the existing pumps are overrated for the actual requirement. A new pump station at Beatrix 3 Shaft mine is presently being commissioned. Therefore there is no need to investigate this inefficient operation. Beatrix 1 Shaft on the other hand is a bigger concern and will be investigated in Chapter 6.

2.3 Average electricity tariffs

Most mines in South Africa are on the Eskom Mega Flex tariff structure. Apart from the electricity connection fees, this structure makes use of time-of-use pricing. The tariff is more expensive during the high peak periods and cheaper during low peak periods.

By increasing the energy usage during standard and off-peak Eskom periods, and decreasing the energy usage during peak periods, the average electricity tariffs can be reduced. To determine the average dewatering electricity tariffs, the daily power consumption profile of a pumping system should be determined. For a system where no electronic data is available, pump log sheets could be used to determine the 24h pumping profile.

After the system's power pumping profile is determined, the average annual cost can be calculated by multiplying each hourly demand with the appropriate Mega Flex tariff cost. Since it is time consuming to determine the average cost for each day over a period of a year, the average power consumption for a month was determined in this study. This average power profile was then extrapolated throughout a year (winter and summer). In this study it was assumed that there are 273 summer days (low Eskom demand) and 92 winter days (high Eskom demand) in a year. Five of the eleven summer public holidays were replaced by a Saturday profile and the remaining six with a Sunday. There are only two winter holidays, which will be replaced with Saturday tariffs. It is also assumed that the winter and summer pumping profiles are the same.

After the annual electricity cost is determined, it can be divided by the average annual electricity usage to get a c/kWh rating as seen in Figure 21.

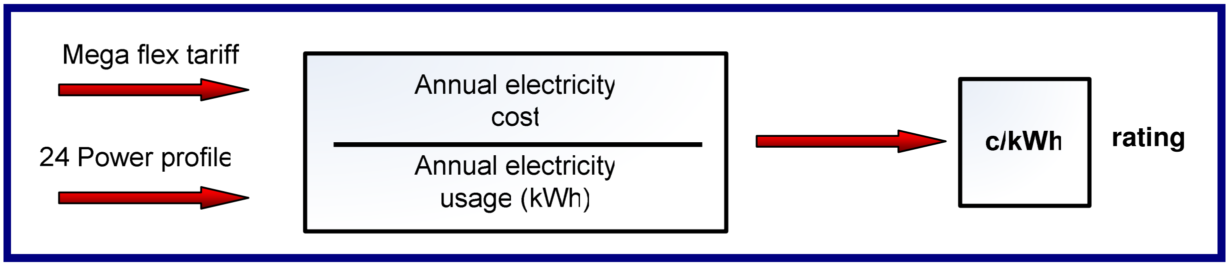

Figure 21: Electrical cost model

Table 3 and Figure 22 show the average annual electricity tariffs (c/kWh) of a few mines. In this table it can be seen that each dewatering system's electricity costs differs. This dissimilarity is due to some mines' success in managing load shift. The average running capacity is also shown. Kloof 8# and Kloof 10# have the highest electricity rate of 16.8c/kWh and 15.6c/kWh respectively. Neither of the two systems has a real-time energy management system installed.

Table 3: Average electricity tariff for mine dewatering systems

Mine	Running capacity (MW)	Average electricity tariff (c/kWh)
South Deep	10.7	12.98
Target	1.2	11.7
Beatrix1,2,3	7	15
Cooke1#	2.8	12.6
Grootvlei	10	15
Mponeng	10.7	12.72
Kopanang	4.6	13.5
Tshepong	3.5	13.6
Kloof 8#	5	16.8
Kloof 10#	6.8	15.6
Tau Tona	14	14.4
Harmony 3#	1.2	13.9
Evander 7#	7	14.1
Kloof 7#	17	14

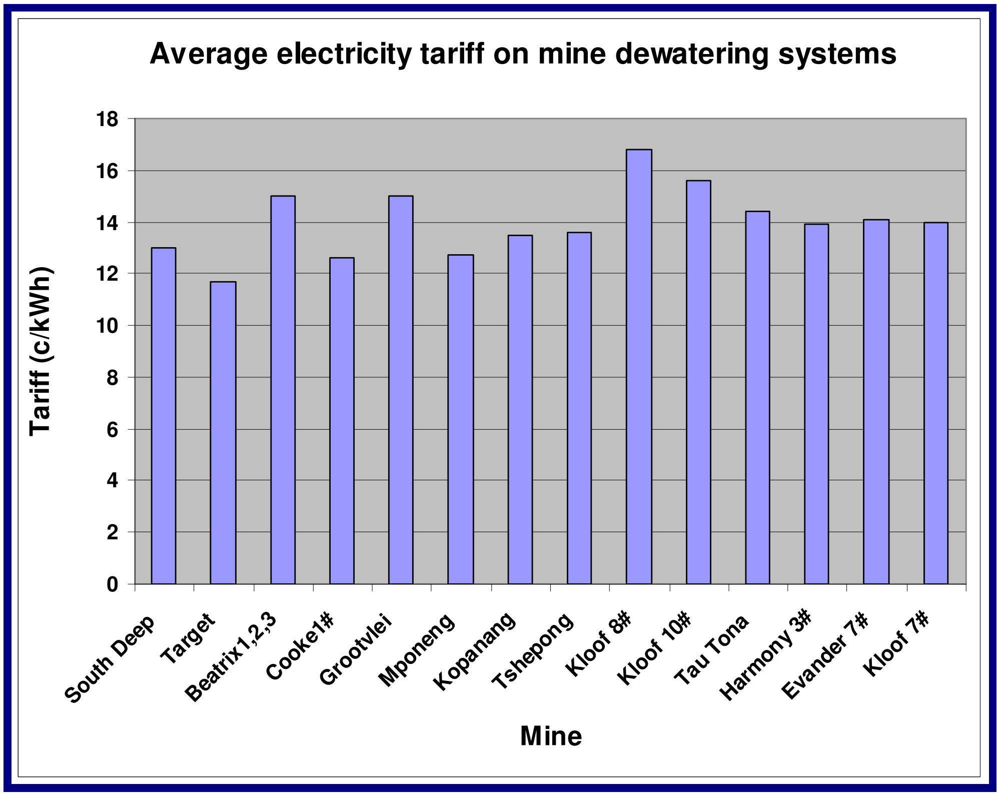

Figure 22: Graph representation of average electricity tariff on mine dewatering systems

Target, Cooke1#, Mponeng, Kopanang, Tshepong and South Deep mines have real-time energy management systems installed. The low tariff cost of the mines proves that the system does work. Kloof 10 Shaft, Kloof 8 Shaft and Grootvlei mines are systems where no load shift is attempted. This is clearly seen in the high average tariff cost. At mines like Kloof 10 Shaft, Evander 7 Shaft, Tau Tona and Harmony 3 Shaft the pump operators starting and stopping the pumps, are attempting load shift. By doing so, the average electricity tariff can be reduced to 14c/kWh.

If the average electricity tariff of a dewatering system can be reduced, the mine will benefit from the cost savings. It is therefore important to investigate the energy management of dewatering systems to reduce electricity rates.

2.4 Water efficiency

As stated in Chapter 1, water needs to be sent underground for drilling, sweeping and cooling purposes. The quantity of water that is used for each of these components is distinct for each mine. In South Africa there is a huge potential for reducing the amount of water that is fed underground. If the water supply is reduced, it should be done without affecting the following:

- Production of the mine.
- Health and safety of the miners.
- Quality of the water.
- Damage to infrastructure.
- Damage to hydropower equipment.

The health and safety of the miners is the highest priority. Formal heat-stress management programmes and administrative control measures are required when wet bulb temperature rises above 28℃. Routine work must not be permitted when the wet bulb temperature exceeds 32.5℃, or the dry bulb temperature is more than 37℃ [47].

The geothermal gradient, the rate at which temperature increases with depth, is typically 12℃ per kilometre. This differs from area to area. Due to the temperature of the underground rock, this is considerably more than the standard adiabatic lapse rate for the air above the ground (6℃ per kilometer) [48]. Figure 23 gives an indication of the virgin rock temperatures in some parts of South Africa at specific depths.

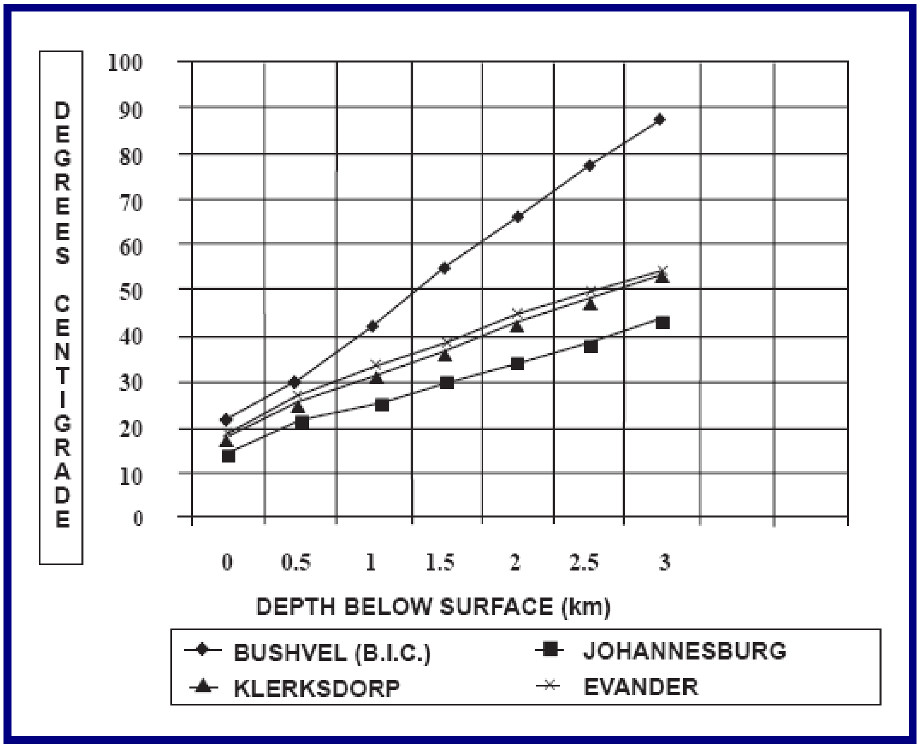

Figure 23: Virgin rock temperatures below surface [49]

To determine the water efficiency of a mine water reticulation system, a few mines were selected for the model. Elements that may affect the water usage were investigated in order to derive a water efficiency model. The elements involved are listed below:

- Virgin rock temperature.
- Service water volume.
- Production (extraction of reef, including waste).

Initially the relationship between the water consumption and virgin rock temperature was investigated. Figure 24 shows this relationship. From the figure it can be seen that there is no correlation between the water usage and the underground rock temperature. Mponeng and Target have more or less the same underground temperature. However the water consumption differs by 35 Ml. The underground temperature of South Deep mine is the highest, but this mine consumes only 10 Ml per day. Therefore the underground temperature has no impact on the daily underground water consumption.

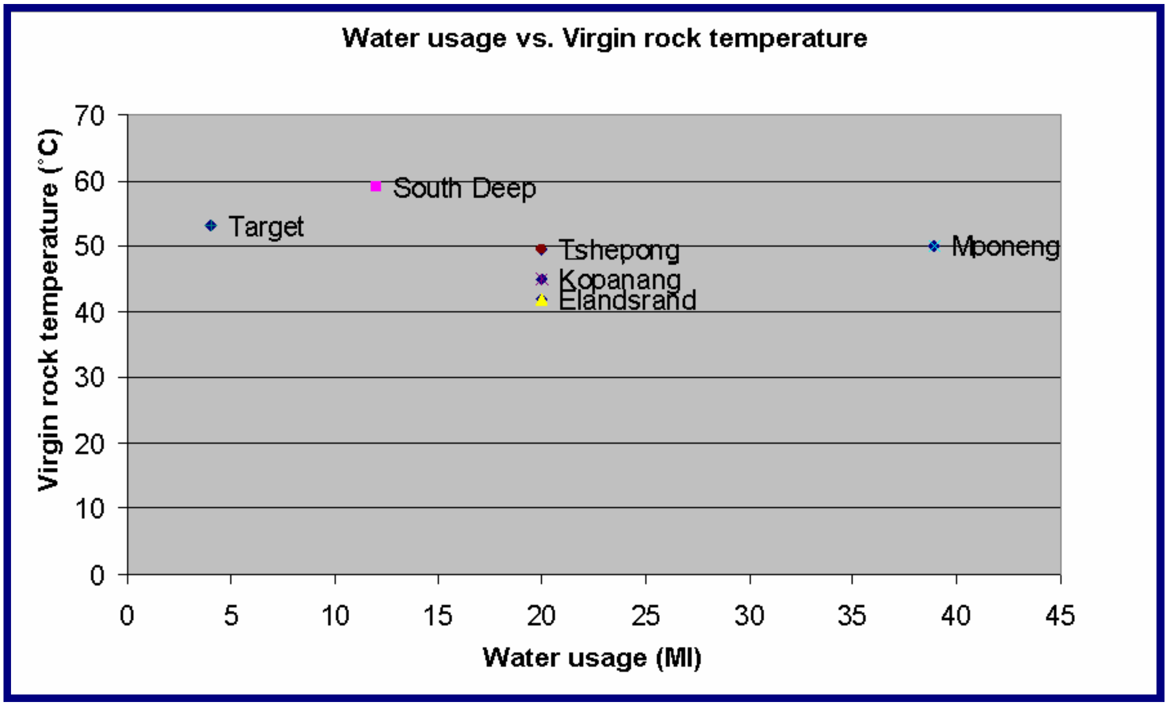

Figure 24: Virgin rock temperatures vs. water usage

The relationship between water usage and underground production was also investigated. The total rock mass that includes waste and reef material was added and used in the calculations. This data is difficult to obtain. It is usually not published due to the competitiveness in the mining environment. An alternative calculation is therefore discussed.

An effective and accurate way to determine the mass production of the mine is to either log the number of winding cycles (skip hoisting trips) from a tachometer [50] or from hoisting reports. The winder is the elevator used to transport waste and reef out of the mine. The mine is obligated, according to law, to log the speed-against-time profile for each winder. Most of the mines therefore install a tachometer to log the velocity of the skips. Each tachograph represents a specific day. From these sheets the number of winder cycles during a specific day can be calculated by counting the number of speed peaks.

The rock winder skips travel the same route on each cycle. Skips are filled at the rock loading boxes from where it is hoisted and emptied at surface. Each skip also has a fixed capacity. Therefore the same amount of rock is hoisted for each cycle. Figure 25 is a part of a tachograph and indicates the typical cycle period.

Figure 25: Example of a rock winder tachograph

The total number of speed peaks during the day can then be multiplied by the winder skip capacity (usually between 10-25 tons) to determine the total mass production of the mine.

Figure 26 shows the relationship between the water consumption per ton of ore hoisted.

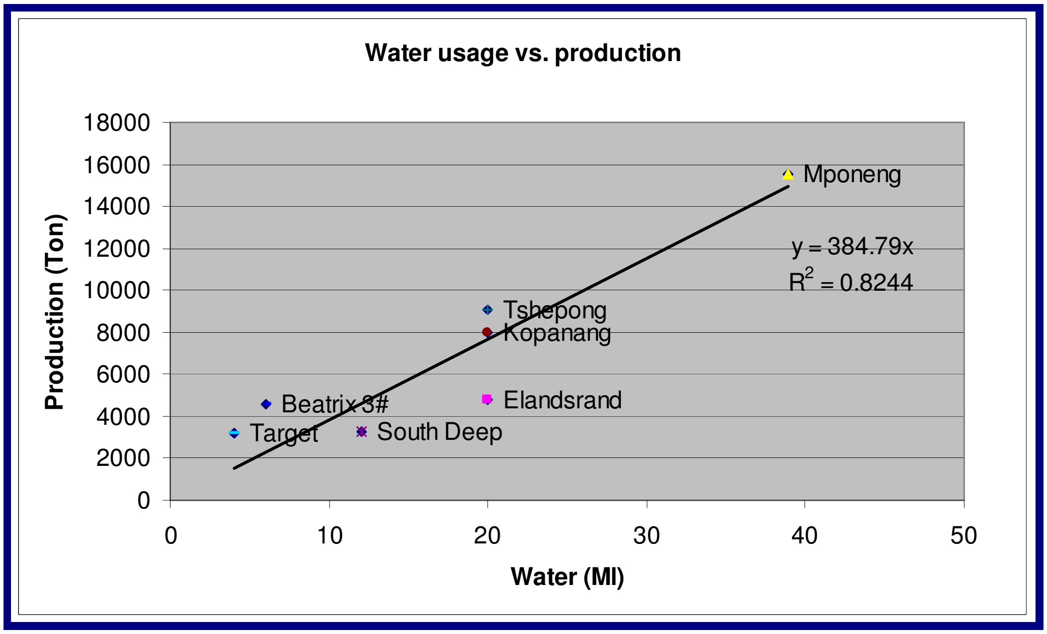

Figure 26: Production vs. water usage

The graph indicates that on average 384 ton of rock is extracted for each Ml of water sent down the mine. Or 2.6 kl of water is needed to mine a ton of reef and waste. The coefficient of determination, R^2, is the proportion of variability in a data set that is accounted for by a statistical model. In this case it is 0.82, which is a good representation of the data points.

Figure 27 was used to compare mine water efficiencies of the various mines. Inputs for this model are the actual daily production figures and underground cold water supply.

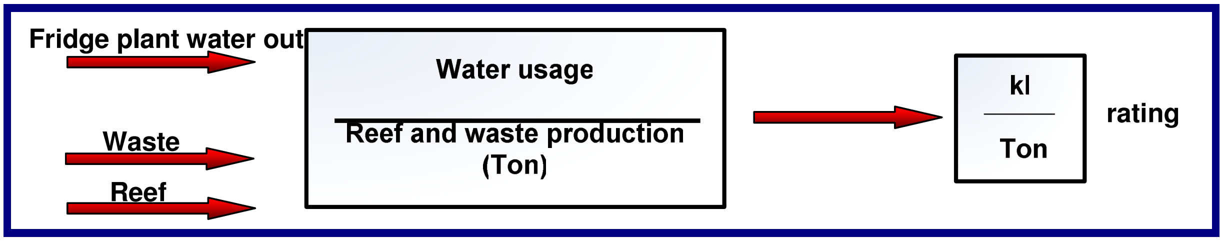

Figure 27: Water efficiency model

Data from seven different mines were used in the model and the results compared. These results are shown in Table 4 and Figure 28.

Table 4: Water usage per ton of reef and waste

Mine	Actual Tonnage	Underground water usage (Ml)	kl/Ton
Beatrix 3#	4 600	6	1.30
Elandsrand	4 815	20	4.15
Kopanang	8 000	20	2.50
Mponeng	15 500	38	2.45
South Deep	3 233	12	3.71
Target	3 200	4	1.25
Tshepong	9 078	20	2.20

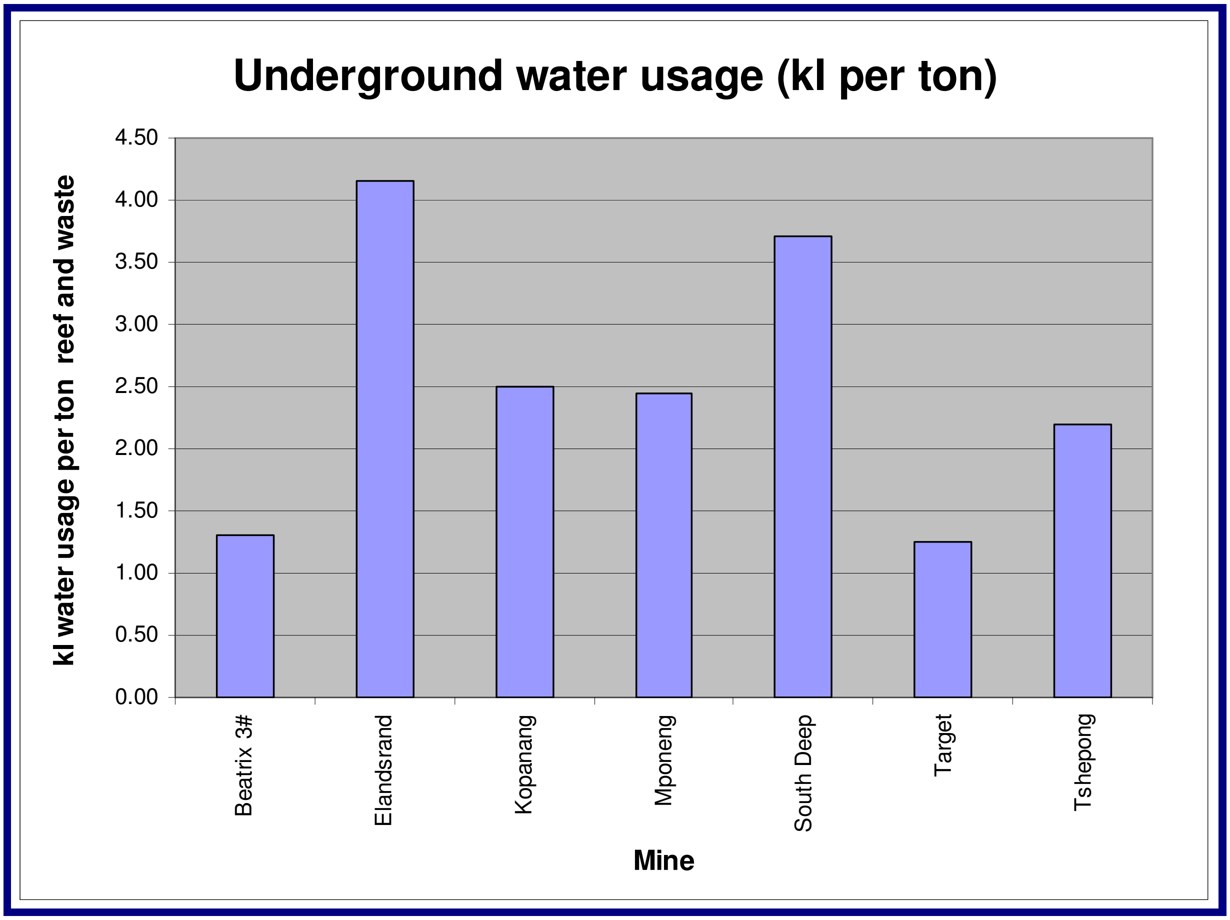

Figure 28: Graph representation of underground water usage

From this table it can be clearly seen that Elandsrand and South Deep mines use much more water per ton of rock than the average of 2.6 kl/ton determined. Both these two mines are presently busy with underground development, which increases the water consumption.

2.5 Novel cost optimisation model

2.5.1 Overview

Historically, electricity costs on deep level mines were relatively small compared to other mine production expenses. The mine therefore did not use electricity efficiently. In 2008 electricity costs increased dramatically, forcing the mines to re-evaluate their energy policies. Due to years of inefficient electricity usage, mining personnel were not educated in this field.

In this section unique models will be developed to assist unskilled mining personnel to reduce electricity costs. To accomplish this, electricity or water must either be used more efficiently, or managed in such a way that the overall cost per kWh is reduced.

This model is divided into three major parts, namely:

- Water efficiency optimisation
- Electricity cost optimisation
- Energy efficiency optimisation

Table 5 lists some techniques and their related requirements that could be applied on water reticulation systems in order to reduce cost savings.

-

Table 5: Techniques and requirements for electricity cost savings

	Instrumentation needed (metering)	Automation needed	Long term payback
Pump operation optimisation			
Manual load shift			
Balancing disk flow	●		
Service water control optimisation	●	●	
Real-time energy management system	●	●	
Turbine-pump installation	●	●	●
3-CPS installation	●	●	●

2.5.2 Energy efficiency

The announcement of the ECS penalties that will be introduced soon, will force mines to use electricity efficiently. If the mine could manage to reduce its electricity demand by means of efficiency, it could utilise the savings to increase production. If this can be done, the mines could increase production and still operate within the set ECS limits.

In this section techniques will be discussed to increase the energy efficiency of the mine dewatering system. Figure 29 is a model that was developed to assist the user to increase dewatering efficiencies. Some of the techniques could help increase system efficiencies or identify inefficiencies in a short period of time. Other solutions, for example the implementation a turbine-pump or 3-CPS, could take up to three years. However, in the long term the mine would benefit from substantial savings.

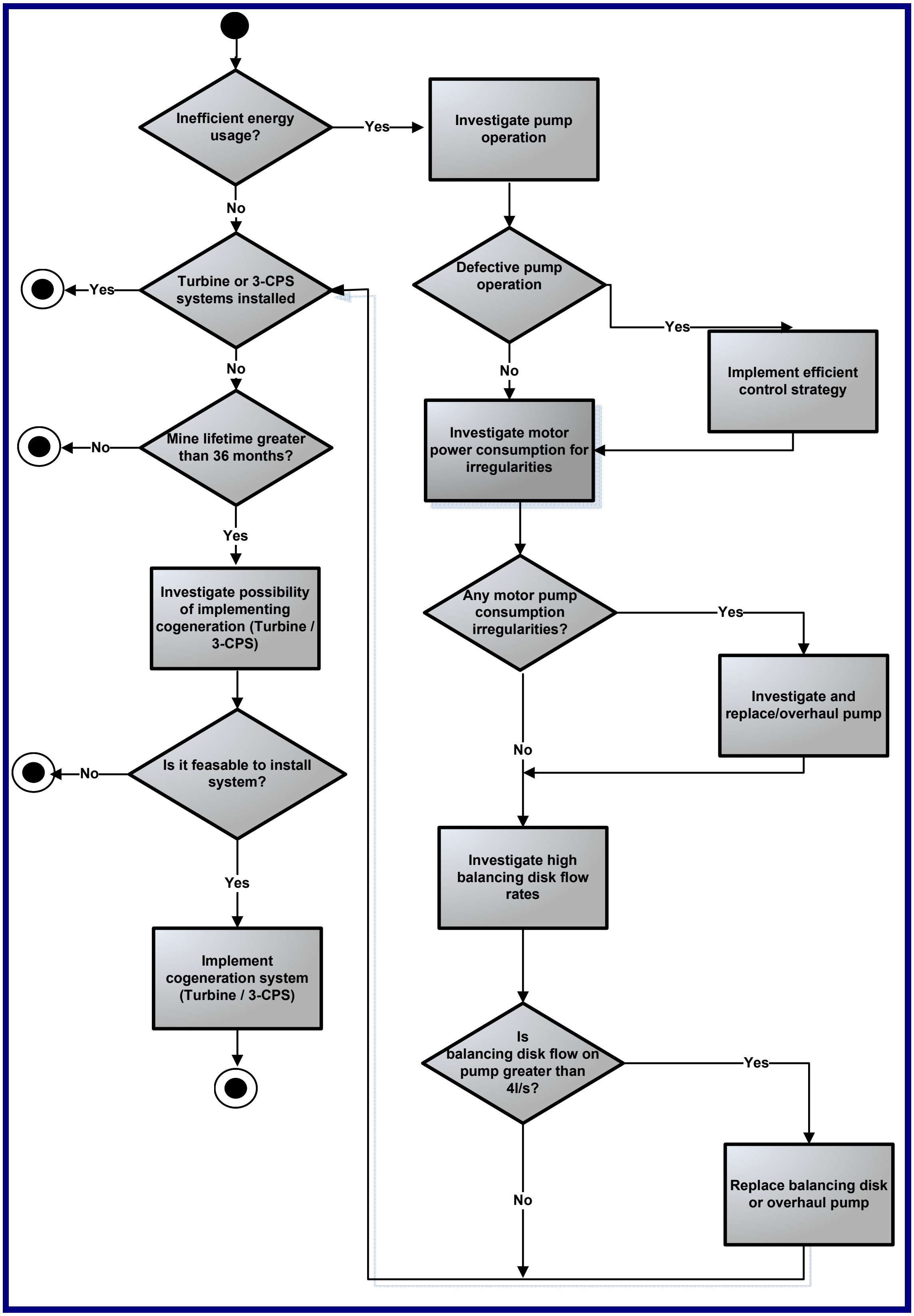

Figure 29: Energy efficiency optimisation model

2.5.2.1 Pump operation optimisation

Clear water pumping systems used by mines make use of multiple pumps operating simultaneously. To meet this requirement, pumps operate in parallel to deliver a single combined performance curve.

In the parallel operation arrangement, the pumps have a common intake manifold and deliver into a common high-pressure manifold. The use of multiple pumps in a parallel arrangement allows the pumps to be switched on and off to meet the varying demand. Figure 30 shows how the pumps are connected in a parallel operation.

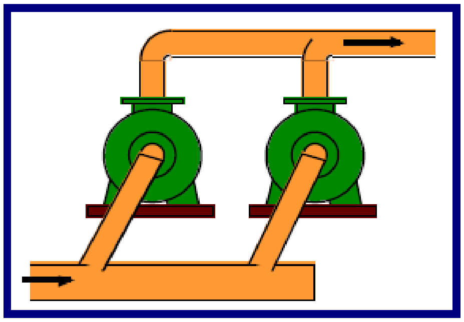

Figure 30: Parallel operation [51]

Two identical pumps operating in parallel are capable of producing double the flow if pumping into separate columns. However, if two pumps pump in the same column, the actual flow rate realised in the system is determined by the intersection of the system curve with the pump curve at a given rotational speed. The increase in the flow therefore depends on the system curve. The flow can only increase to the point at which the system curve intersects the two-pump curve, which may not be the point of maximum efficiency. This is shown in Figure 31 [51],[52].

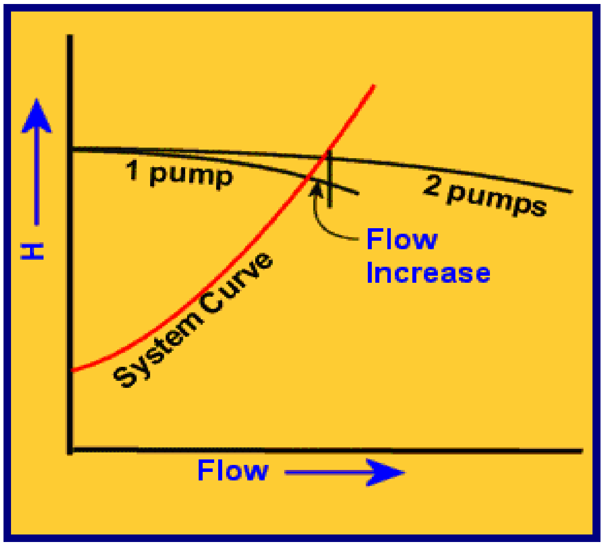

Figure 31: Flow increase due to parallel operation [53].

Because of the reduced flow rate when pumps operate in parallel, a steady increase in the number of pumps will reduce the flow rate through each pump. This could result in each pump adding less than a fraction of its capacity to the system output as is indicated in Figure 32.

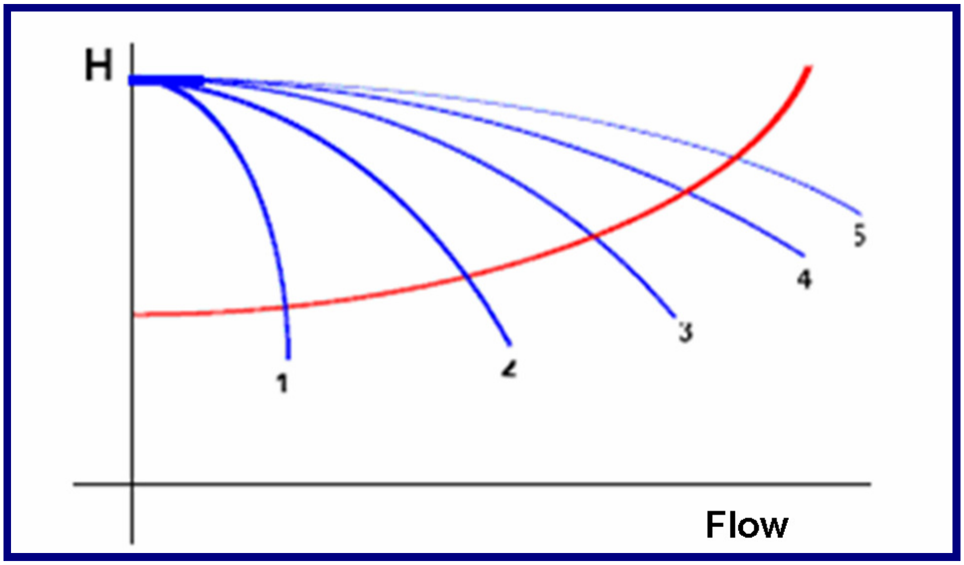

Figure 32: Performance curve for multiple pumps

The operators of the pumps are not always aware of the potential impact of pumps operating in parallel. By examining the physical pumping layout and by making the necessary changes, the system efficiency can be improved.

2.5.2.2 Balancing disk flow

Multi-stage pumps are commonly used in the mining environment. In this design all impellers are stacked in one direction, pushing the rotor towards the suction with great force. To overcome this resulting axial thrust, some discharge flow is led through an annular clearance to act against a balance drum or balance disk. The resulting force is self-adjusting, depending on the pump flow. This results in a smaller thrust loading on the bearings. Figure 33 shows such an arrangement.

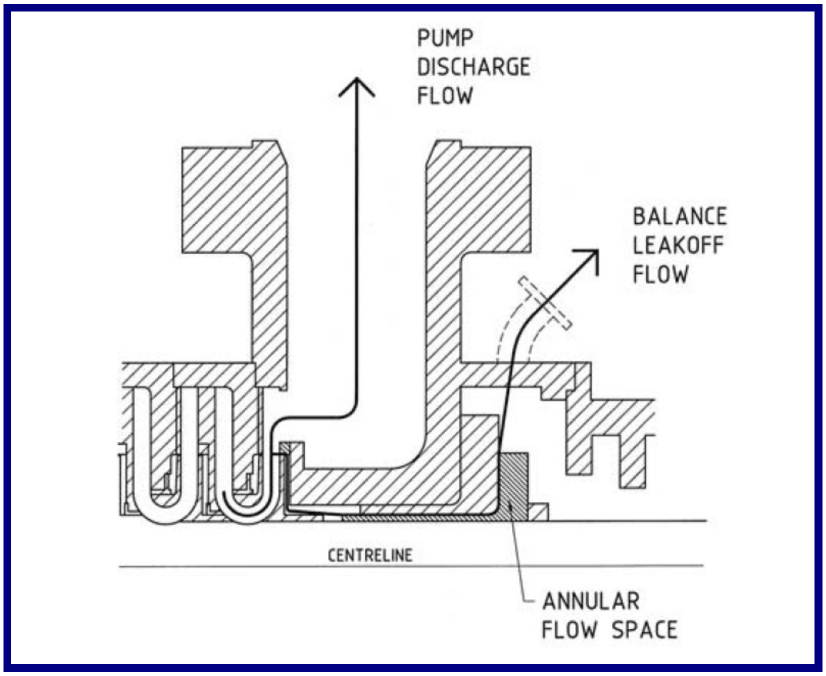

Figure 33: Cross-section of horizontally-split multi-stage pump, showing thrust balance device [54]

The balance leakoff flow will increase as the annular clearance between the device and the pump casing increases with wear. A water flow meter can be installed to measure this flow. Because this flow is usually less than 20 l/s, calculating the time can make an estimate of the flow it takes for a drum of known capacity to be filled. This measurement should be taken on a regular basis to monitor the pump wear.

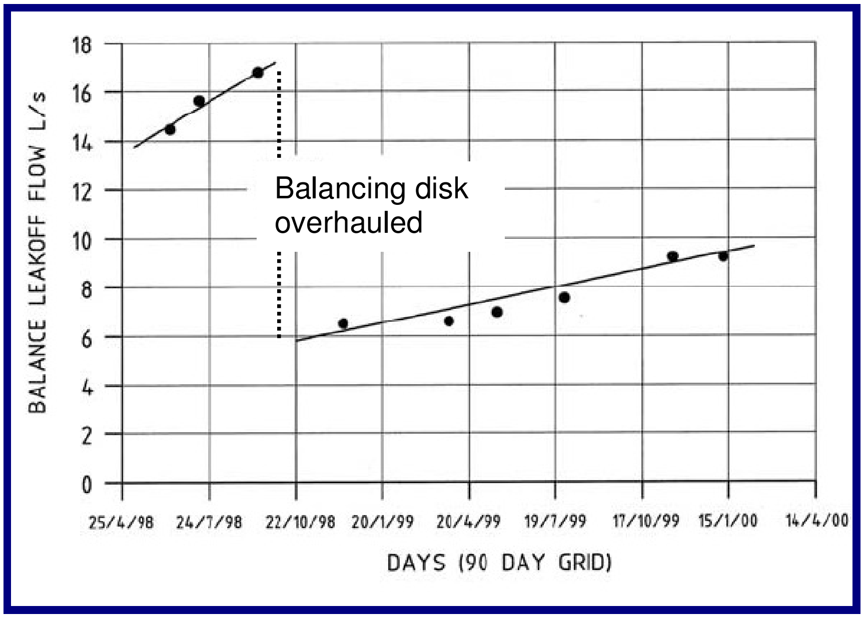

Figure 34: Data plot of balance leak off-flow for a multi-stage pump [54]

Figure 34 shows the balance leakoff wear and the effect it has on the balance leakoff flow. In this graph, the balance leakoff flow is plotted against time. It can be clearly seen that the balance leakoff flow was 17 l/s before the balancing disk was overhauled. The leakoff adds to the internal pump water recirculation which means that the power consumed to generate this flow is being wasted. This leakoff water is fed into the water trench of the pump that feeds the settlers. Therefore this leakoff flow contributes to pump inefficiency.

The cost of replacing a balancing disk is presently in the order of R 15 000. This is less than 1% of the lifecycle maintenance costs of the pump [55]. Table 6 shows the average hourly loss in revenue at a specific head and balance leakoff flow. These calculations were based on an average electricity cost of 15c/kWh.

Table 6: Cost of balancing disk flow loss per hour

		Disk flow (l/s)			
		6	**8**	**10**	**12**
Head (m)	**600**	R 19.05	R 25.40	R 31.75	R 38.10
	800	R 25.40	R 33.87	R 42.34	R 50.80
	1 000	R 31.75	R 42.34	R 52.92	R 63.50
	1 200	R 38.10	R 50.80	R 63.50	R 76.20

Figure 35 shows the payback period after a balancing disk was replaced. In this graph it is assumed that the balance wear is zero due to the minimal deterioration for such a small period. If the leakoff flow can be reduced by 12 l/s (at a head of 1 000 m) the replacement costs would be covered after 220 hours of operation. Therefore, to increase the energy efficiency of the pump and save electricity costs, the balancing disk should be replaced as soon as any wear is detected.

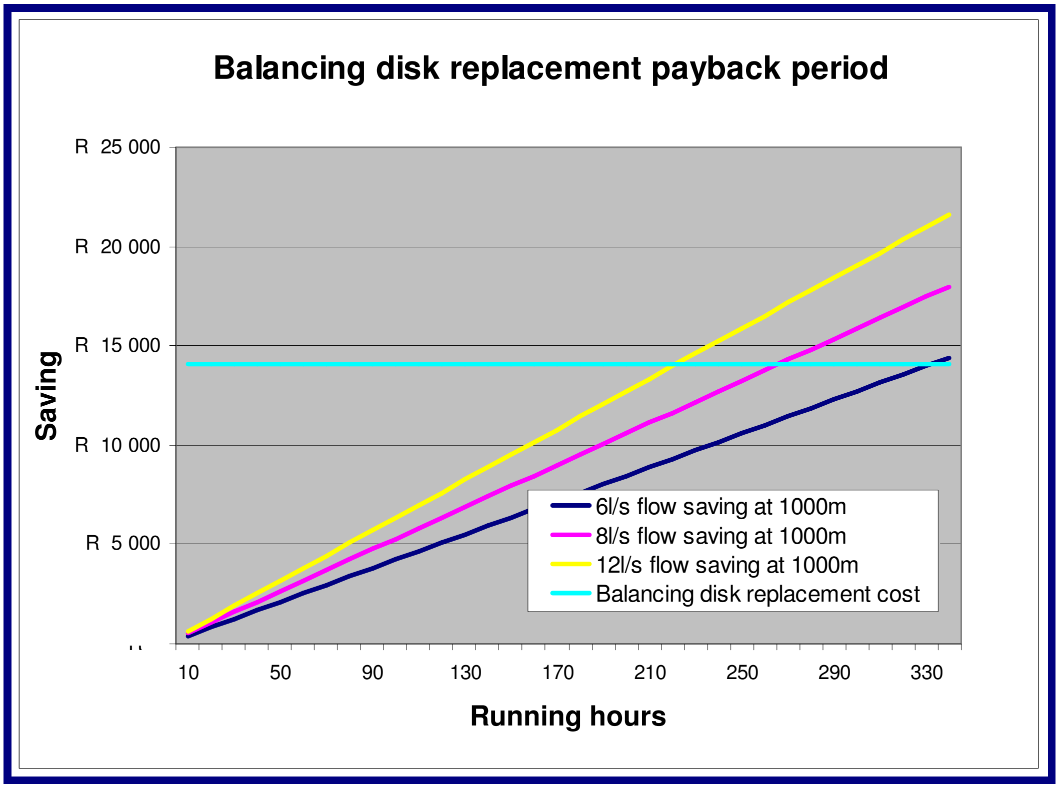

Figure 35: Balancing disk replacement payback period

One of the biggest gold producing companies in the world has a standing rule that the balancing disk should be replaced as soon as the leakoff flow exceeds 4 l/s.

2.5.3 **Long term cost saving solution**

2.5.3.1 Introduction

To achieve long-term cost savings, an entirely new pumping system configuration will be required. The most commonly used cogeneration energy systems in mining, and more specifically in the water reticulation systems, are turbines and three chamber pipe system (3-CPS).

Both of these systems or configurations require a very high capital input to be installed. In most cases the capital return period is less than three years. As previously discussed, both these systems make use of cold water that is sent down the mine.

2.5.3.2 Turbine-pump configuration

For a turbine-pump configuration to be efficient, the minimum water supply height should be 600 m. Naturally, the more water is sent down the shaft, the more energy could be generated to pump the water from the shaft. The efficiency of the turbine is typically 85% [56], and a typical deep level dewatering pump 80% [57]. Therefore the total turbine-pump efficiency is in the order of 68%.

The capital cost required to install a turbine-pump configuration can vary from R 8-million to R10-million for depths of 600 m to 800 m [56]. Recent studies also showed that due to the long manufacturing period of a turbine, conventional dewatering pumps could also be used as a turbine to drive another dewatering pump [57].

By installing a turbine-pump configuration at these depths, up to 48 MWh of potential energy can be recovered daily. This implies that it will cost typically R 4.5-million per MW to install a turbine-pump configuration.

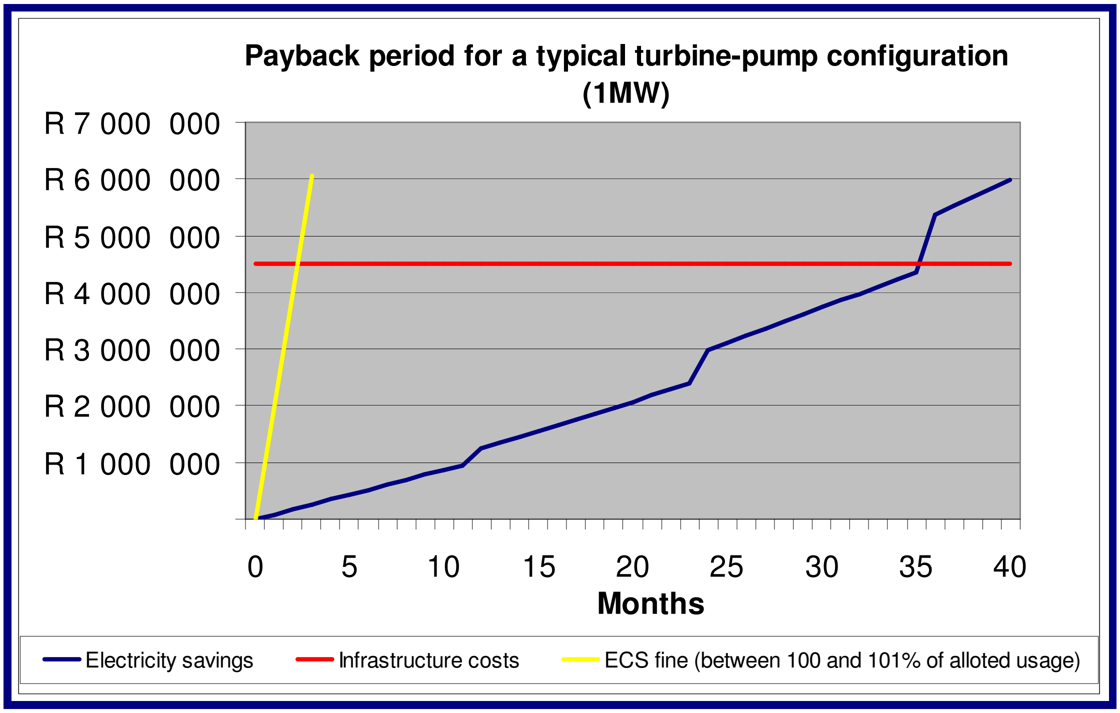

Figure 36: Payback period for a typical turbine-pump configuration

Figure 36 shows the payback period for a typical turbine-pump configuration. In this graph the assumption was made that capital expenditure to install a turbine is R4.5-million per MW. It is also assumed that the annual electricity cost will increase by 30%. If the turbine-pump operates for 70% of the day, and the average annual electricity cost is 15c/kWh, the payback period of a turbine-pipe configuration is an estimated 34 months (Table 7). However, by installing a turbine-pump and avoiding a penalty of R 2.80/kWh by doing so, the payback period will reduced to less than 3 months, as seen in Table 7.

Table 7: ECS and electricity cost saving payback for a 1 MW turbine-pump

Year	Cost [Rands]	Saving [MW]	Minimum ECS saving		Electricity cost saving	
			Tariff [R/kWh]	Yearly saving [R]	Tariff [R/kWh]	Yearly saving [R]
2008	4 500 000			-4 500 000	0.15	-4 500 000
2009		1.00	2.80	24 528 000	0.20	1 708 200
2010		1.00	2.80	24 528 000	0.25	2 220 660
2011		1.00	2.80	24 528 000	0.33	2 886 858
2012		1.00	2.80	24 528 000	0.43	3 752 915
2013		1.00	2.80	24 528 000	0.56	4 878 790
Payback period [months]			2.2		34	

To implement a typical turbine-pump configuration on an existing pump station takes around 9 to 18 months. Due to the present demand for the turbines, a lead-time of between 10 and 12 months are expected to get a turbine on site.

2.5.3.3 Three chamber pipe feeder system

One of the latest innovations presently being installed in South Africa with great success is the 3-CPS. This system makes use of a valve configuration to displace hot water from the mine by making use of the potential energy generated by the cold water that is fed into the mine. This system technology is developed locally which reduces the cost.

The installation costs will be dependant on the physical layout of the mine. On average R 5.5-million is needed to install a system that could recover 24 MWh of potential energy daily by pumping hot water out of the mine [58].

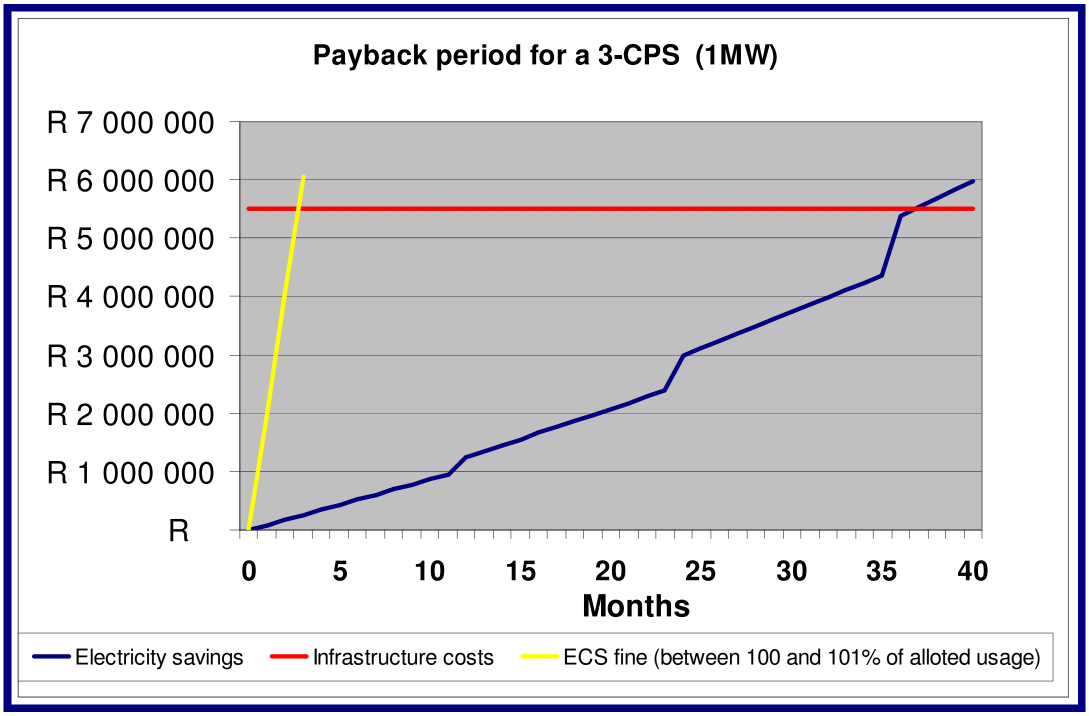

Figure 37: Payback period for a typical 3-CPS

Figure 37 indicates the payback period for a typical 3-CPS. The assumption was made that installation cost of a typical 3-CPS to be installed is R 5.5-million. Assuming that the 3-CPS is in operation for 70% of the day, and that the electricity cost is 15c/kWh, the typical payback period of a 3-CPS is 40 months. However, by installing a 3-CPS and avoiding a penalty of R 2.80/kWh by doing so, the payback period will reduced to less than 3 months, as seen in Table 8.

Table 8: ECS and electricity cost saving payback for a 1 MW 3-CPS

Year	Cost [Rands]	Saving [MW]	ECS saving Tariff [R/kWh]	Yearly saving [R]	Electricity cost saving Tariff [R/kWh]	Yearly saving [R]
2008	5 500 000			-5 500 000	0.15	-5 500 000
2009		1.00	2.80	24 528 000	0.20	1 708 200
2010		1.00	2.80	24 528 000	0.25	2 220 660
2011		1.00	2.80	24 528 000	0.33	2 886 858
2012		1.00	2.80	24 528 000	0.43	3 752 915
2013		1.00	2.80	24 528 000	0.56	4 878 790
Payback period [months]			2.7		36.0	

Converting a conventional pumping chamber to accommodate a 3-CPS could take between 18 to 36 months. The high demands of labour and steel piping adds to the 3-CPS' implementation period.

A study was launched on the 3-CPS of Tshepong mine to determine the efficiency of the system. More than 500 water flow samples were measured. The water fed to underground, as well as the water extracted from the mine by means of the 3-CPS were logged. The data points were plotted against each other as shown in Figure 38.

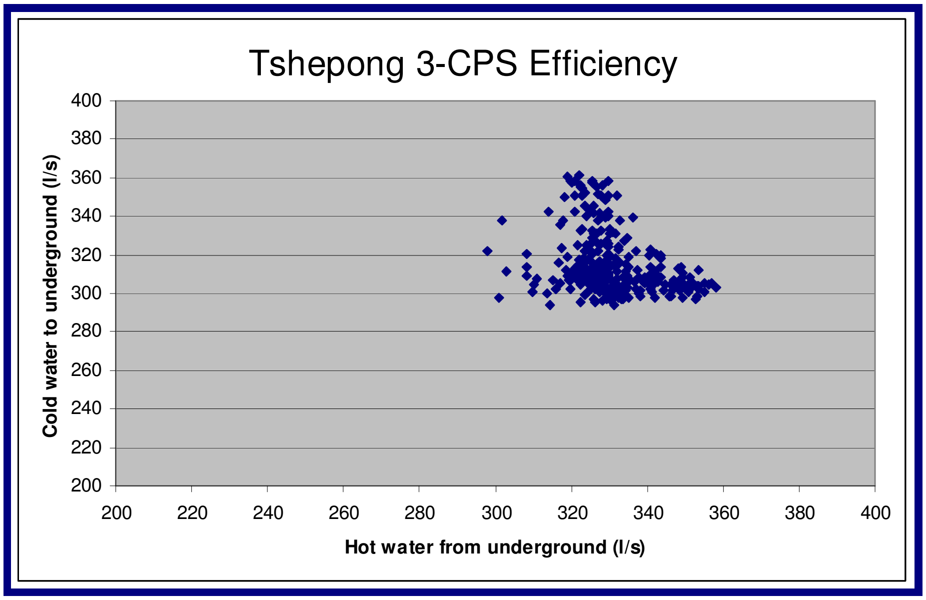

Figure 38: Tshepong mine 3-CPS efficiency calculation

On average the 3-CPS uses 330 l/s to extract 314 l/s of water from the mine. This proves that the efficiency of a 3-CPS can be as high as 93% [59].

The high efficiency of the 3-CPS makes it much more popular that the turbine-pump configuration. However the turbine-pump is still suited for applications where more water is fed underground than extracted.

2.5.4 Electricity costs optimisation

2.5.4.1 Overview of electricity cost optimisation

Load shift from the expensive tariff periods can assist the mine to reduce its electricity (c/kWh) rates. In a typical mine with a life-time longer than 29 months it will be feasible to implement a real-time energy management system. By doing so the dewatering system first needs to be automated.

If the capital expenditure does not allow the dewatering system to be automated, manual load shift can be attempted. Due to the human element involved in this strategy, savings are usually not as high as in the automated strategy.

Figure 39 shows the process that needs to be followed to decrease the average tariff rate of a dewatering system. The elements involved in this system are discussed in the next section.

Due to annual Eskom tariff increases, the average REMS electricity rate and manual load shift rate were made variables. At the time of writing, the following electricity rates applied:

- REMS electricity rate = 13c/kWh
- Manual load shift electricity rate = 14c/kWh

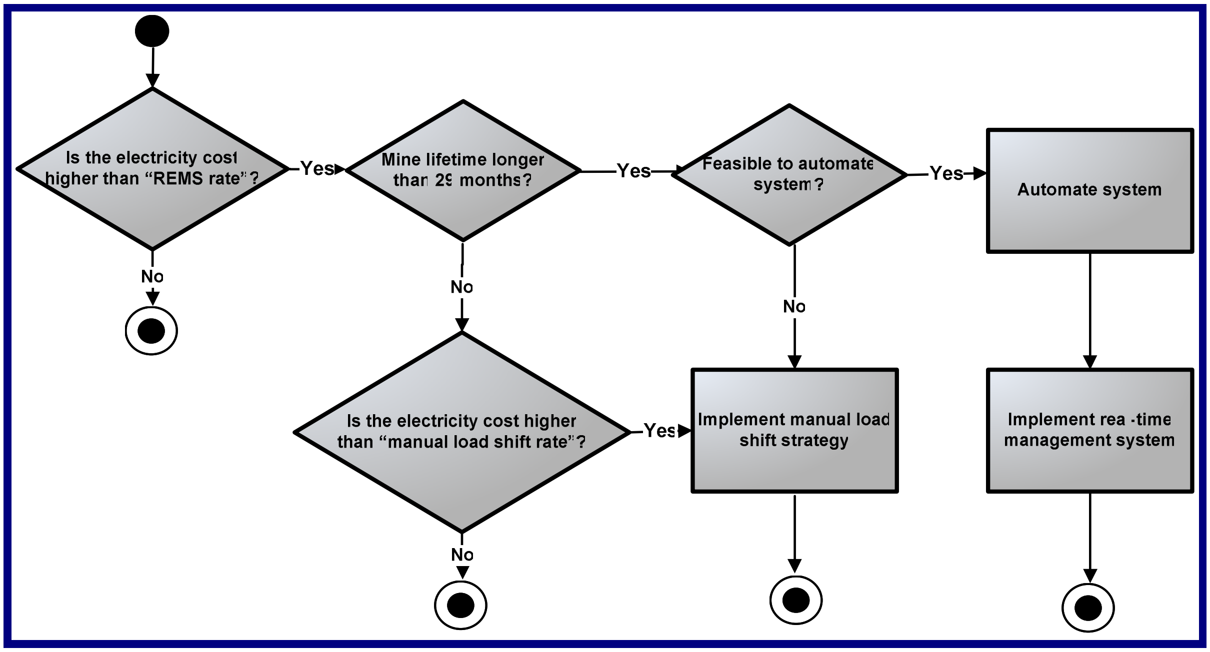

Figure 39: Electricity cost (c/kWh) optimisation model

2.5.4.2 Manual load shift

In a manually operated simplistic pump configuration system, more pumping can be attempted during the lowest cost periods and less pumping during the expensive tariff periods. In these cases the pump operator is usually issued with a variable pricing tariff wheel. The tariff wheel is shown in Figure 40. This procedure has not been very successful in the past, the main reason being the human element involved.

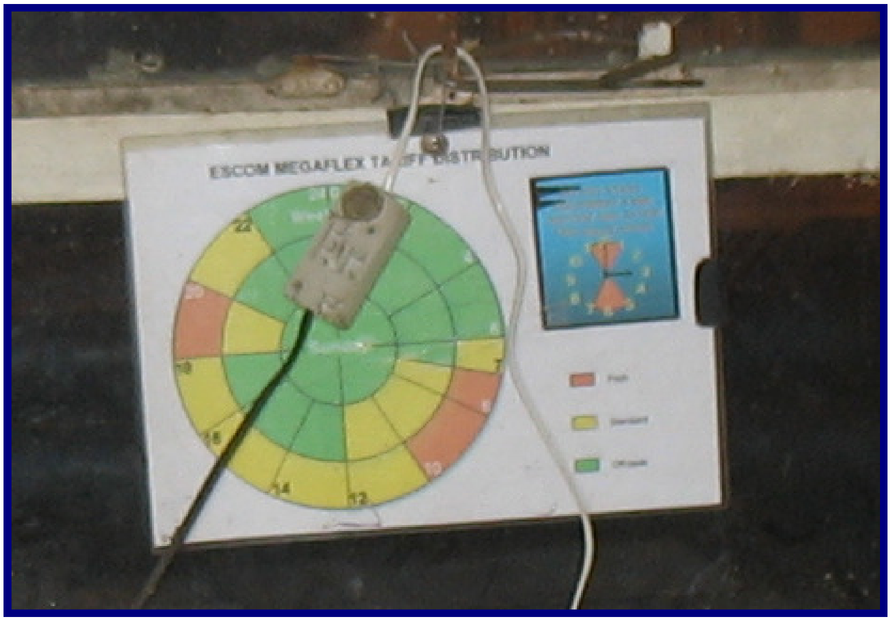

Figure 40: Variable tariff wheel issued to the mining personnel

The operator is required to use the Mega Flex tariff chart at own discretion to run the minimum number of pumps during the peak periods between 18:00 and 20:00 in the evening and 07:00 and 10:00 in the morning.

Table 9 summarises the estimated annual cost savings when morning and evening load shift is done. These savings were calculated using the 2008/2009 Eskom tariff costs. This table can be used to motivate mining personnel to enforce load shift on the mining systems.

Table 9: Annual load shift savings calculation

		Morning load shift (MW)							
		0	1	2	3	4	5	6	7
Evening load shift (MW)	0	R 0	R 176 000	R 352 000	R 528 000	R 704 000	R 880 000	R 1 056 000	R 1 232 000
	1	R 117 000	R 293 000	R 469 000	R 645 000	R 821 000	R 997 000	R 1 173 000	R 1 349 000
	2	R 234 000	R 410 000	R 586 000	R 762 000	R 938 000	R 1 114 000	R 1 290 000	R 1 466 000
	3	R 352 000	R 528 000	R 704 000	R 880 000	R 1 056 000	R 1 232 000	R 1 408 000	R 1 584 000
	4	R 469 000	R 645 000	R 821 000	R 997 000	R 1 173 000	R 1 349 000	R 1 525 000	R 1 701 000
	5	R 586 000	R 762 000	R 938 000	R 1 114 000	R 1 290 000	R 1 466 000	R 1 642 000	R 1 818 000
	6	R 703 000	R 879 000	R 1 055 000	R 1 231 000	R 1 407 000	R 1 583 000	R 1 759 000	R 1 935 000
	7	R 820 000	R 996 000	R 1 172 000	R 1 348 000	R 1 524 000	R 1 700 000	R 1 876 000	R 2 052 000

Figure 41 shows a prediction of what can be expected implementing manual load shift. The magenta line shows the average power consumed at a specific time. The power consumption is reduced during the Eskom morning and evening peak periods. However, in this example during the morning peak period, the load was shifted an hour too early. This is considered to be a missed opportunity.

The blue line shows the dam level for the specific pump station as well as the expected dam level increase during peak periods. During the morning peak period the dam level increased to 65% of the maximum capacity. But during the evening peak periods it increased to less than 60% of the dam capacity. This indicates that the maximum load was not shifted during the evening peak period, and more pumps could have been stopped. By doing so, increased savings would have been generated.

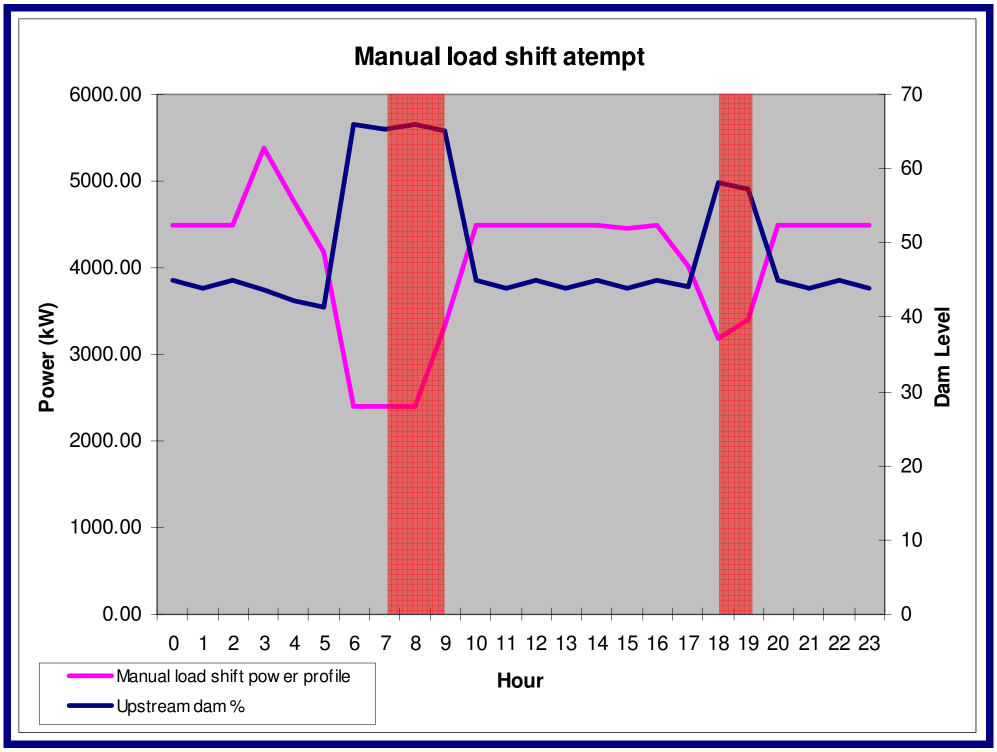

Figure 41: Manual load shift prediction

A number of mines attempted manual load shift. Table 10 shows results of the few mines where manual load shift resulted in savings. From this table it can be seen that on average a mine can actually reduce its average electricity costs rate from 16c/kWh to 14c/kWh doing manual load shift.

Table 10: Manual load shift: average annual electricity cost

Mine	Running capacity (MW)	Average electricity costs (c/kWh)
Tau Tona	14	14.4
Harmony 3#	1.2	13.9
Evander 7#	7	14.1
Kloof 7#	17	14
Average electricity costs (c/kWh)		**14.1**

In the next section the benefits of implementing a real time energy management system is discussed.

2.5.4.3 Real-time energy management system

After all the required instrumentation has been installed to automate the pumping system, a real-time energy management system can be implemented. Not only will this system generate savings by ensuring that the largest amount of energy is used during the cheaper Eskom off-peak periods, but due to automation, labour cost can also be reduced.

The following aspects have an impact on the savings generated for a typical cascaded dewatering system:

- Inflow of water from mining levels during specific periods in a day
- Capacity of the underground dams
- Pumping capacity
- Mine dewatering layout
- Pump availability

Table 11 shows the average electricity cost on mines where a REMS system has been implemented. From this table it can be seen that the average electricity cost decreased to 12.8c/kWh.

Table 11: REMS annual electricity cost

Mine	Running capacity (MW)	Average electricity costs (c/kWh)
South Deep	10.7	12.9
Target	1.2	11.7
Beatrix1,2,3	7	12.8
Cooke1#	2.8	12.6
Mponeng	10.7	12.7
Kopanang	4.6	13.5
Tshepong	4.5	13.6
Average electricity costs (c/kWh)		12.8

Figure 42 shows the payback period if a system is automated and a REMS system implemented. In Appendix A the average dewatering system automation cost was calculated at R 460 000/MW. Figure 42 shows the payback periods for a system where manual load shift was done in the past, as well as when no load shift was done. The annual electricity cost increase of 30% was included in these calculations. Therefore the electricity saving trends are not straight lines. According to the calculations an automated system with no manual load shift history is paid back in less than 16 months. If a system has a history of manual load shift results, the payback period is estimated at less than 29 months.

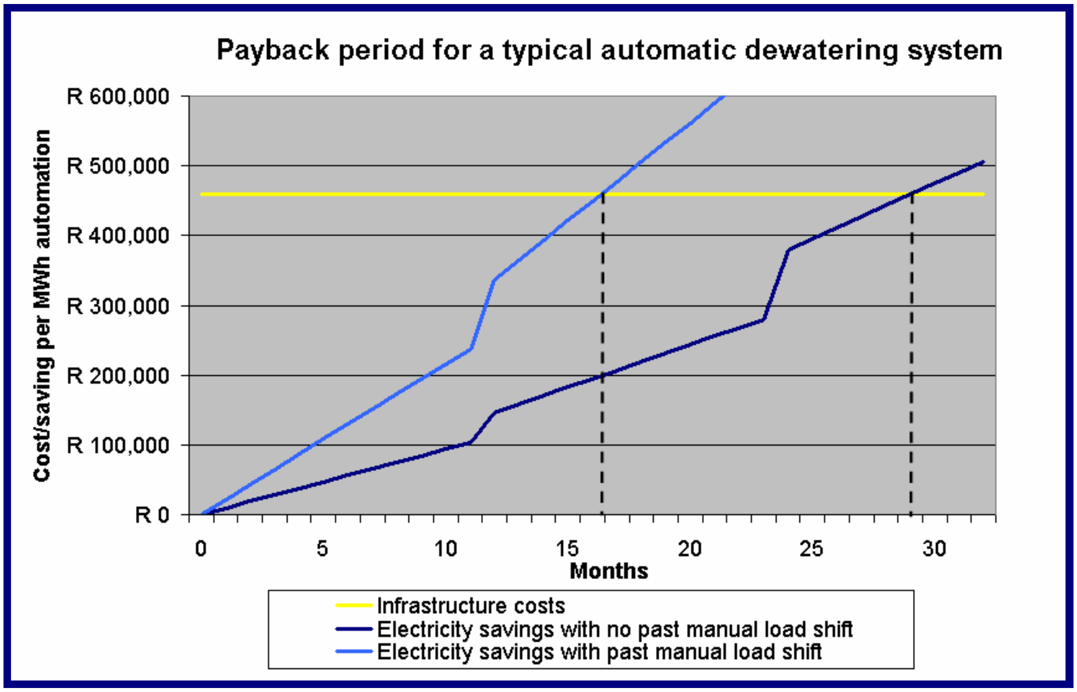

Figure 42: Comparison between manual and evening load shift and payback period

Table 12 shows the annual savings per MW automated running capacity and the payback period. The system will realise an annual saving of more than R 500 000 in the year 2011 if automated.

Table 12: Electricity savings and payback period with automated REMS

Year	Cost		Electricity cost saving on system with no load shift		Electricity cost saving on system with a history of manual load shift	
	[Rands]	[MW]	Tariff [R/kWh]	Yearly saving [R]	Tariff [R/kWh]	Yearly saving [R]
2008	460 000		0.03	-460 000	0.01	-460 000
2009		1.00	0.04	341 640	0.02	148 044
2010		1.00	0.05	444 132	0.02	192 457
2011		1.00	0.07	577 372	0.03	250 194
2012		1.00	0.09	750 583	0.04	325 253
2013		1.00	0.11	975 758	0.05	422 828
Payback period [months]			16		29	

Therefore, depending on the lifetime period of the mine, as well as previous savings generated, the feasibility of implementing an automated REMS system can be determined. If no load shift is attempted and the mine has the capital to automate and install a real-time energy management system, the savings generated by the mine will be enough to cover the cost in 16 months. If, however, success has been achieved with manual load shift, the system will normally take 29 months to generate enough savings to cover the initial installation costs.

2.5.5 **Water efficiency optimisation**

2.5.5.1 Overview of water efficiency optimisation

Water usage is related to electricity usage. The more water is fed down the shaft, the more electricity is needed to extract the water from the shaft. If water can be managed more efficiently, electricity usage can be reduced. Figure 43 is a water optimisation model. This model can be used to assist the mine to reduce their water wastages.

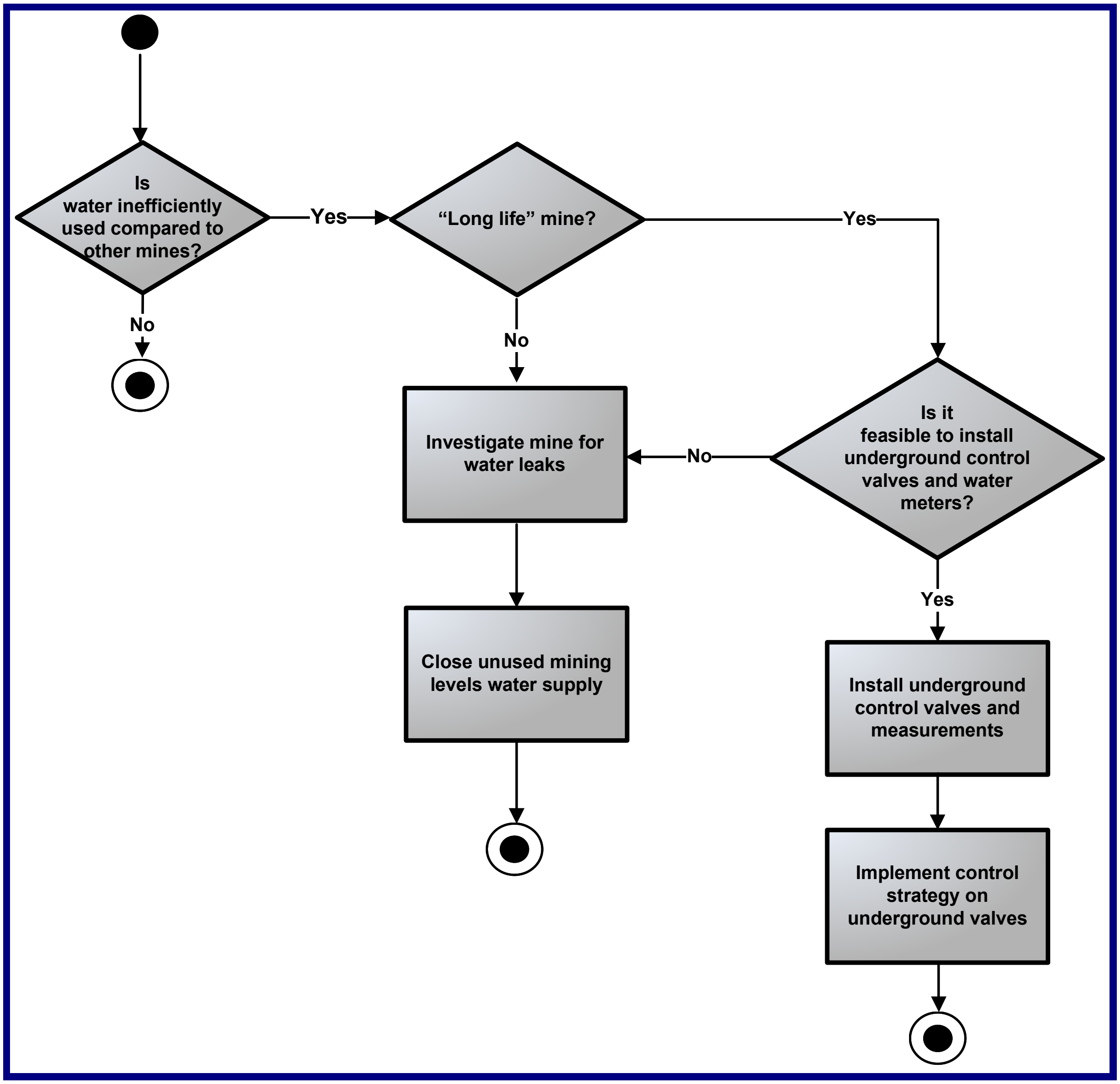

Figure 43: Water efficiency optimisation model

Water wastage is common in deep level mining. In the past water was wasted. The reason for this is that the distribution of water is not properly managed. It is commonly found that closed-off mining levels are still supplied with water. Even if the pipe end is blanked-off, water leaks can still occur between the shaft water column and the closed-off mining section. Therefore it is suggested that the pipe be blanked-off as close to the shaft as possible.

For optimal water management, each mining level's water supply should be managed individually. This is done because each level has different water requirements. The initial capital needed to invest in underground water management might seem a lot, but the payback period of such a system could be less than three years.

2.5.5.2 Service water control optimisation

One technique to reduce water wastage is to control the water pressure entering underground mining levels. If this can be optimally controlled, all other components will benefit. The result will be a more efficient water reticulation system, due to the other components using less energy to fulfil their functions. In this section novel techniques were developed to reduce the water consumption of a typical mine. A controller was also developed for the REMS system. This controller enables the underground level valves to be controlled automatically via a centralised control room.

Water stored in the underground cooling dams is fed to the different mining levels, where it will be used for cooling and other services such as drilling and sweeping. Each level has a valve configuration near the shaft that can regulate water flow during emergencies or non-production periods. A typical valve configuration is shown in Figure 44.

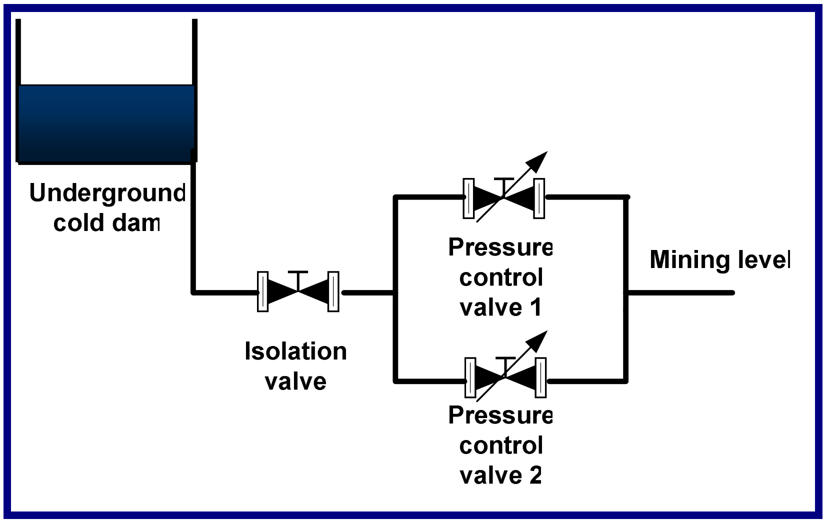

Figure 44: Water supply valve configurations

In this figure a configuration consisting of two pressure control valves is shown. In some configurations the valve can be controlled to give a predetermined downstream pressure.

Depending on the mining section's requirements, these valves can be set according to a specific pressure. When the mining section is operational, the set point is selected to ensure sufficient flow and water pressure supply. The second pressure control valve is installed as a backup. The isolation valve can stop the water supply to both the pressure control valves. This valve is usually closed on non-production days when no water is required, or in case of emergencies. The isolation valve can only be fully opened or closed.

To control the water delivered underground, a detailed investigation into underground water requirements must be made. Various levels use water for different purposes. For example, a development section will usually require water 24 hours a day as shown in Figure 45. On the other hand, closed-off sections might use no water at all.

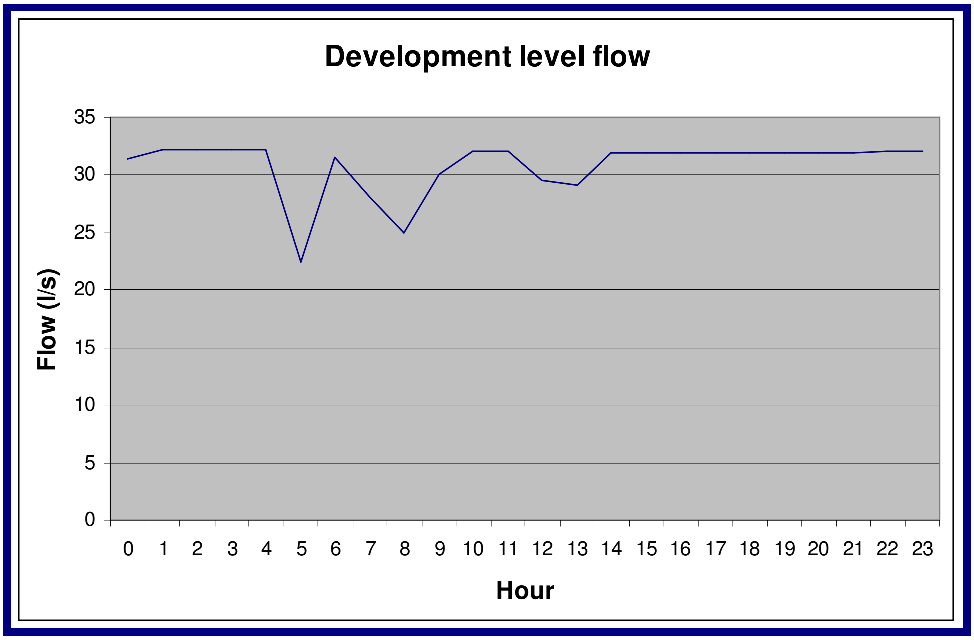

Figure 45: Water usage on a typical development level

It is important that the water column is filled with water at all times. If for some reason the water column has been drained, water hammer could occur during refilling. This may damage equipment or even burst the pipe columns.

Figure 46 is a typical water usage trend of a production level with the pressure control valve set at a specific fixed set point. The water usage was highest from 08:00 to 12:00. This was as a result of water being consumed by the drilling shift, which started at 06:00 and ended at 14:00. The two hours prior and subsequent to the high water demand periods was the time when the shift personnel were transiting to and from the work areas. Water consumption outside the 08:00 to 12:00 bracket is usually water that is being wasted. Contributing factors to water wastage are water leaks and the production crew not closing off the working level water valves.

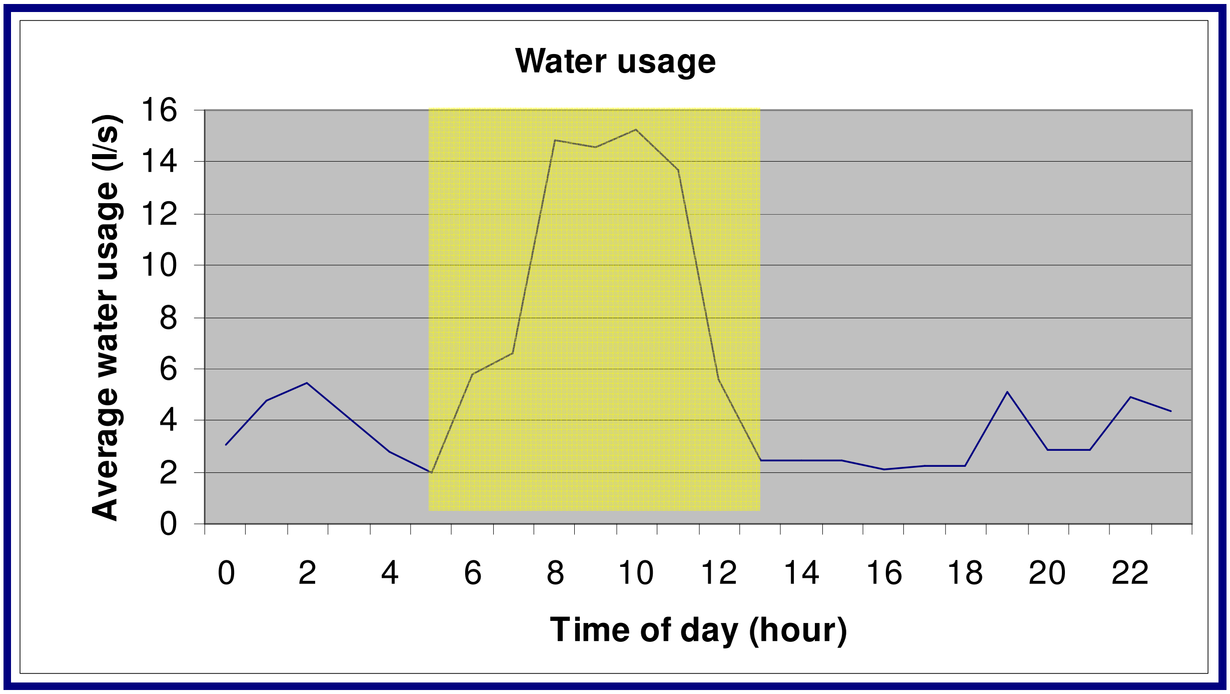

Figure 46: Water usage on a typical production level

For optimum results, an investigation into the water usage of each level is required. By doing so, the pressure set point of each level at a specific time can be calculated. These new set points can, in consultation with the engineers and production personnel, be used to determine the most optimised schedule, which will not adversely influence production.

The result of these investigations showed that different schedules were required for specific days. These days are defined as the following:

Weekdays, between Monday and Friday, the most water is used. A high water pressure is required throughout the day, except for blasting times, which commences at 16:00 and lasts until 20:00. During this period, limited quantities of water are used and the pressure at these levels can be reduced.

Saturday (non-production day) is for those weekends where no mining occurs. The water consumption is reduced to a minimum and some of the underground water level valves can be closed off.

Saturday (production day), is for weekends where mining resumes. These days can be considered as weekdays, except for the period between 20:00 and 22:00. During this period water pressure can be reduced due to the start of the Sunday profile.

During **Sundays**, the minimum amount of water is supplied for mining activities. However, the water pressure must be increased before 22:00. This is when the normal weekday operation begins.

The effect of the reduction in water pressure on the flow is shown in Figure 47. The water flow is reduced from about 12 l/s to less than 2 l/s during a Saturday. This is done by reducing the water pressure in the underground level supply.

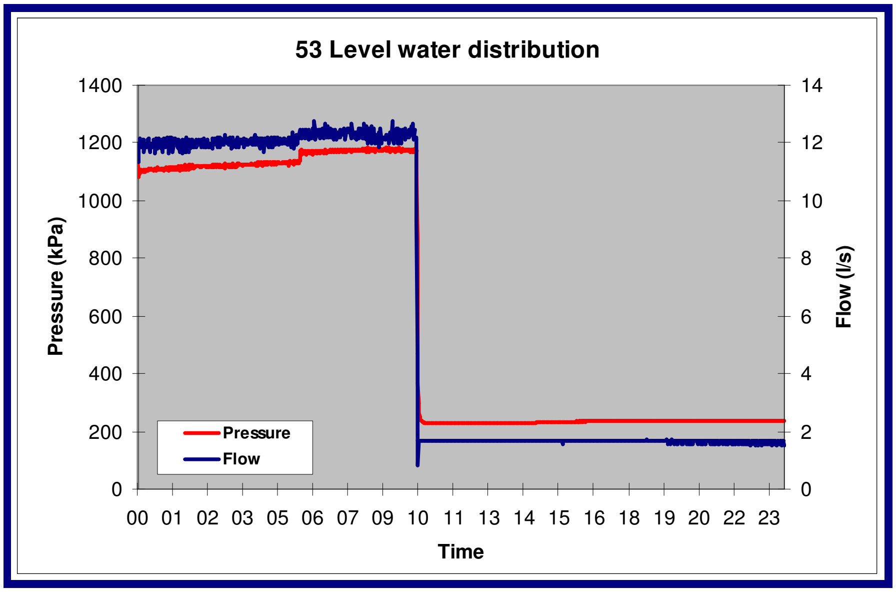

Figure 47: Water pressure drop due to the closing of the level pressure control valve

Figure 48 shows the relation between the water pressure and the water flow downstream of the valve. It can be clearly seen that if the water pressure is lowered, the water flow automatically adjusts accordingly to a logarithmic fitting. This trend is unique for each level and is dependent on the valve specification, pipe layout and equipment installed downstream of the valve.

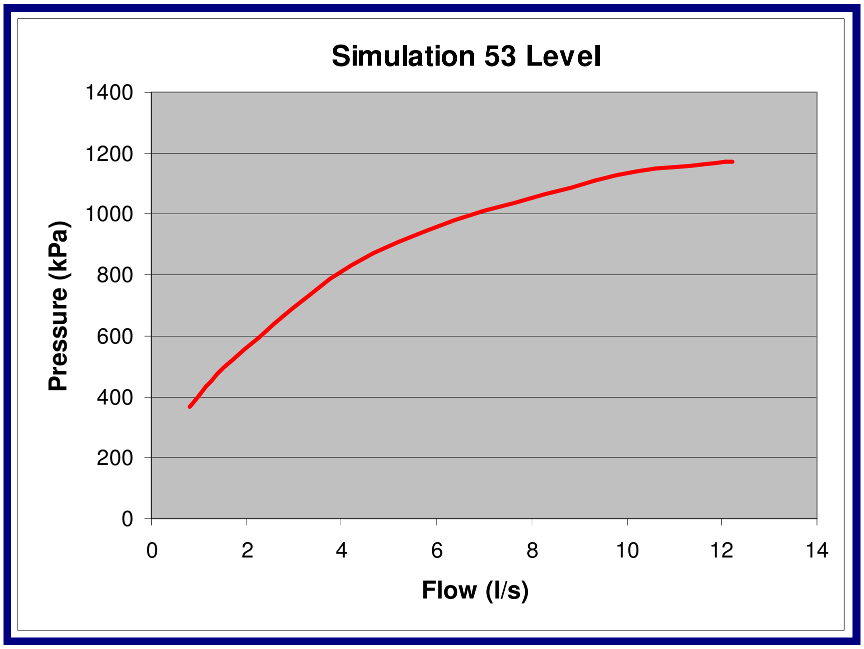

Figure 48: Relation between water pressure and flow

Figure 49 indicates how optimising the pressure control schedule can reduce water usage. Water is still supplied to the production levels when it is required, but during the so-called non-production times, the pressure valve can be controlled to minimise water wastage. During these periods the downstream pressure can be reduced by partially closing the valve.

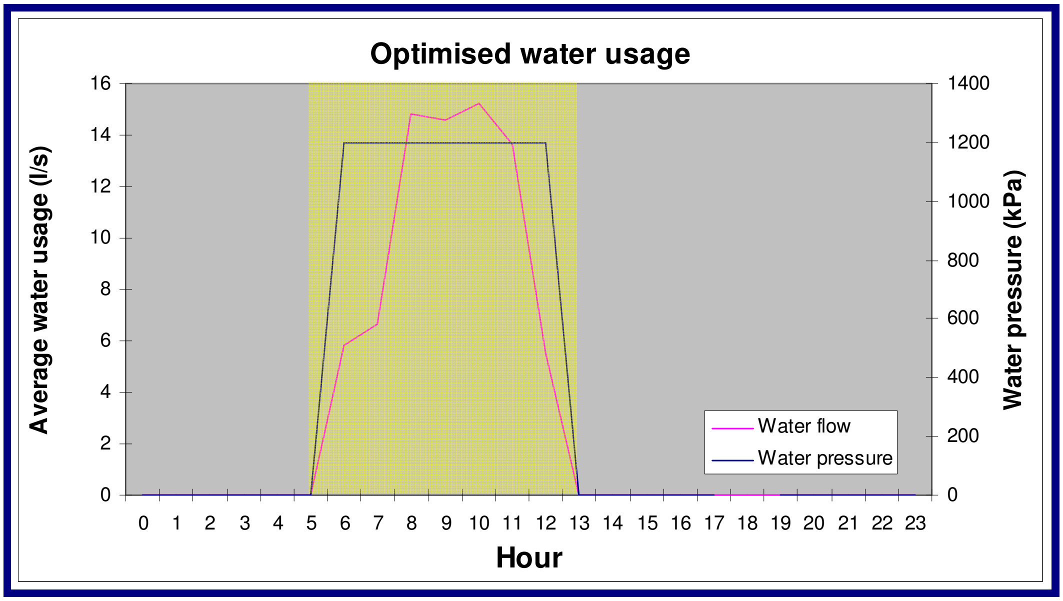

Figure 49: Optimised water schedule

2.6 Conclusion

In this chapter unique models were developed to analyse mine dewatering systems. By keeping the model simplified and by making use of easy accessible data, these models can be used by unskilled mine personnel.

The models were broken down into three parts, namely:

- Energy efficiency
- Water efficiency
- Average electricity cost tariff

The mine dewatering system needs to be evaluated by all three the above models. Conventional efficiency models only focused on energy efficiency of a specific component. The newly developed models are independent of each other, and it might happen that a system performs well in one field, but is inefficient in another. Therefore these models give a much more accurate representation of a dewatering operation.

By assessing a mine according to the above models and comparing the results to other mines, less efficient operations can be identified. If a system is identified to be less efficient in one sector, an optimised model could be used to improve the inefficiencies. The unique optimised models could assist the user in identifying and resolving common mine dewatering inefficiencies. These inefficiencies could be reduced by means of short or long-term solutions.

For the long-term solutions, the payback period was also determined. This could assist the mine in selecting a feasible solution.

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CHAPTER 3: Application of novel efficiency optimisation techniques (Case studies)

Chapter 2 identified Beatrix 1 Shaft pump station to be inefficient. An investigation into the inefficiency is launched and the dewater efficiency optimisation model applied. Water wastages on Kopanang Mine are also reduced by implementing the newly developed underground level water valve controller.

3.1 Introduction

The newly developed techniques and models to identify an inefficient dewatering system were applied during an investigation on Beatrix 1 Shaft in Chapter 2. The outcome of this investigation highlighted the inefficient energy usage of this shaft compared to other shafts. The average tariff cost was calculated at 15c/kWh and the dewatering efficiency of Beatrix 1 Shaft at 41%. The energy efficiency dewatering optimisation model will be used in an attempt to resolve some of the energy inefficiencies on Beatrix 1 Shaft.

Kopanang mine was also used as a case study. At this mine the new underground level valve controller was installed. Its underground water usage per ton of reef and waste is 2.67 kl. The effect of the controller on the water savings, as well as the effect on electricity savings, is discussed in this chapter.

3.2 Energy efficiency optimisation

3.2.1 Background on mine

Beatrix Gold Mine is located ±20 km south of the town of Virginia in the Free State Province. It is part of GoldFI Mining South Africa (Pty) Limited, owned by Gold Fields Limited [30]. The mine consists of four shafts, including Beatrix 1 Shaft, Beatrix 2 Shaft, Beatrix 3 Shaft, and Beatrix 4 Shaft. The ore is processed at two metallurgical gold plants. During the 2007 financial year, Beatrix Mine milled 1.78-million tons of ore with an average yield of 4.7g/ton [61]. This translates into a total of 16 903 kg gold produced in 2007. At time of writing the gold price was R 227,526/kg. Therefore the market value for 16 903 kg gold produced is R 3 845-million.

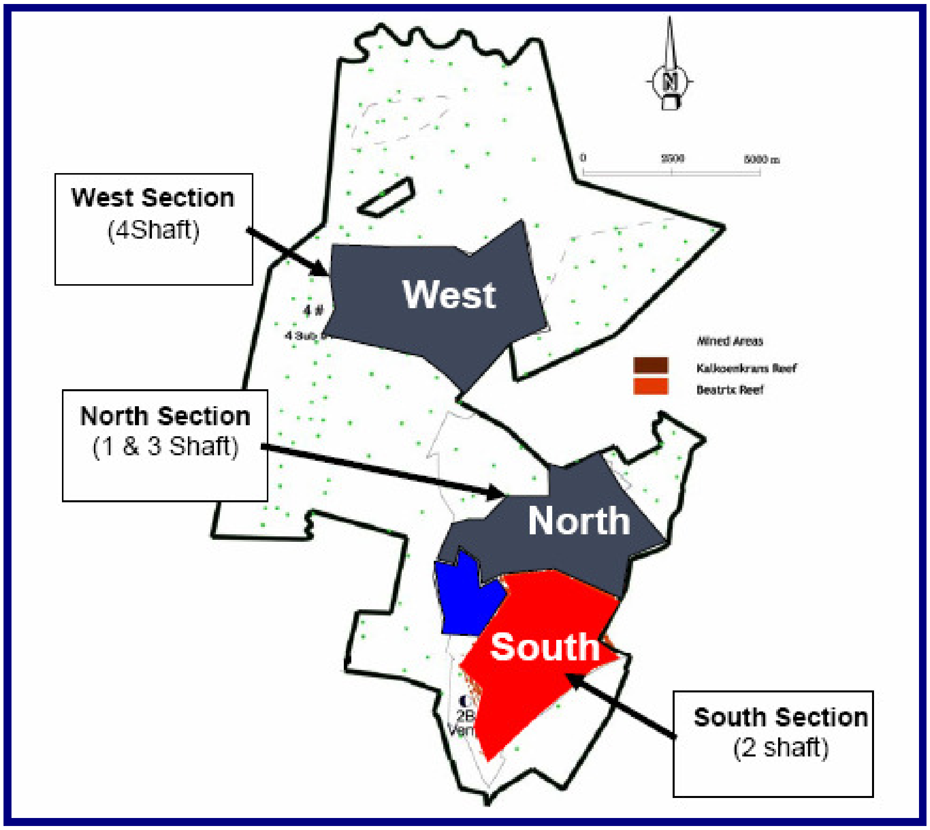

Figure 50: Area section for Beatrix mine

Figure 50 shows the area section of the different Beatrix shafts. Beatrix 1 Shaft and 3 Shaft is included in the North section, Beatrix 2 Shaft is part of the South section and Beatrix 4 Shaft is part of the West section.

Beatrix 1 Shaft, Beatrix 2 Shaft and Beatrix 3 Shaft are connected via 16 Level. Each of these mines consists of a single pumping station. The detailed layout can be seen in Appendix B. Beatrix 4 Shaft is isolated and its water reticulation system is independent of the other Beatrix Shafts.

An average 8.4 megalitres (Ml) per day must be pumped from 27 Level on 3 Shaft to the clear water dam at 16 Level on 1 Shaft. This includes 4.32 Ml/day of water sent down for services, plus 4.08 Ml/day of fissure water.

1 Shaft pump station pumps the water used for underground services, underground fissure water and the water coming from 3 Shaft pump station. An estimated 20.5 Ml/day of water

is pumped to the surface via the pump station at 16 Level on 1 Shaft. Beatrix 2 shaft pumps an estimated 10.2 Ml/day. Figure 51 summarises the water reticulation volumes of Beatrix 1, 2 and 3 Shafts.

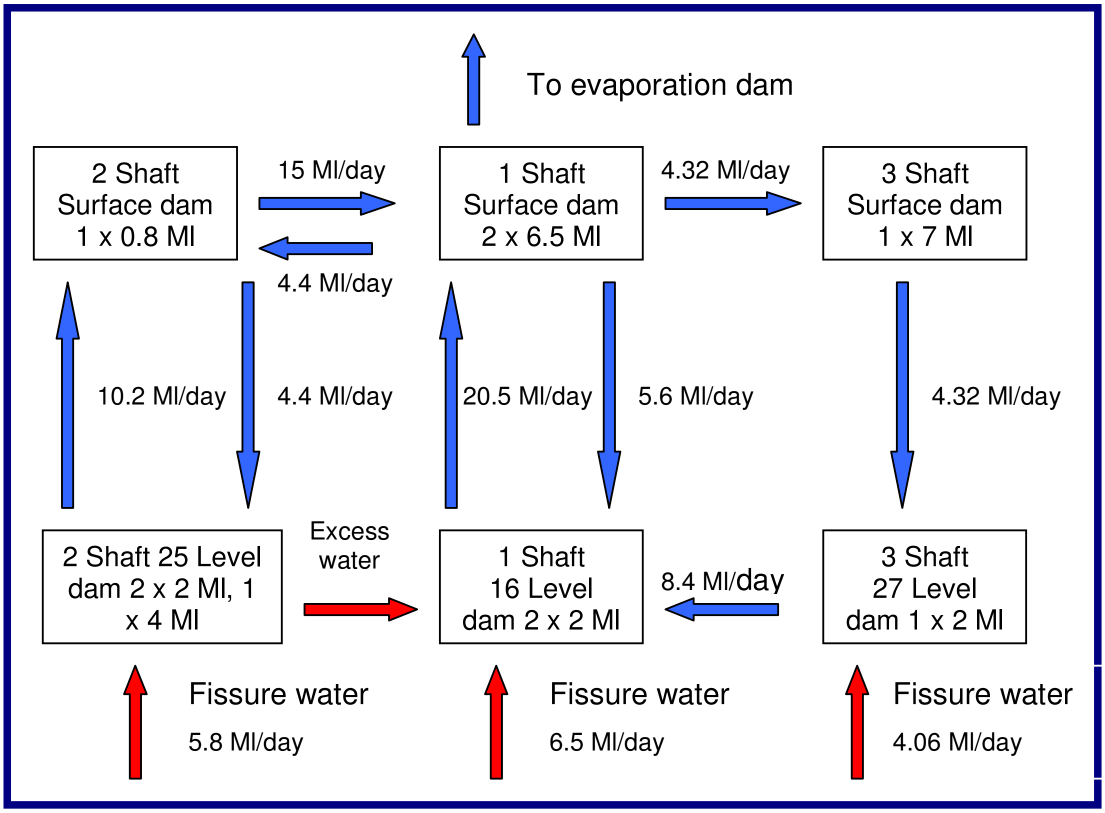

Figure 51: Beatrix 1 Shaft, 2 Shaft and 3 Shaft water network

An upgrade on 3 Shaft's pumping station is presently underway. In future, 3 Shaft will pump an estimated 9 Ml/day from its 27 Level pump station directly to the surface. This will reduce the water volumes from 1 Shaft considerably.

3.2.2 Investigation

To find a solution for the inefficient operation of 1 Shaft, more focus should be laid on the pumping station itself. The pump station's information and control constraints are shown in Table 13.

Table 13: 1 Shaft pump station information and control constraints

1 Shaft pump station	
Maximum number of pumps available	6
Maximum number of pumps utilised	4
Number of columns available	3
Number of pumps for each column	2
Each pump's electrical demand	2 000 kW
Each pump's flow rate	± 120 l/s
Upstream 16 Level	
Dam size	2 x 2 Ml
Maximum dam level	80%
Minimum dam level	20%
Downstream surface dam	
Dam size	2 x 6.5 Ml
Maximum dam level	90%
Minimum dam level	40%

The first step in identifying the inefficiency of a pump station is to analyse the pump operation. Beatrix 1 Shaft pump station consists of three different columns from which the water is pumped to surface. Pump numbers 1 and 2 pump water into column 1, Pumps 2 and 3 into column 2 and Pumps 5 and 6 into column 3. Figure 52 is a pie chart representing the utilization of the Column 1. From this chart it can be seen that 59% of the time, Pumps 1 and 2 simultaneously pump into Column 1. This increases friction and pressure in the column, resulting in a dramatic decrease in efficiency.

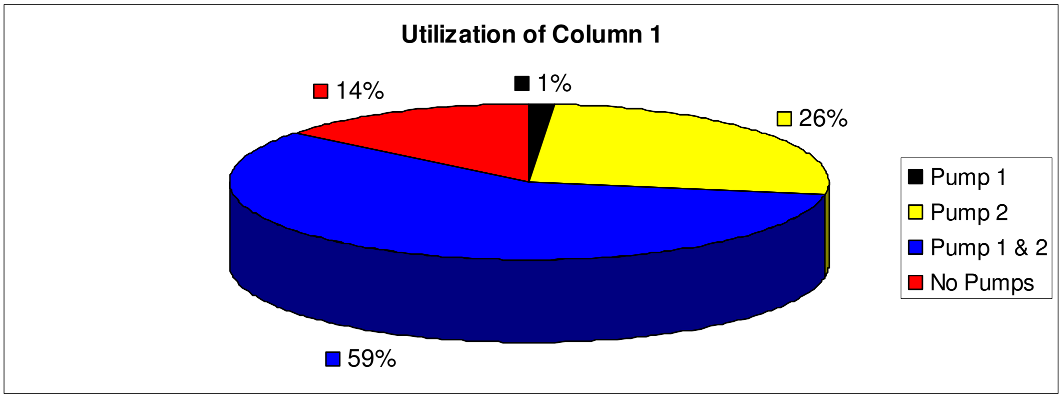

Figure 52: Utilization of Column 1

Figure 53 shows a pie chart of the utilization of column 2. From this chart it can be seen that 81% of the time this column is not being utilised. Sufficient capacity is therefore available in Columns 2 and 3 to minimise the inefficient pumping in Column 1.

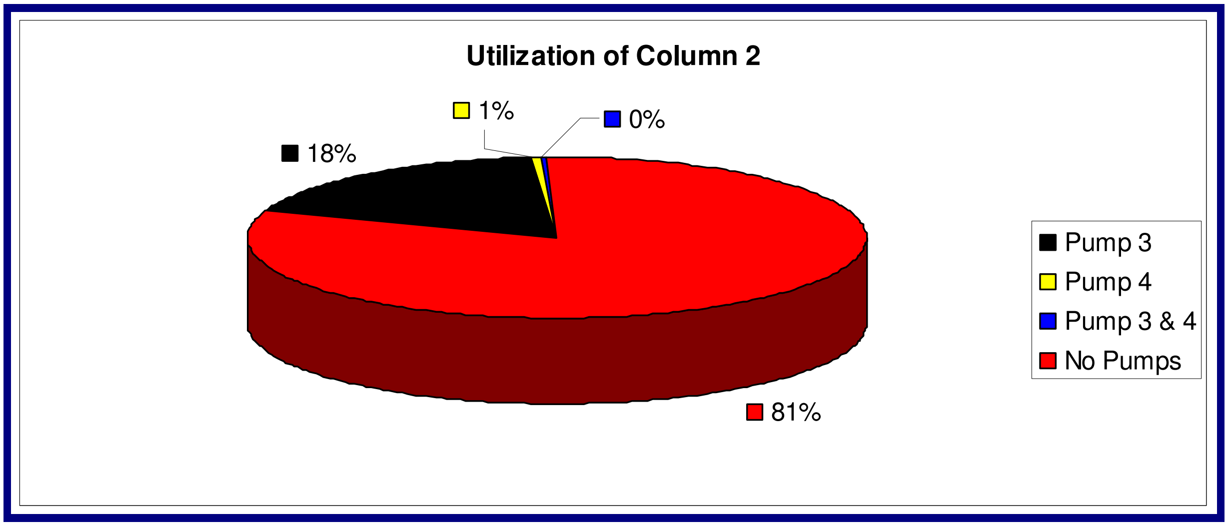

Figure 53: Utilization of Column 2

By optimising the REMS Pumps system installed on the mine, the inefficient pumping was rectified. The system efficiency is considered before the pump is started. In Figure 54, Figure 55 and Figure 56 a significant change in column utilization can be seen. These figures show that multiple pumps operating into a single column have been dramatically reduced.

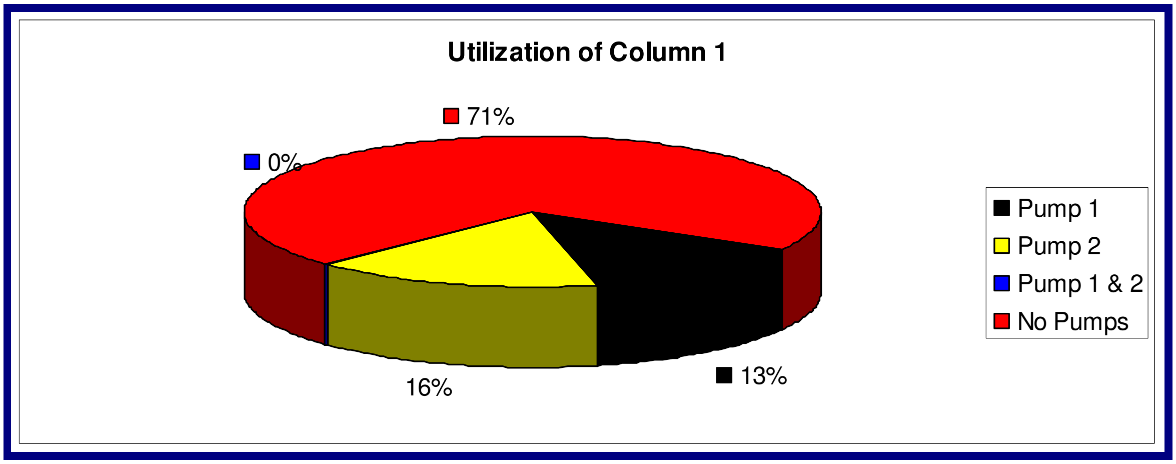

Figure 54: Optimised utilization of Column 1

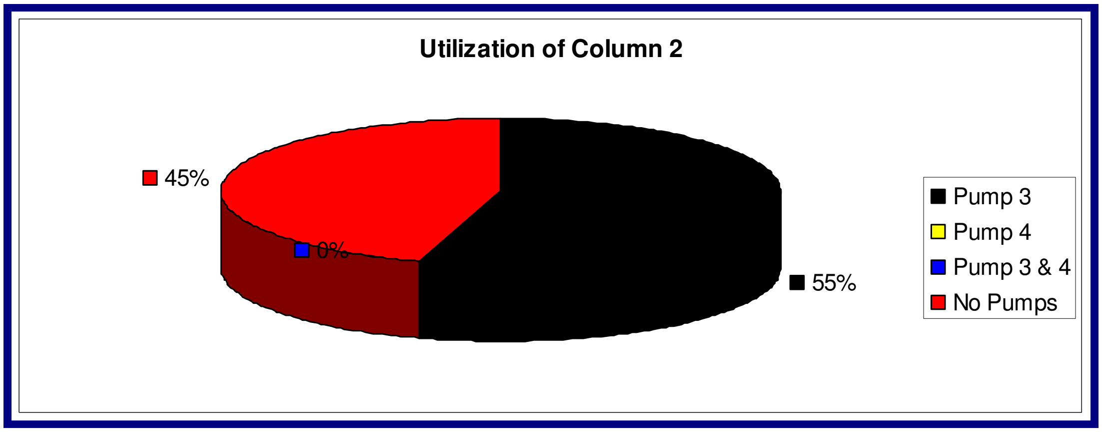

Figure 55: Optimised utilization of Column 2

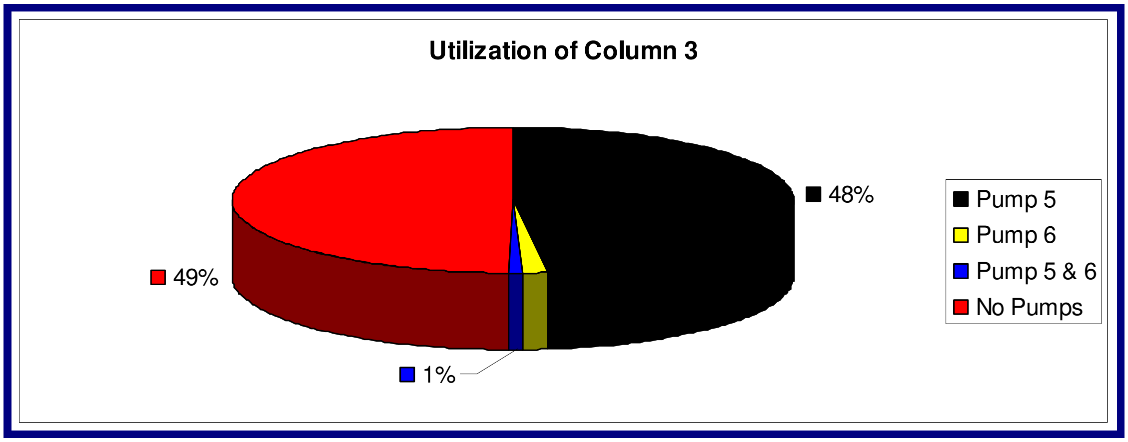

Figure 56: Optimised utilization of Column 3

3.2.3 **Results**

To calculate the effect of the more efficient pumping operation, the relationship between power usage and the amount of water pumped was investigated. Analysis of this relationship entailed investigation of the historical water data and the energy consumed due to the inefficient pumping operation. The daily amount of water pumped was plotted against the energy used. This plot is shown in Figure 57 [62].

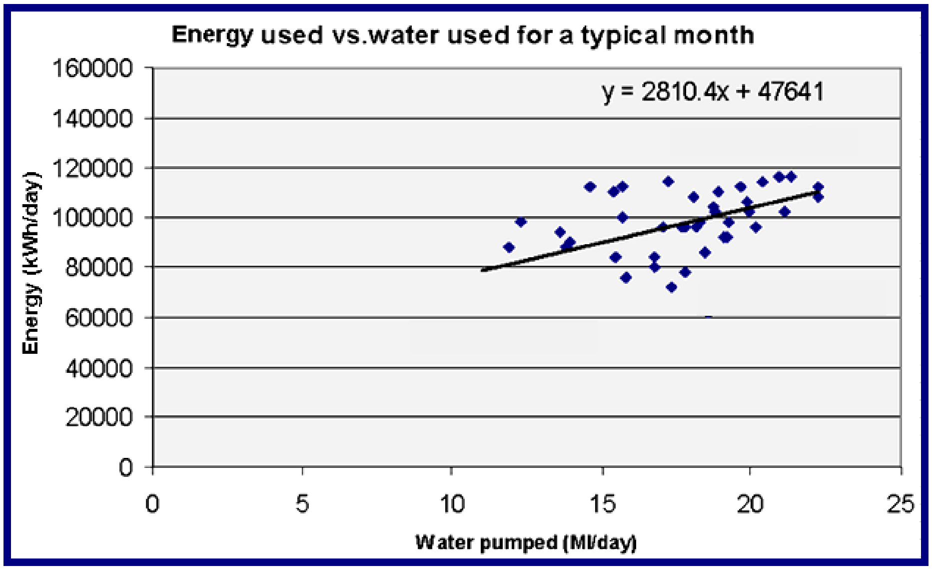

Figure 57: Beatrix 1 Shaft water pumped against power used

In Figure 57 it can be seen that the energy consumption per amount of water for each day is different. The reason for this is that different pump combinations are run for each day. Therefore the efficiency component of each day also differs.

Equation 3-1 was derived by making use of the least squares method.

$$y = 2810.4x + 47641 \qquad (3\text{-}1)$$

Where:

y = energy (kWh/day) usage

x = amount of water in Ml/day.

By using equation 3-1, the energy required to pump a certain amount of water can be calculated. If the same amount of water pumped per day after the pump optimisation is inserted into equation 3-1, the energy consumption before the optimisation can be calculated. After the operation was optimised, 1 Shaft consumed 70 MWh to pump 13 Ml per day. According to the calculation, had the operation not been optimised, the dewatering system would have consumed more than 84.4 MWh to pump 13 Ml. Therefore an energy saving of 17% was realised. Figure 58 represents the electricity profile of Beatrix 1 Shaft, 2 Shaft and 3 Shaft combined.

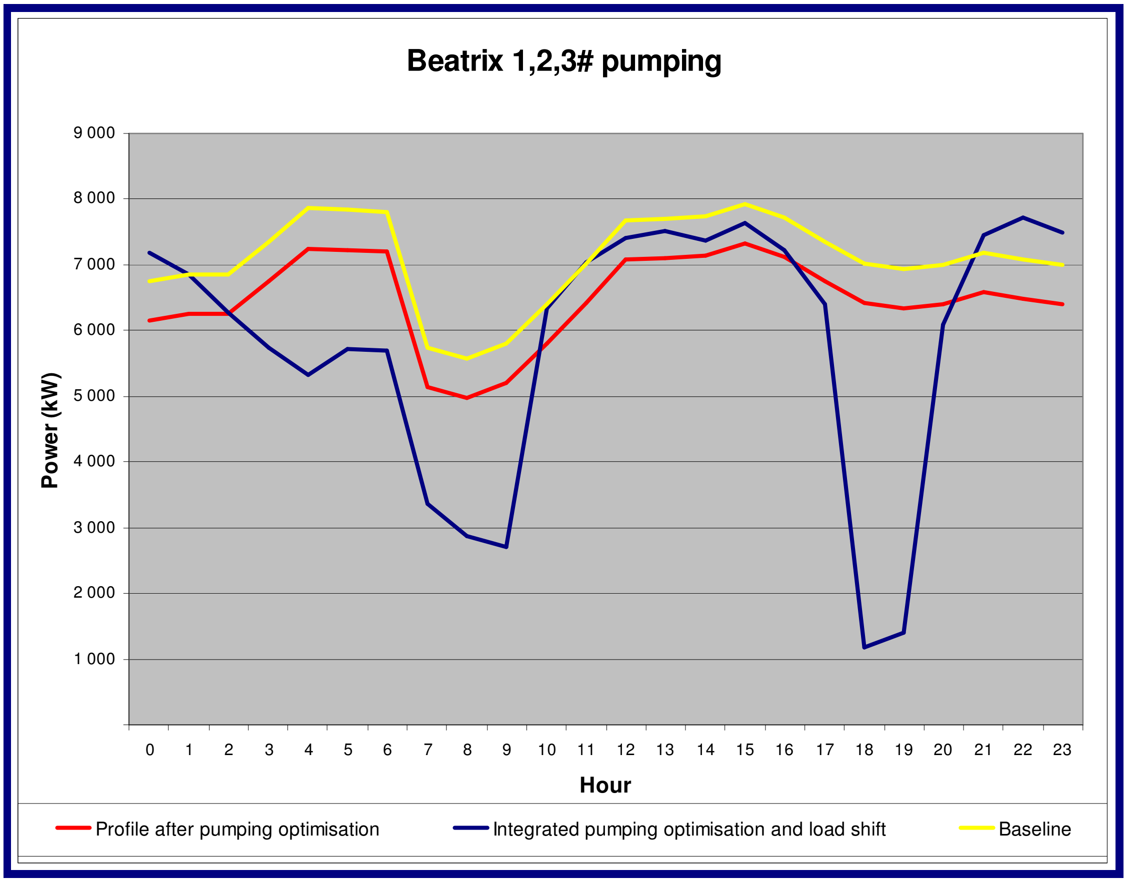

Figure 58: Load shifted and energy efficiency profile against historical profiles

In Figure 58 the yellow line shows the baseline before implementing REMS and optimising the pumping schedule on Beatrix 1 Shaft. After the energy efficiency application was implemented, the baseline was reduced and shown by the red line. This figure shows that the total baseline was reduced by 600 kW throughout the entire day. This resulted in a daily energy efficiency saving of 14.4 MWh, which translates into a cost saving of R800 000 per annum. The blue line in the graph shows the total effect of the REMS Pumps system on Beatrix 1, 2 and 3 shafts. The graph includes energy efficiency, as well as the load shifting. By implementing the optimised pump operation, the dewatering efficiency of Beatrix 1 Shaft increased from 41% to 48%, as shown in Figure 59.

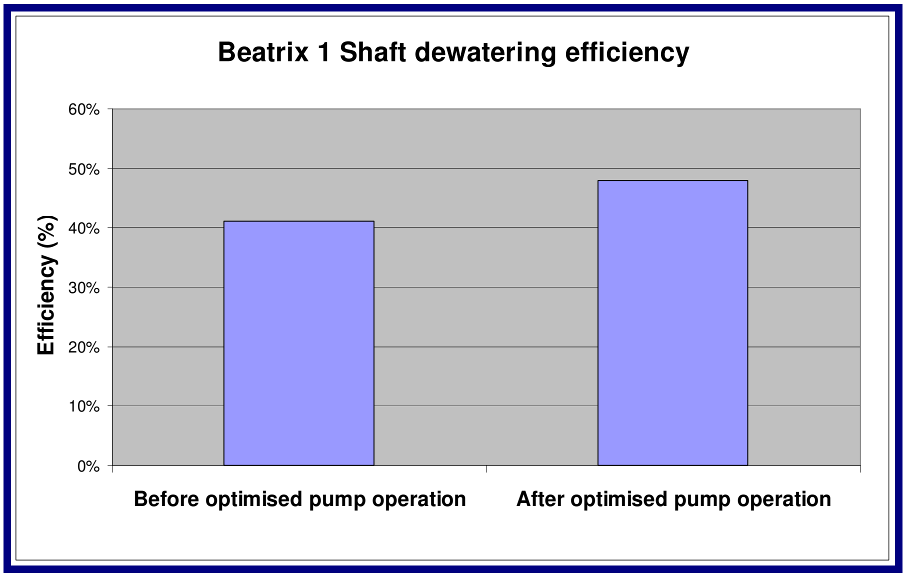

Figure 59: Beatrix 1 Shaft dewatering efficiency

By implementing REMS Pumps, the average annual electricity tariff of Beatrix 1, 2 and 3 shafts reduced from 15c/kWh to 12.3c/kWh, as shown in Figure 60.

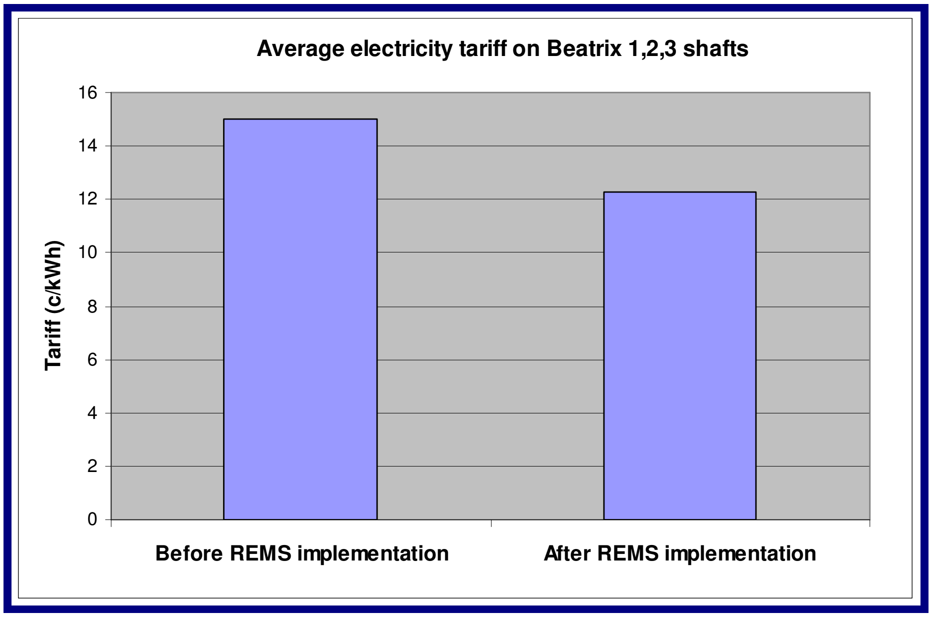

Figure 60: Beatrix 1, 2 and 3 shafts electricity tariff

The average load shift and energy efficiency results are shown in Table 14.

Table 14: Beatrix 1,2,3 load shift results

Beatrix 1 Shaft pumping operation optimisation			
	Apr-08	**May-08**	**Jun-08**
Morning load shift (kW)	2 700	2 500	2 400
Evening load shift (kW)	5 700	6 230	6 114
Energy efficiency (kW)	600	600	600
Monthly savings	R 149 700	R 137 162	R 324 451
Annual estimated savings	R 2 500 000		

Therefore, by using the optimised energy model and implementing REMS, the pump station on Beatrix 1 Shaft operated more efficiently. This load shift together with the efficiency, realised an annual saving of R 2 500 000 for the Beatrix mines.

3.3 Water efficiency optimisation

3.3.1 Background on mine

To improve the water efficiency, a strategy was developed for the underground level water supply at Kopanang mine. In this section it will be shown that by reducing the amount of water consumed, energy efficiency is introduced.

Kopanang mine is one of four mines, which make up the AngloGold Ashanti's Vaal River operations. Great Noligwa, Tau Lekoa and Moab Khotsong are the other three mines. These mines are situated near the towns of Klerksdorp and Orkney in the North West Province and the Free State respectively.

The Vaal River complex has four gold plants, one uranium plant and one sulphuric acid plant. It is able to process between 180 000 and 420 000 tons of ore per month [63]. The Vaal River operations produce uranium oxide as a by-product, but its value is insignificant relative to the value of the gold produced.

During the 2005 financial year Kopanang mining plant milled 21-million tons of ore, with an average gold recovery of 8.38 g/ton [63]. During this specific year Kopanang produced 14 992 kilogram of gold. The total costs of operation to extract a kilogram of gold was

R 56 427 per kilogram. In 2005 the average price for a kilogram of gold was more or less R 230 000. As a result, the mine realised a profit of R 2 600-million during the 2005 financial year.

According to the chamber of mines, the average cost of electricity amounts to 11.4% of the total mining cost [20]. Therefore the 27% electricity increase in June 2008 had a limited effect on the larger mines like Kopanang. However, the ECS penalties of more than 18 times the average energy tariff could harm even the larger mines.

3.3.2 Underground level water supply

At Kopanang the pumping and refrigeration systems together consume 34% of the total electricity consumption, as shown in Figure 61 [64].

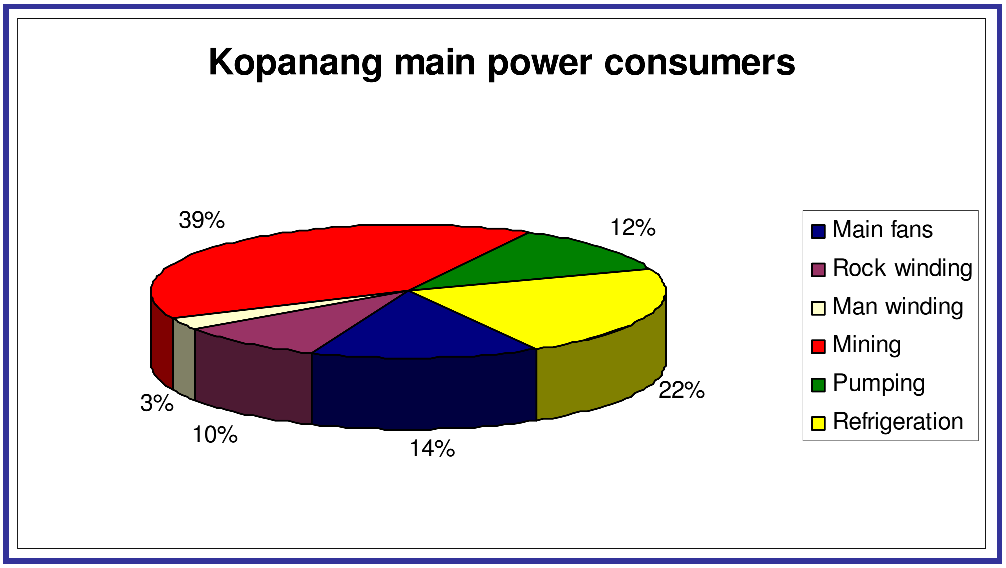

Figure 61: Kopanang electricity distribution

These systems are used to cool water for underground services. Kopanang mine consists of nine underground mining levels. If the water supplied to these levels can be reduced, less electricity will be consumed to extract this water from the mine. The load on the refrigeration plants will also be reduced, because less underground water needs to be cooled. The mining levels on Kopanang are each equipped with a water pressure control valve as shown in Figure 62. In this figure it can also be seen that at 59 Level, 62 Level and 64 Level mining splits into two sections, namely D West (DW) and D South (DS).

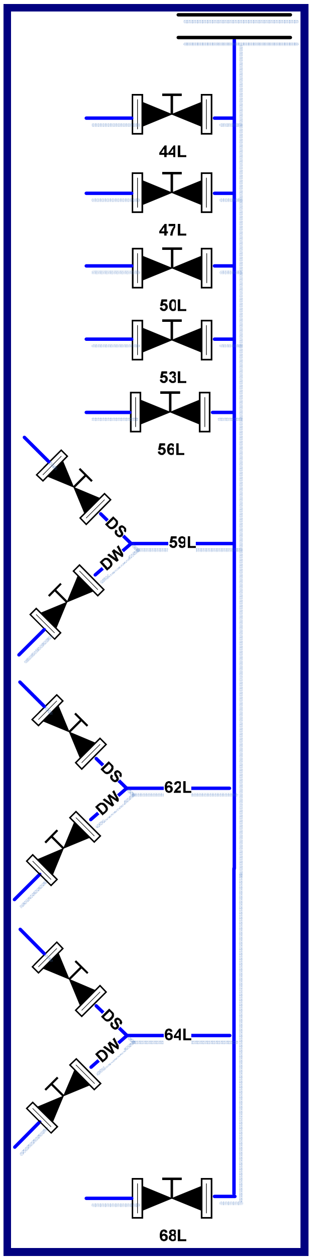

Figure 62: Underground level water distribution layout

Figure 63 shows the percentage water consumption of each mining level. From this chart it can be seen that water to 44 and 47 Levels is shut due to no mining activities. However, from 56 Level down to 64 Level, mining activities increase and therefore more water is consumed.

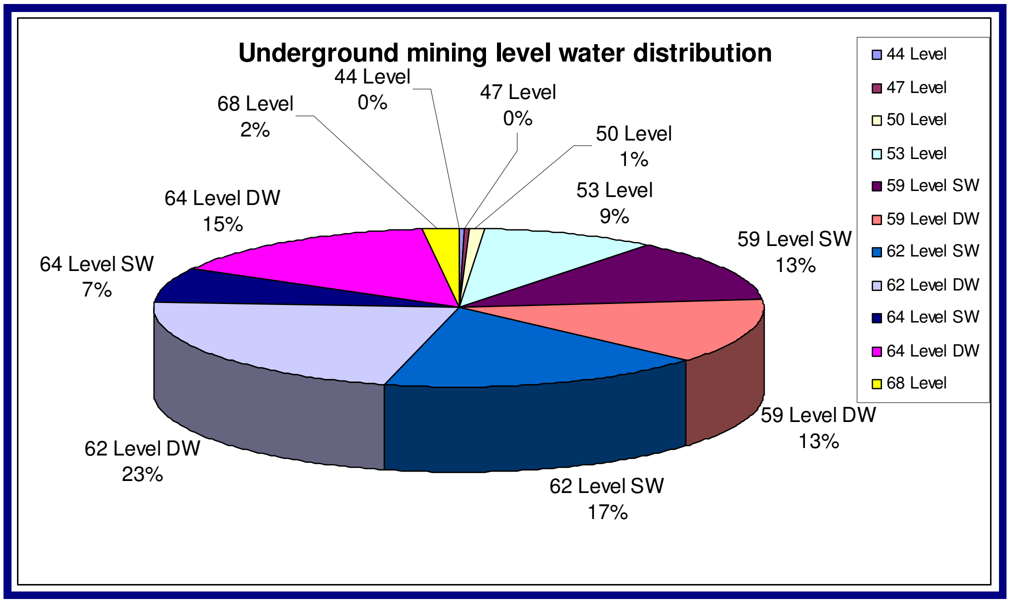

Figure 63: Underground level water distribution

As previously mentioned, mining water is used for services and cooling. After the water column enters the specific levels, it is fitted with an isolation valve in series with a pressure control valve. These valves can be controlled according to specific pressure set points that can be changed from the surface control room SCADA.

Originally, these valves were primarily installed to restrict or completely shut off the water supply to the different mining levels, in case of emergencies and over weekends. This study recognised that these same valves could be used to control the water flow into specific levels at specific times. A controller was then developed, which enabled REMS to control these valves at specific predetermined set points.

Figure 64 shows the water flow reduction due to the pressure drop as a result of restricting the flow through the control valves. From 16:00 to 20:00 the average downstream pressure is lowered from 1 200 kPa to 1 070 kPa. The yellow line represents the water flow prior to the implementation of the underground valve control. The blue line shows the actual water supplied to the levels.

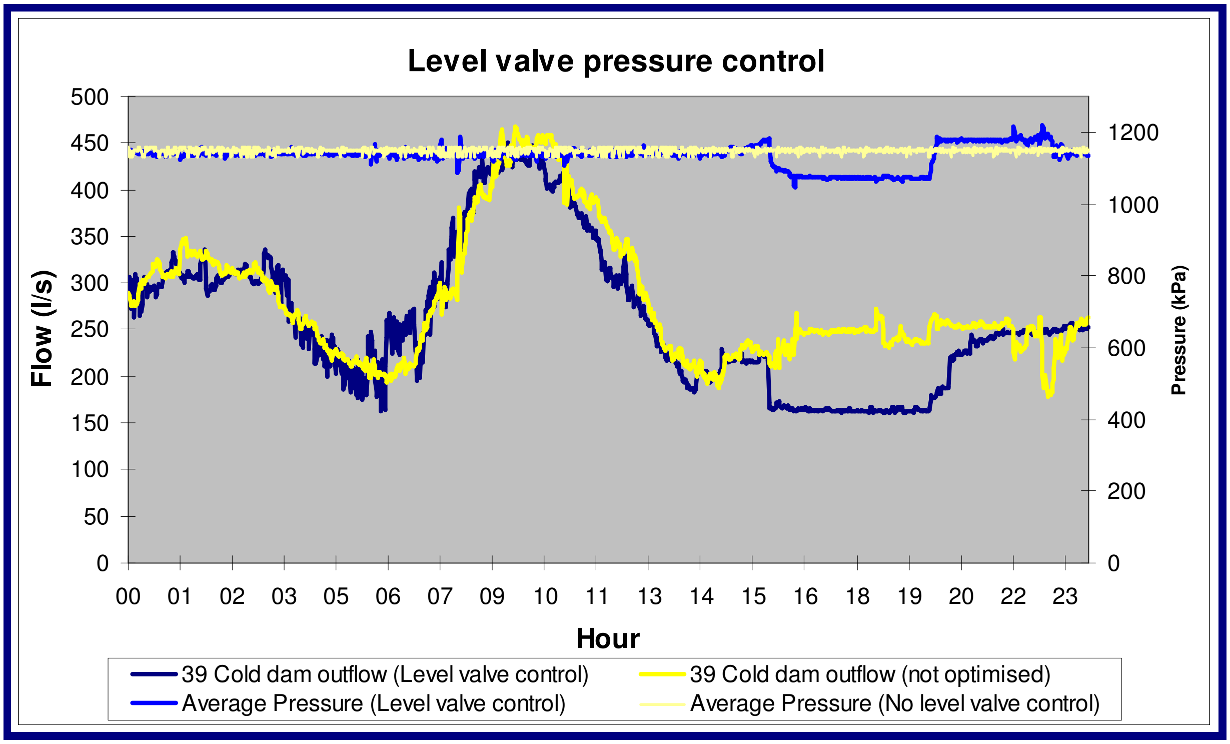

Figure 64: Weekday water flow reduction due to level water pressure drop

Figure 64 shows that from 16:00 to 20:00, after the pressure control valves on multiple levels were partially closed, the total amount of water supplied to the mining levels was instantly reduced by 90.4 l/s. This resulted in a reduction of 1.3 Ml water per day. With this saving, the average water consumption per mass production of Kopanang is reduced to 2.2 kl/Ton.

The rate at which the water is consumed can also be seen from Figure 64. The water consumption for drilling between 6:00 and 12:00 is shown on this graph. Unfortunately the mine only gave permission to partially close the valves during 16:00 and 20:00. During this period blasting takes place and minimum water is consumed.

Due to the water reduction, energy efficiency is introduced on both the refrigeration and dewatering systems. In order to determine the efficiencies, the energy consumption to pump or cool down the reduced amount of water must be calculated. Data from a month prior to the water reduction implementation was used to calculate these savings. During this month an average of 17 Ml of water was pumped daily. The average electricity consumed to pump this amount of water was 141 MWh. By reducing the water consumption by 1.3 Ml/day a saving of 7.6% was achieved. Therefore the daily electrical dewatering saving is estimated at 10.78 MWh.

Before the water reduction strategy was implemented, water was pumped 24h/day. Therefore an energy efficiency of 10.78 MWh a day is translated into a constant power reduction of 449 kW over 24 hours. Figure 65 shows the average power consumption before and after the water saving. By using this profile and the 2008/2009 Eskom Mega Flex tariff, it can be shown that the average summer month saving is R 40 500 and average winter month saving is R 76 000. This results in an annual cost saving of R 600 000, as shown in Table 15.

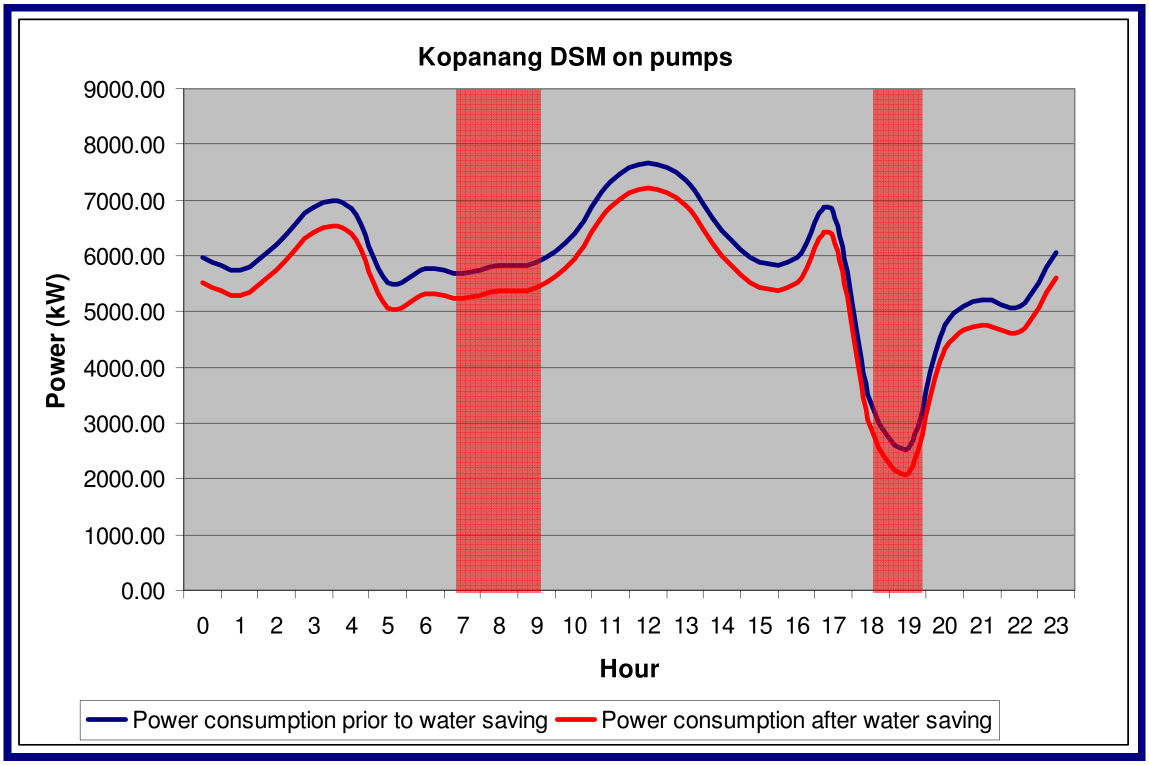

Figure 65: Average daily pumping power profile of Kopanang mine prior to water saving

Table 15: Water reduction saving on dewatering system

Kopanang water reduction saving on dewatering system	
Daily energy efficiency	10.78 MWh
Winter saving per month	R 76 000
Summer saving per month	R 40 500
Annual savings	R 600 000

To calculate the effect of the reduced water flow on the energy usage of the refrigeration system, the water reticulation of the plant must first be analysed. This is done to determine the amount of energy required to cool the water for underground services. The overall power consumption of the refrigeration plant cannot be used, because the refrigeration plant water is also used for ventilation through the BAC system. The BAC water is not distributed underground, but only circulated on surface. Note that the underground water reduction has a minimal effect on the underground temperature.

Figure 66 is a diagram illustrating the average water flow through the refrigeration plant system. In this figure it can be seen that the average flow through the BACs is 680 l/s during a typical summer weekday. It can also be seen that the water enters the BACs at ±3.5℃ and leaves the system at ±8℃. Water is also delivered to the underground operations at an average rate of 196 l/s. This water returns to the refrigeration plant system after the pre-cool towers at a temperature of ±15℃.

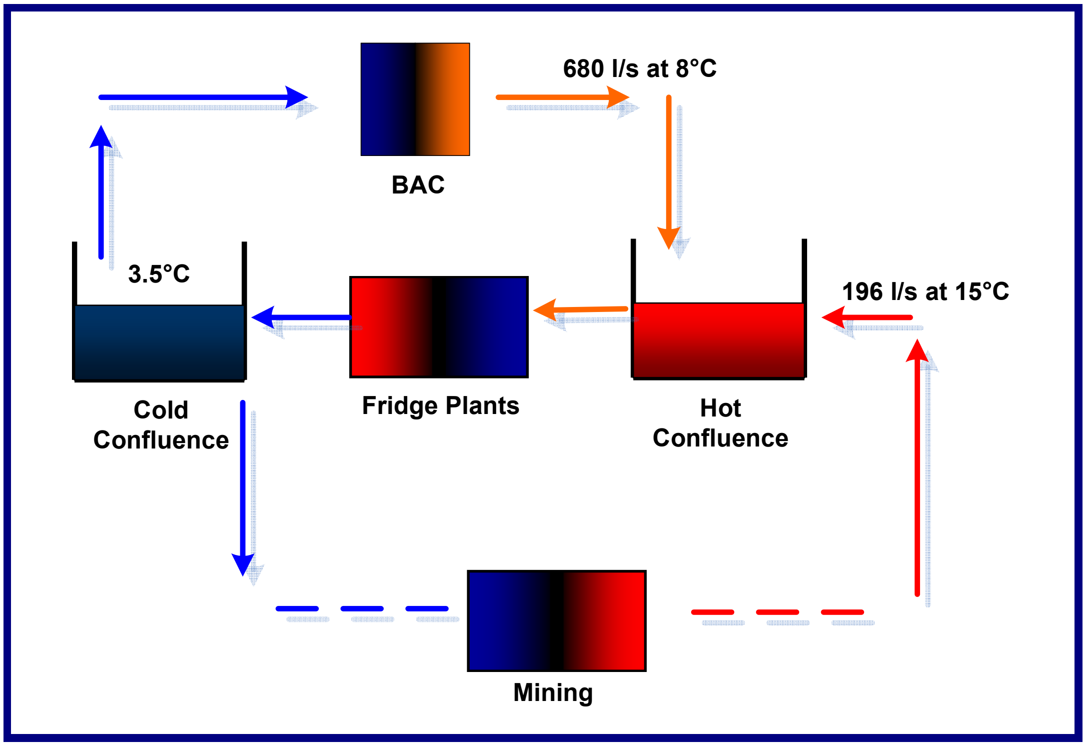

Figure 66: Water reticulation of Kopanang refrigeration plant system

The percentage energy consumed by the refrigeration plant to cool the water for the BACs and underground services is calculated by using equation 3.2.

$$q = c_p \, \Delta T \, m / t \qquad (3\text{-}2)$$

where:

q = heat transfer rate (kW)

c_p = specific heat capacity for water 4.19 kJ/kg.K

ΔT = change in temperature of the fluid (K)

m / t = mass flow rate (kg/s)

By using the above calculation, the percentage energy consumed by the refrigeration system to cool water for the BAC and services is calculated below.

BAC : Services

680 l/s x 4^{o}C : 196 l/s x 11.5^{o}C

55% : 45%

This calculation shows that the BACs consume 55%, and the underground services 45% of the cold water generated by the refrigeration plant. On an average summer weekday, Kopanang refrigeration plant uses 168 MWh to cool the total amount of cold water. Because only 45% of this consumption is used for underground purposes, an estimated 75 MWh is needed to cool water for underground services. By introducing the water efficiency project, 7,6% less water is required to be cooled. Using the above assumptions, it is estimated that a saving of 5.7 MWh per day is introduced on the refrigeration plant.

The refrigeration system cools water 24h/day. The energy savings will therefore take place throughout the day. Therefore the constant 24 hour cooling demand was reduced by 240 kW for a weekday. Figure 67 shows effect of the water reduction on the refrigeration system prior to the DSM.

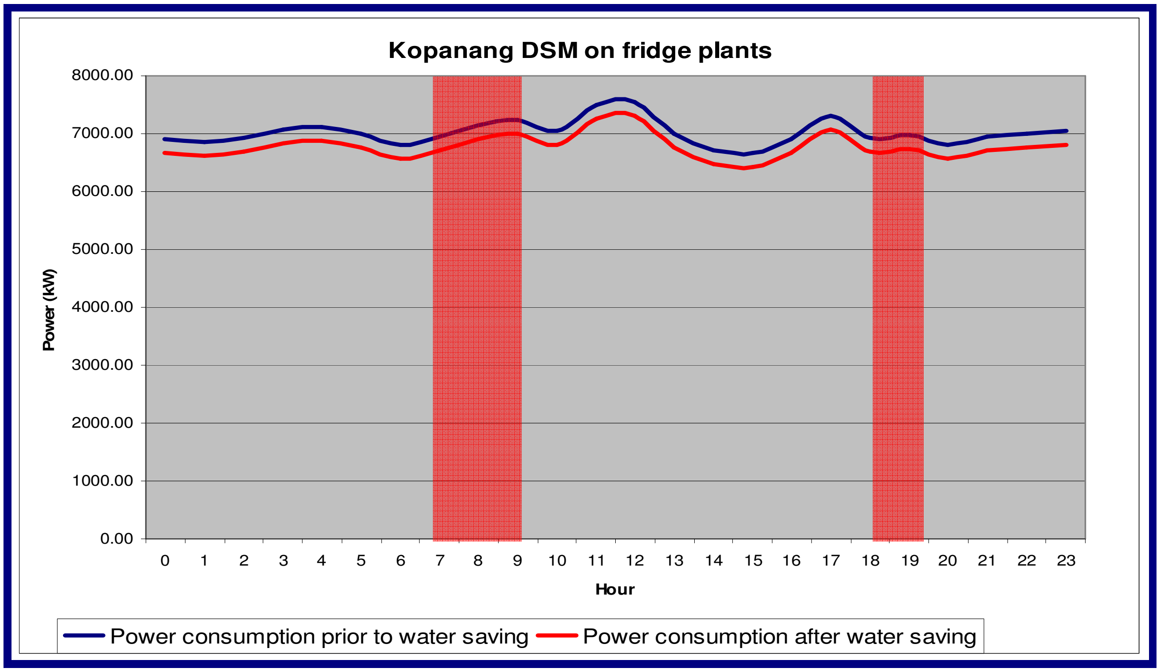

Figure 67: Average daily refrigeration power profile of Kopanang mine prior to water saving

Using the above power profile and the 2008/2009 Eskom megaflex tariff, it is calculated that on an average summer month the saving is R 22 000. Due to the lower temperatures during the winter months from June to August 2008, the refrigeration plant energy consumption will be reduced by 33% [23]. This reduction in energy requirement would occur regardless of the energy savings project. By implementing the water savings project, the average winter month savings will increase by R 13 500 per month. This will result in an annual cost saving of R 235 000 as seen in Table 16.

Table 16: Water reduction saving on dewatering system

Kopanang water reduction saving on refrigeration system	
Daily energy efficiency	5.7 MWh
Winter month savings	R 13 500
Summer month savings	R 22 000
Annual savings	R 235 000

By implementing the underground water management philosophy, the amount of water consumed per ton of reef and waste was reduced from 2.50 kl to 2.33 kl, as seen in Figure 68.

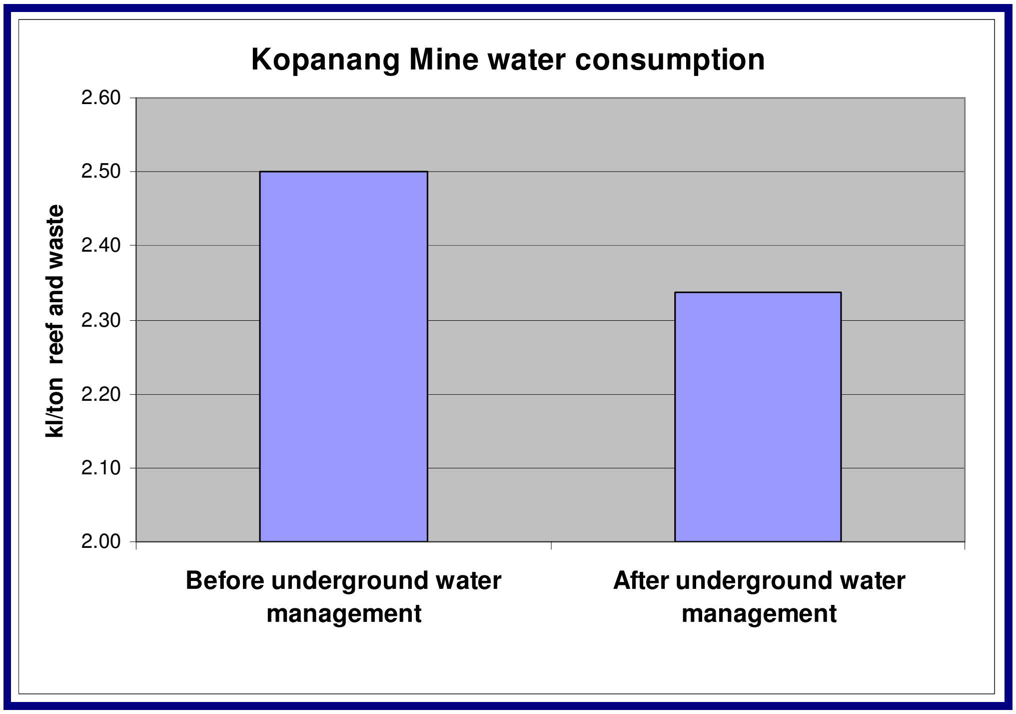

Figure 68: Kopanang Mine water consumption reduction

3.4 Expanding research to other mines

The optimisation models developed in this study can be applied to any deep level mine water reticulation system. In chapter 3 it was shown that by managing the underground level water supply, the underground water usage could be reduced to 2.2 kl/ton. Applying these principles to Elandsrand, Mponeng and South Deep mines, electrical efficiency can be introduced. From the case study done on Kopanang, it was found that by reducing the water wastages, savings could be realised on the refrigeration, as well as dewatering systems.

Table 17 shows an estimation of how much energy can be saved if water management is applied on Elandsrand, Mponeng and South Deep. An estimated annual saving of R 3.8-million and a daily electricity efficiency of 72 MWh is possible.

Table 17: Estimated annual savings for underground water usage at 2.2 kl/Ton

Mine	Daily target (ton)	Normal underground water usage (Ml)	Underground water usage (Ml) at 2.2 kl/ton	Depth (m)	Energy saving (kWh)	Annual savings
Elandsrand	4 815	20	10.5	3 000	35 879	R 2 095 363
Mponeng	15 500	38	34.1	3 600	17 850	R 827 442
South Deep	3 233	12	7.1	3 000	18 641	R 877 719
Total estimated annual savings					**72 371**	**R 3 800 525**

3.5 Conclusion

In Chapter 3 the newly developed mine dewatering efficiency model highlighted the inefficient operation of Beatrix 1 Shaft. In this chapter the energy efficiency optimisation model was applied to this mine. It was found that the pumping operation could be optimised by installing a REMS system. The REMS system was upgraded to take efficiency into consideration when controlling the dewatering pumps. Therefore an efficiency component of 600 kW was realised by applying the novel efficiency models.

A new underground level water controller was developed and implemented on the underground level valves at Kopanang mine. This controller enables the mine to reduce water wastages in periods when the minimum amount of water is consumed. By making use of these novel water reduction techniques, the water consumption on Kopanang was reduced by 1.3 Ml per day to realise a total energy efficiency of 700 kW.

By applying this concept to Elandsrand, Mponeng and South Deep mines, a daily energy efficiency of 72 MWh can be saved for weekdays. This is translated into an annual saving of R 3.5-million.

3.6 References

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CHAPTER 4: Innovative water management of a complete mine water reticulation system

Demand side management projects have been done on a number of refrigeration and dewatering systems, but have never been integrated to optimise cost savings. This chapter will discuss new techniques and simulations to integrate and optimise a complete water reticulation system.

4.1 Introduction

4.1.1 Background on complete water reticulation

One of the contributions of this study is to develop a unique model that will simulate and optimise a complete water reticulation system of a typical South African deep level mine. The various elements of the model should be integrated and the complete system optimised to generate maximum savings. Any change of parameter of a specific component in the system will be recognised and may alter the values of other components in the system.

The system described in this chapter was specifically developed for the mining environment. The input parameters used are all based on easily accessible data from the mines. One of the main aims of this study is to simplify component complexities so that they can be used and developed further by unskilled mining personnel.

The foundation of this study is based on a Real-time Energy Management System, REMS, for pumps and fridge plants. These models were integrated into one platform, but the programming is beyond this scope. This system had to be further developed and modified in order to simulate, optimise and automate a complete mine water reticulation system.

4.1.2 Simulating total water reticulation

As previously discussed, the complete water reticulation system needs to be simulated in order to evaluate the optimised total cost impact. Each component must be assessed individually and then integrated into the total system. To accomplish this, components should consist of individual models that represent their own particular characteristics, as well as the effect they have on the system.

When developing the simulation model, the static and dynamic components of the system must first be identified. Static components cannot change the state of the system whereas dynamic components can. A dynamic component has a direct effect on, and can change the state of the system when operational.

Static components

- Hot water surface dams
- Hot water underground dams
- Cold surface dams
- Cold underground dams

Dynamic components:

- Refrigeration plants
- Pumps
- Turbines
- 3-chamber pipe systems
- Valves
- Dissipaters
- Service water

Figure 69 shows these dynamic and static components. As can be seen from this figure, the mine water reticulation is divided into various sections. These sections are linked together to complete the water reticulation cycle. Each of these sections will be discussed in this chapter.

The main sections are:

- Water cooling and underground water supply
- Mining level water control
- Underground hot water management

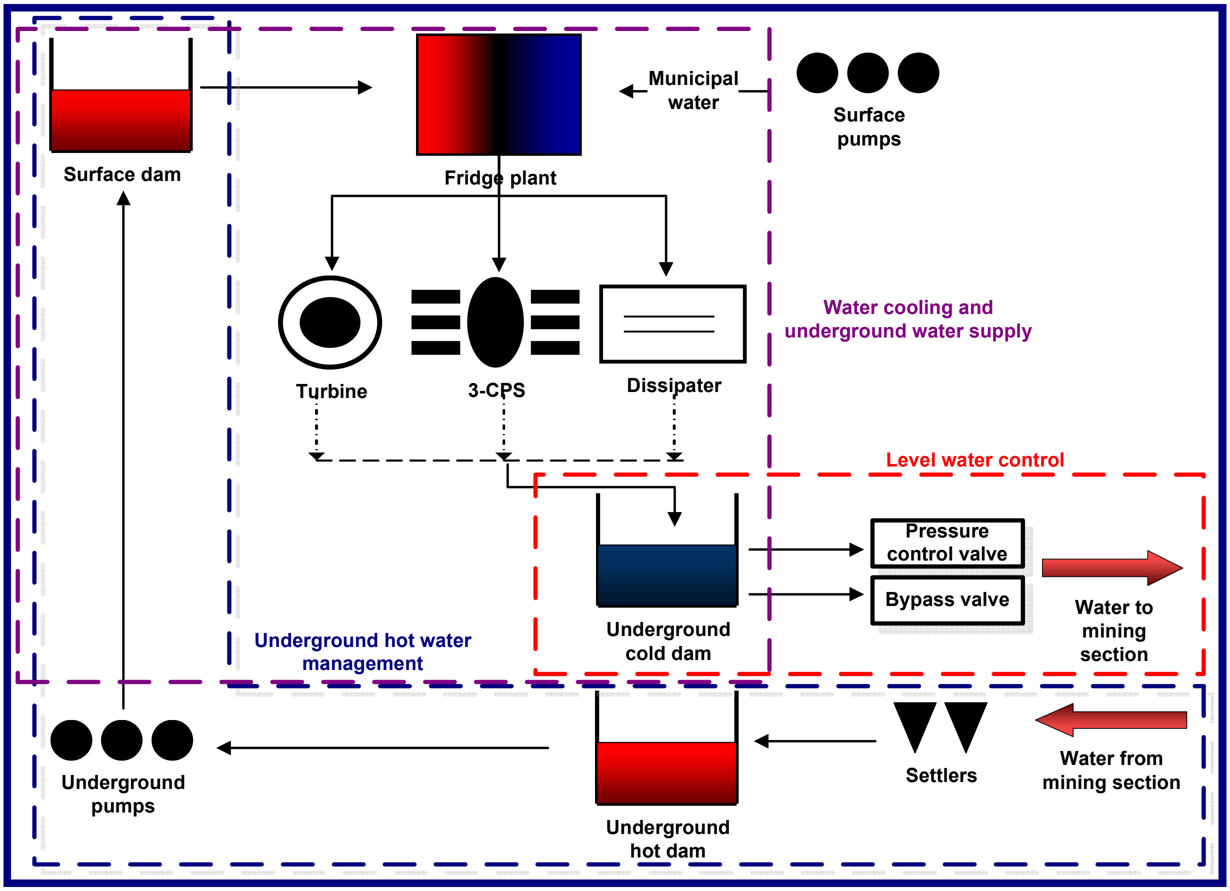

Figure 69: Water reticulation layout

4.1.3 Optimising total water reticulation

After the simulation model has been created, an optimisation scheduler can be developed. The purpose of this scheduler is to develop the most cost-effective operation of the total water reticulation system.

Many of the electric motors on the mines are operated manually. It is often difficult for the personnel involved to understand the workings of a complete water reticulation operation. A typical example is the dewatering pump station operator. This operator will only be aware of the dam level on his pump station. If the dam is nearly full, he will start extra pumps to reduce the level. He may be completely unaware of the status of the dam level into which the water is being pumped, and therefore cannot determine the optimised pumping schedule.

This single example should be sufficient to highlight the requirement for a complete management system. This system would analyse the entire system before a decision is made. The most influential inputs required for optimum decision-making are:

- Price of electricity at a specific time.
- Amount of energy consumed.
- The influence an action will have on other components of the system.

The optimisation control philosophy must first be validated before any action can be taken. Loop tests are repeatedly executed to analyse the effect of the action taken on the system. If any alterations are made, loop tests are repeated until the feasible control philosophy has proven itself. Only then can the new control philosophy be implemented on the mine system.

The optimisation process is a general and dynamic procedure. The programme is developed in such a way that it can skip or return to any of the steps in the optimisation procedure. This dynamic process adjusts to the problem and gives a more reliable and faster method to obtain the required solution.

Figure 70 shows the optimisation cycle that is used for component scheduling and control. In the first three steps the components and their operation schedules are determined individually. The integrated operation schedule, which includes all components, is determined in steps four and five.

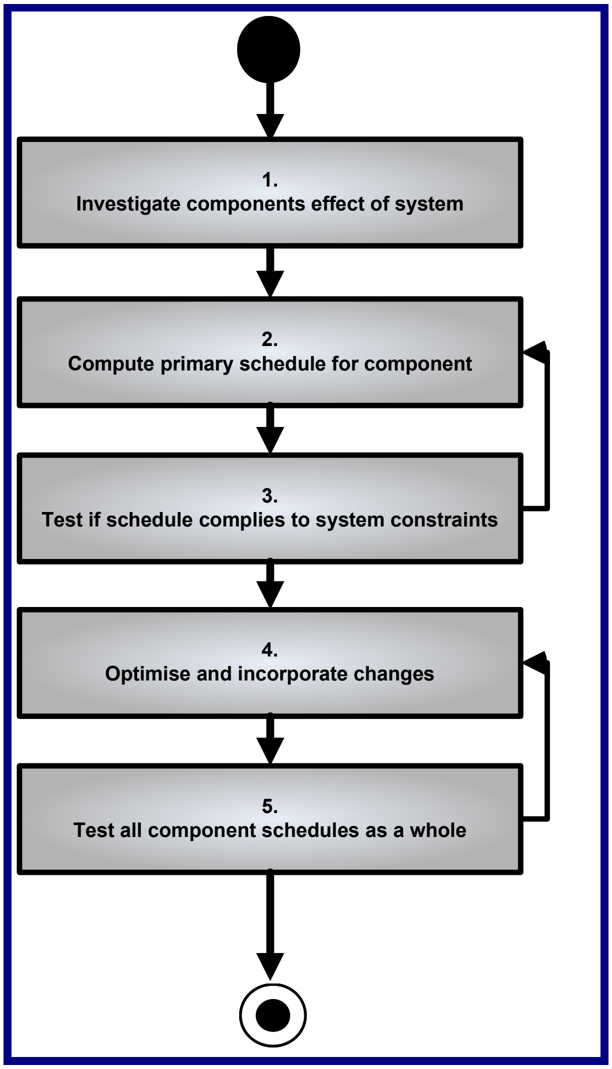

Figure 70: Optimisation cycle.

The first step of the optimisation cycle uses properties of the system simulation model. Simulations of the specific components are executed to investigate the effect that each component operation will have on the total system. This information is required before proceeding to the next step.

In the second step the information on how each component will affect the system must be known in order to compute a primary schedule for each individual component. This is accomplished during step two of the optimisation cycle and is required to obtain the optimum electricity costs for the system. Running a simulation of the system and multiplying the projected electricity consumption by the electricity pricing profile calculates the cost.

Step three in the optimisation cycle will test the schedules that have been calculated for the individual components and compare them to the system constraints. If any constraint is exceeded, the computation will return to step two, where the schedule will be changed until the constraints are within the prescribed limits.

The test procedure is conducted by running the simulation and applying the applicable component schedule. Actual initial system values are used to begin the system simulation. An immediate simulated prediction can be computed to determine the effect of the newly tested schedule on the system.

Optimisation is accomplished during step four. The optimum schedules for the individual components are then calculated and integrated into one complete system. This system will then have to be modified so that all the schedules of all the components operate as a single unit.

During step 5 the complete system is tested once more in the simulation model. All the operation constraints are tested and validated. If any constraint is exceeded, the optimisation cycle will return to step 4, where the schedules will be changed. This loop is repeated until the problem is solved.

4.2 Underground water supply components

4.2.1 Overview

The underground cold water supply is the critical link between the cooling plants and the underground cold dams. These dams are used as storage facilities and should be kept sufficiently full to provide services with water until the off-peak drilling period. Water is fed to the various mining levels from these dams.

To complete the link between the cold water cooling from the refrigeration plants and the underground cold water supply, essential components should be modelled, simulated and optimised. There are three major components that could be included in this link:

- Dissipater
- Turbine-pump configuration
- 3-CPS

The turbine-pump configuration, as well as the dissipater is one of the most commonly used underground cold water supply components in the South African mining sector. The 3-CPS has only recently been developed, and very few are operational.

4.2.2 Dissipater

Due to the vast depths of most mines, extremely high water pressures are experienced at the lower levels. These high pressures are as a result of the weight of the water in the delivery pipes. A 300 mm diameter delivery column with a vertical distance of a 1 000 m delivers an estimated pressure of 10 MPa at the bottom of the column. This pressure needs to be reduced before entering the underground storage dam. In some cases the water pressure is lowered by means of a dissipater. The dissipater converts the potential and mechanical energy into unrecoverable heat energy, which increases the temperature of the water. In some cases the dissipater is forced to operate. In these instances cogeneration components like turbines configurations or 3-CPSs are unable to operate within system constraints. However, most of these instances can be avoided by implementing the new integrated control philosophy.

4.2.3 Turbine-pump configuration simulation

Where circumstances permit, a turbine can be installed at a lower level to convert the mechanical energy into usable shaft work. In principle, a turbine configuration extracts potential energy, which can be used to do work. The shaft work is the energy that becomes available to pump part of the used water out of the mine. A common configuration is the turbine-pump, where the water supplied to the underground services is used to drive a dewatering pump.

The efficiency of a turbine-pump is typically 68%. To simplify the simulation model, no further losses are assumed. Therefore, if the supply and dewatering heads are equal, the dewatering flow rate is typically in the order of 68% of the underground water supply rate.

The turbine-pump configuration cannot be installed as a stand-alone system. This system requires the back-up of conventional electrically driven pumps. If no water is sent underground, then no water will be available to drive the turbine pump. In such a configuration electrical dewatering pumps must always be included to complement the turbine-pump system.

4.2.4 Turbine-pump system optimisation model

The simulation model of the systems creates the opportunity to develop an optimisation mechanism. This mechanism is used in the system simulation to create an optimised component scheduler.

The Figure 71 shows all the components that are affected by the turbine-pump operation.

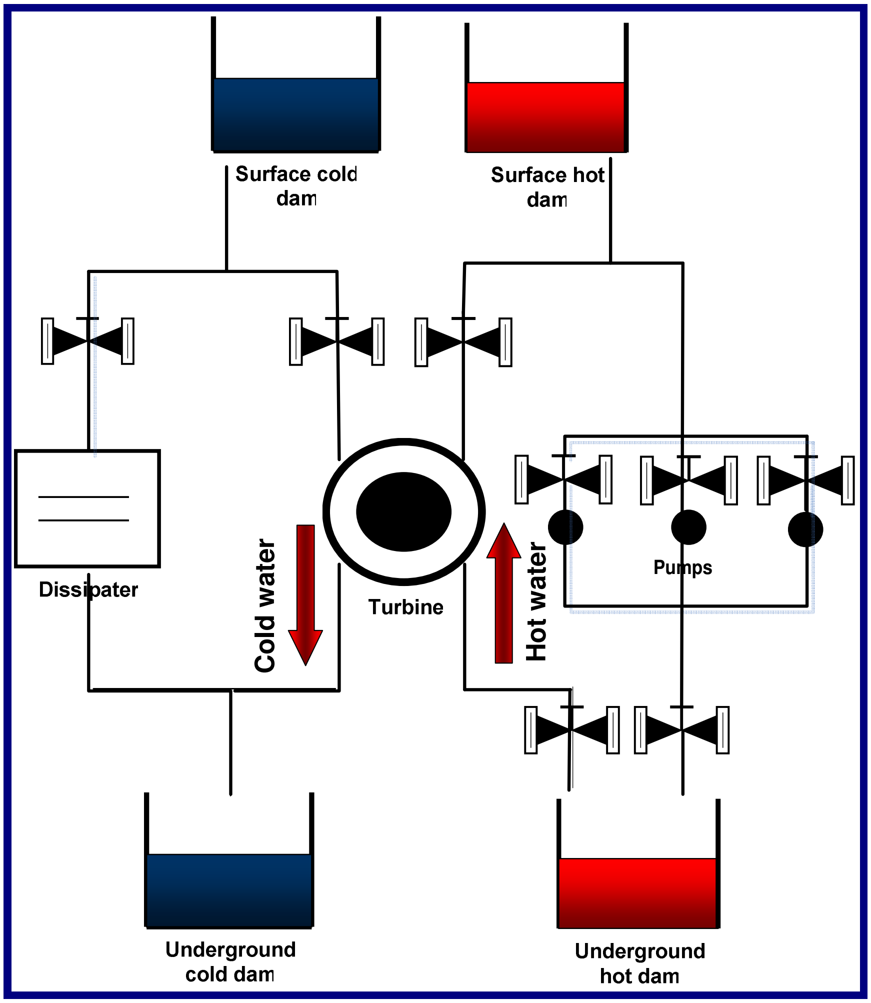

Figure 71: Turbine-pump system

Figure 71 illustrates how the turbine-pump configuration is configured together with underground dewatering pumps to form an integrated system. Static components in the turbine-pump configuration optimisation include the surface and underground hot and cold water dams. The constraints of each of these components must be satisfied.

If the turbine-pump becomes inoperative for any reason, the dissipater, in conjunction with the back-up dewatering pumps, will be able to fulfil the function of the turbine system. The underground dewatering pumps will be able to extract the hot water from the mine and the dissipater will be able to control the underground cold water supply.

The turbine-pump system has a direct effect on:

- the dewatering system
- the refrigeration plant water
- the underground water supply

Maximising the operational run time of the turbine-pump configuration is an important requirement to ensure optimum savings of this system. During turbine-pump operation, power consumption on the underground dewatering pumping system will be reduced.

To implement efficient load shifting, it is important to control the respective dam levels in such a way that they are at optimum capacity prior to the peak periods. This will ensure that the turbine-pump configuration is used to its full potential during peak times.

Inefficient operation of the turbine-pump system could result in the inefficient operation of other components. If the turbine-pump configuration does not take the statuses of the dewatering pumps, dam levels or the refrigeration plant operation into account, the water reticulation system may not operate optimally.

4.2.5 Three chamber pipe system

The 3-CPS is a critical link between the dewatering, refrigeration and underground water supply systems. To optimise mine electricity savings, the 3-CPS, if installed, must also be included in the complete water reticulation control strategy.

A number of studies on the 3-CPS did not include the fact that the maintenance cost of this system is high. Similar to the turbine-pump system, the availability of the 3-CPS is also dependent on the flow of water in the supply shaft. Neither the storage capacities of the hot and cold water dams, nor the maximum underground cold water temperature were considered in these studies. When simulating a 3-CPS, these constraints should be included to improve accuracy.

As mentioned in the previous chapters, the 3-CPS typically operates on an efficiency of 90-95%. To simplify the simulation model, internal head losses are assumed to be negligible. Therefore, if the supply and dewatering heads are equal, the dewatering flow rate is typically in the order of 90-95% of the underground water supply rate.

4.3 Water refrigeration

A very important component in modern deep level mining environment is the cooling of water. The water supply for this system is dependent on two other components, namely the dewatering system and the external water supply.

Most of the water supplied to the refrigeration plant comes from the recycled underground mining services, as well as the underground fissure water. This water is chemically treated and filtered in underground settlers, before it is pumped to surface. Recycled underground mine water is sometimes insufficient to ensure efficient operation of a closed loop reticulation system. Additional water must then be obtained from outside suppliers such as local municipalities, other mines in the region or government water schemes. This water generally comes at a high cost and the water losses in the system should be kept to a minimum wherever possible.

The turbine-pump, dewatering pumps and 3-CPS supply the refrigeration plants with water. These components should be integrated and optimised so that the maximum load shift can be obtained during the Eskom evening and morning peak periods. The surface hot water dam normally flows directly into the pre-cooling tower and stores water in the pre-cooling dam before entering the refrigeration plant. This configuration is shown in Figure 72.

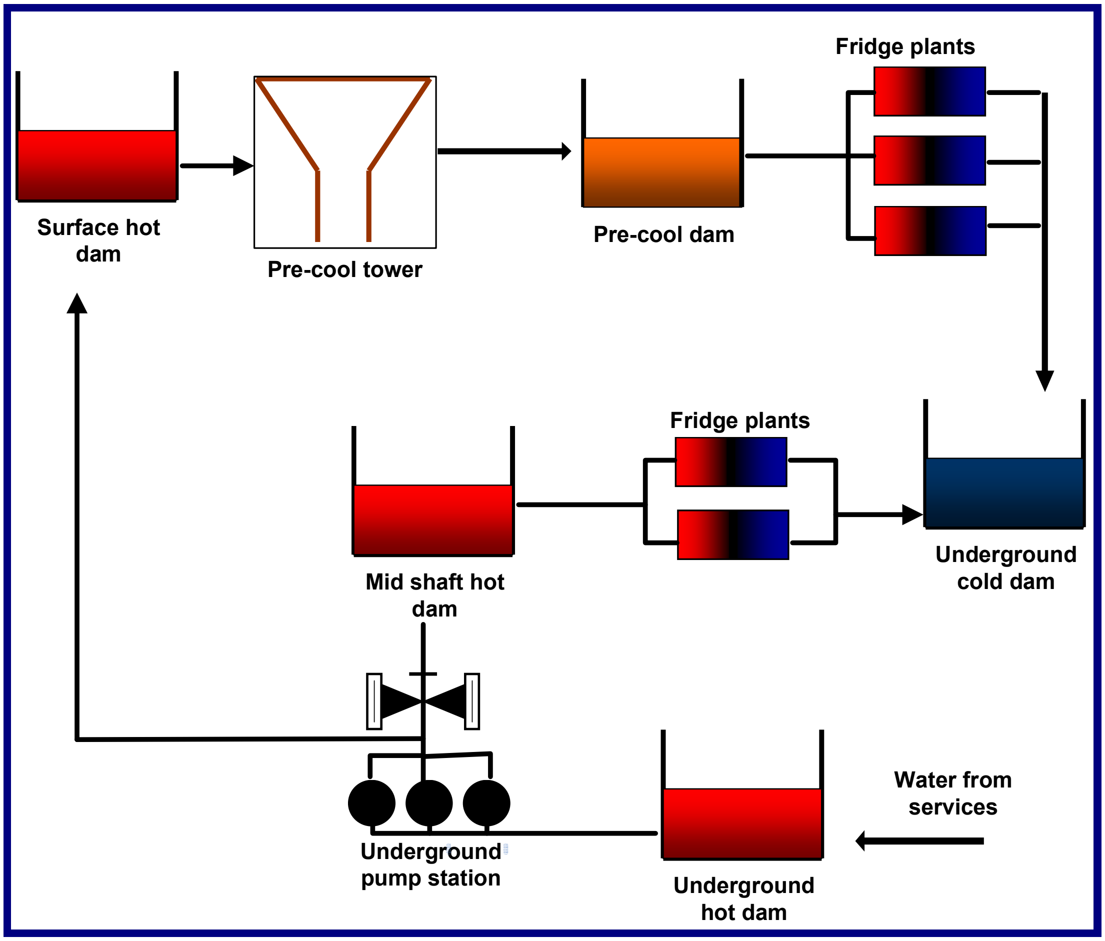

Figure 72: Dewatering supply to refrigeration plant

By optimising the water flow to the refrigeration plant, further electrical savings can be generated. The greater the flow of water through the refrigeration plants, the higher the energy load required to cool this high water volume. The theoretical power required for cooling is given by equation 4.1 [65]:

$$q = c_p \Delta T\, m / t \qquad (4\text{-}1)$$

where:

q = heat transfer rate (kW)

c_p = specific heat capacity for water 4.19 kJ/kg.K

ΔT = change in temperature of the fluid (ºC)

m / t = mass flow rate (kg/s)

This effect was also simulated in Figure 73. In this figure it can be seen that the water flow through the refrigeration plant follows the same trend as the corresponding refrigeration plant power consumption.

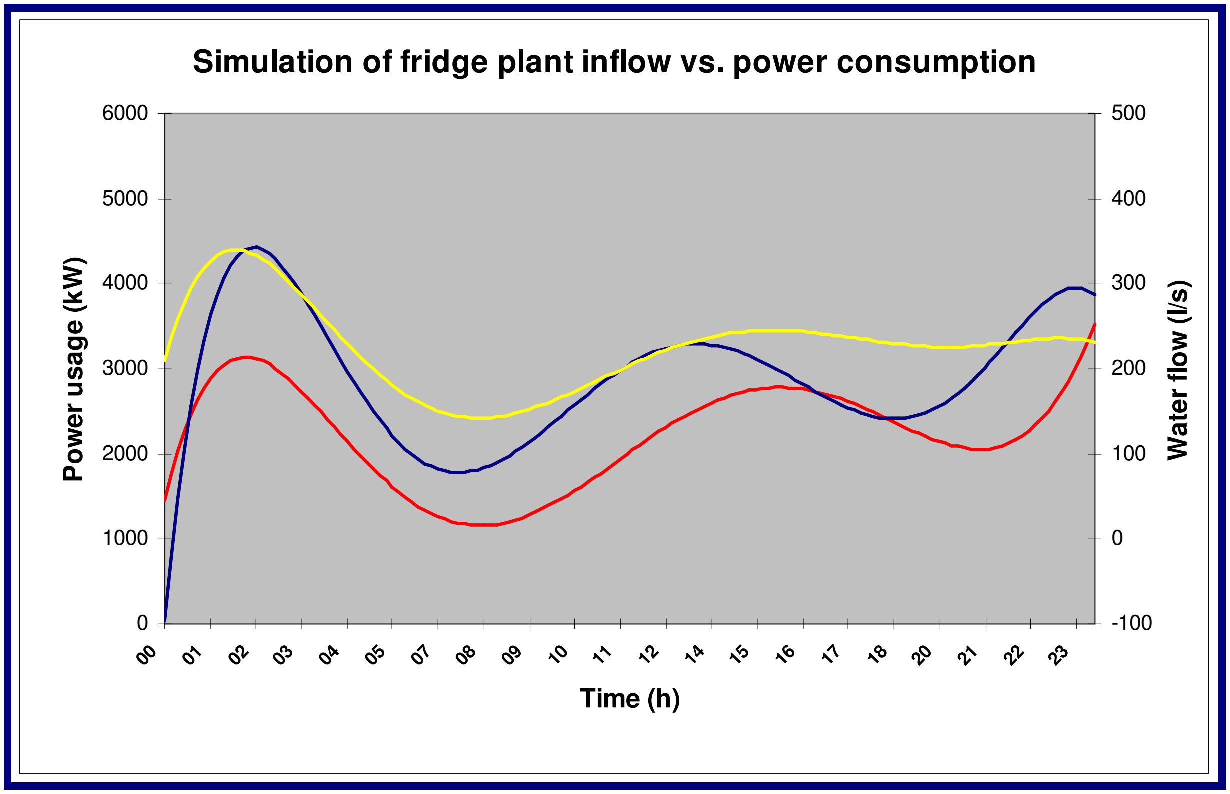

Figure 73: Simulation of refrigeration plant water inflow against the power consumption

By increasing the flow through the refrigeration plants during off-peak and standard periods and reducing the flow rate during peak periods, the mine will realise significant savings.

Before the underground cooling water is distributed to the mining levels, it is first stored in the underground cold dams. By scheduling the turbines, 3-CPS or dissipaters, this underground dam could be set at a specific level at a specific time. In some cases the demand from the cold dam is much higher than the supply. This usually occurs during drilling and sweeping shifts, which consume large amounts of cold water. It is therefore critical that the underground water supply system and refrigeration plant be integrated with the underground level water supply valves. This will ensure that the water demand on the different levels can be efficiently controlled by filling underground cold dams before these high demand periods.

The refrigeration system is also dependent on the atmospheric conditions. A daily ambient temperature drop from 26°C to 16°C, is shown in Figure 74. This has a significant effect on the power demand of the refrigeration plant. This temperature decrease will result in a lower inlet water temperature to the refrigeration plant, which means less energy is required to cool underground air and water.

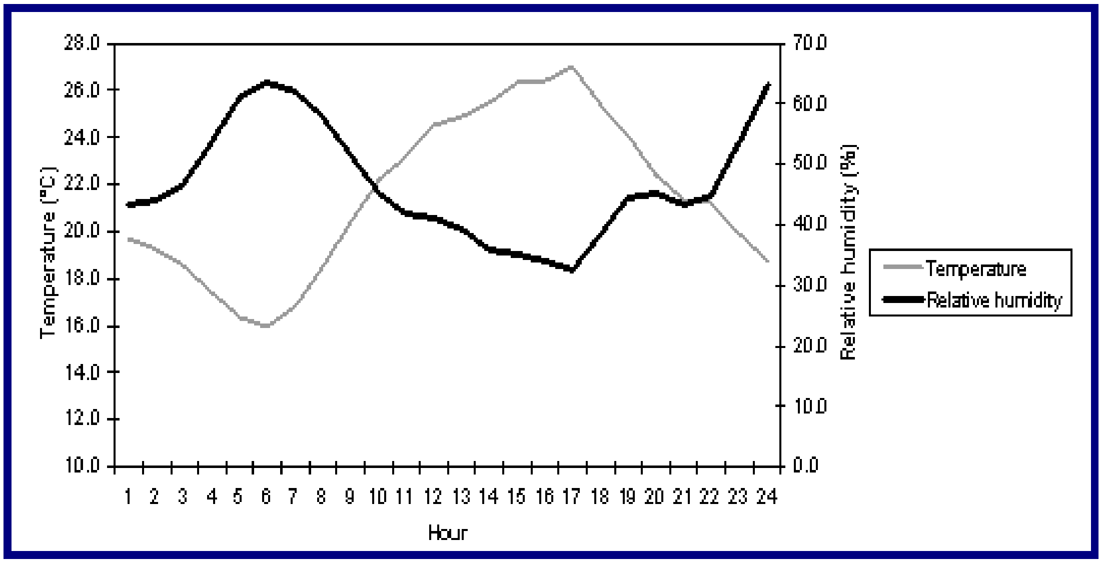

Figure 74: Relation of the outdoor air temperature to the relative humidity [23]

During these periods more water can be cooled and sent underground. The period between 01:00 and 06:00 can be utilised to cool as much water as possible for underground services. By optimising the in- and outflows of the refrigeration plants, most of the cooling can be done during off-peak periods when electricity costs are low.

On the other hand, if the refrigeration plant can be taken off-load during peak periods, the minimum amount of water needs to be pumped to surface to feed the fridge plants. By reducing this flow, the dewatering pumps do not have to operate during peak periods, and significant energy savings will also be realised.

In Figure 72 the remote, or underground, refrigeration plant can also be seen. The underground dewatering pumps can either pump water to the surface or to the mid-shaft hot dam. The mid-shaft hot dam feeds the remote underground refrigeration plants. In modern deep level mines, underground refrigeration plants are installed to minimise the increase of water temperature. These refrigeration plants are located much closer to the underground cold dam than the surface cold water dams. Therefore the heat generated by the friction in the columns and the pressure-reducing stations will be minimised. Due to the requirements of the surface BACs, the surface refrigeration plants cannot be taken off-line permanently. The BACs must be supplied with cold water throughout the day to cool the underground ventilation air.

By increasing the load on the underground refrigeration plant and decreasing the load on the surface refrigeration plants, further energy savings will be realised by the dewatering system. This is because of the reduced vertical pumping distance.

4.4 Water reticulation system volume

A very important component to consider when optimising a complete water reticulation system, is the total amount of water in the system. By controlling the system according to the optimum system volume, there will be enough water in the system to prepare the dam levels so that maximum load can be shifted during the peak periods.

Figure 75 shows a simulation of system volume vs. cost savings per day done by means of REMS. This simulation was developed to determine the optimum amount of water needed in the system to realise maximum savings for the mine. System constraints, such as the maximum and minimum dam levels, minimum underground water temperatures, etc. were used as input parameters.

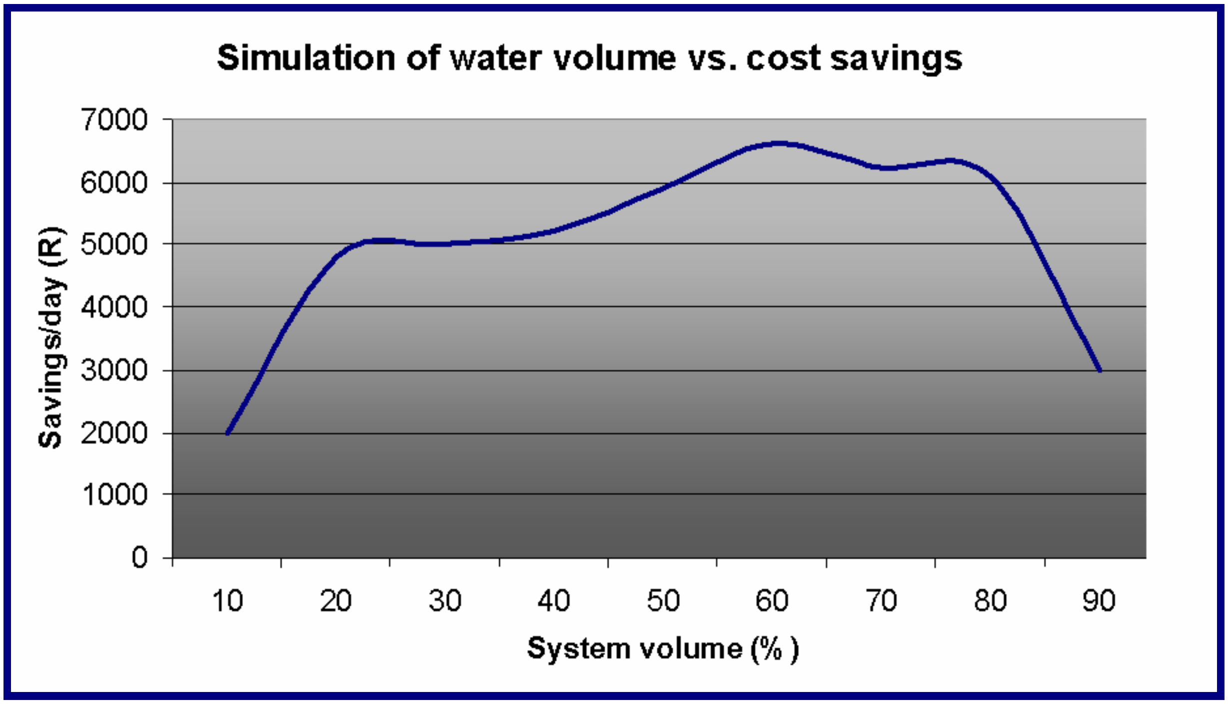

Figure 75: Simulation of system water volume vs. savings/day

If the water volume decreases below the optimum level, water must be added to the system. This water must be purchased from an external water supplier. The costs vary from one supplier to another. On average the price is R 4.60 per kilolitre of water. Water could also be pumped out of the system when the volume gets too high. Great care should be taken when replenishing or reducing the system water level, as this could have a negative impact on the environment.

Simulations were conducted to determine the ideal time to add and utilise the additional water. The results indicated that the Eskom evening peak period was the best suited period. During this time, as shown in Figure 76, most of the water returning from the mining levels is stored in the underground dams. Because the water levels of the underground dams are measured, the total system volume can be estimated. In addition, the extra incoming water can also be used to supply the refrigeration plant with water during the evening demand periods.

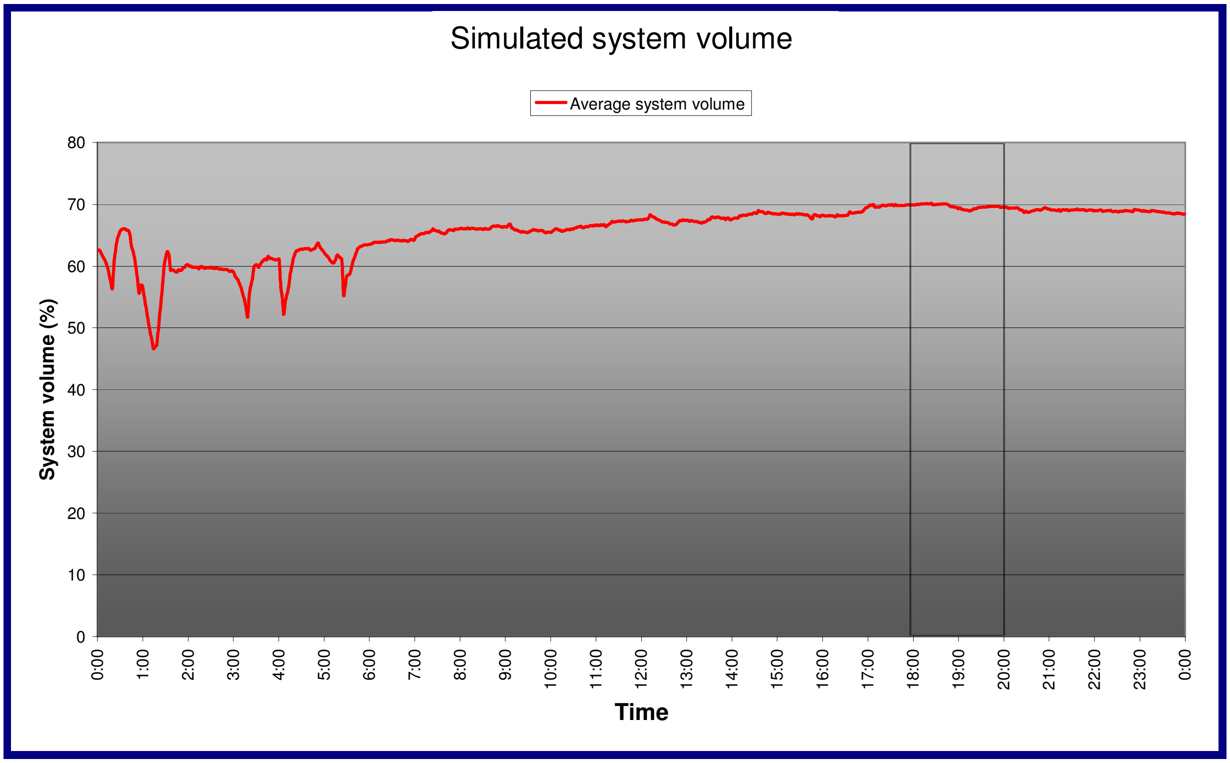

Figure 76: Simulated system volume

4.5 Conclusion

In this chapter the importance of integrating all components of the water reticulation system was highlighted. The importance of including components such as turbines, dissipaters and three pipe feeder systems in the total water reticulation strategy was also discussed. Newly developed simulations and optimised strategies, which can be integrated to form a complete water reticulation system, were developed. These new strategies will realise extra savings for the mines.

A new simulation that can calculate the optimum water volume in the system was also developed. By controlling the system according to the optimum system volume, maximum cost savings will be realised.

4.6 References

[65] "Calculating the amount of steam in non-flow batch and continuous flow heating processes", The Engineering ToolBox, Available: www.engineeringtoolbox.com, September 2008.

CHAPTER 5: Verification of the mine water reticulation management system (Case studies)

To evaluate the effect of an integrated control strategy on a complete water reticulation system, the strategy in Chapter 4 was implemented on two mines. At Kopanang the dewatering, turbine-pumps and refrigeration systems were integrated, and at Tshepong Mine the 3-CPS, dewatering and refrigeration systems were integrated.

5.1 Introduction

The new integrated water reticulation strategy was implemented on the water systems of Kopanang and Tshepong gold mines. The purpose of this strategy was to optimise cost savings by either load reduction or energy efficiency. Before the optimised schedule can be implemented, it must be tested, using the newly developed integrated simulation model. The simulations will verify whether any equipment, process, maintenance or safety constraints will be violated.

The result of the optimised energy management will assist Eskom with their existing electricity supply problems. Further benefits of these newly developed simulations and techniques include electricity cost savings for the client. To accurately determine the effects of these unique projects on the national electricity grid, new measurement and verification (M&V) methods must be established and clarified.

5.2 Turbine-pump system integration

5.2.1 Need for turbine-pump integration

Traditionally, DSM projects only focused on specific components such as refrigeration plants and dewater pumping systems. The problem with this was that the systems were treated as independent and stand-alone systems. The previous chapter made it clear that, to achieve optimum savings, the total water reticulation system should be integrated as a single system.

5.2.2 Water reticulation layout

At Kopanang water is cooled down at the refrigeration plants before being sent underground for mining and cooling purposes. After the water has been used, it is fed into the underground settlers. From these settlers the water is pumped by the clear water pumping system back to surface. This water cycle is repeated throughout the day.

Kopanang mine pumps water from 75 Level to the hot water dam on 38 Level. From 38 Level the water is pumped to the surface surge dam. 75 Level pump station is equipped with four clear water pumps and the 38 Level pump station with three pumps and two turbine-pump configurations.

The mine water enters the surge dam from the underground operations at an average temperature of 27℃. This water is pumped through the two pre-cooling towers. The pre-cool towers cool the water down to an average temperature of 15℃, after which it flows into the hot confluence dam. Here it mixes with the water that returns from the bulk air coolers. This water is then pumped to the refrigeration plant via the evaporator pumps for further cooling.

The plant consists of six identical refrigeration machines, giving a combined cooling capacity of 33 MW. The coefficient of performance (COP) of the machines is 4.

The evaporator pumps pump the hot water through the evaporator to the cold confluence dam. This water leaves the evaporator at a temperature of 3.5℃. Each refrigeration machine has its own condenser-cooling tower to provide the necessary heat transfer.

As seen in Figure 77, the water from the cold confluence dam flows to the underground turbine at a flow rate of 230 l/s and to the bulk air cooler at 250 l/s per cell. The bulk air cooler (BAC) consists of three cells in parallel, each with its own water pump. The BAC is used to cool the ventilation air entering the mineshaft. The exit temperature of the BAC water is ± 8℃.

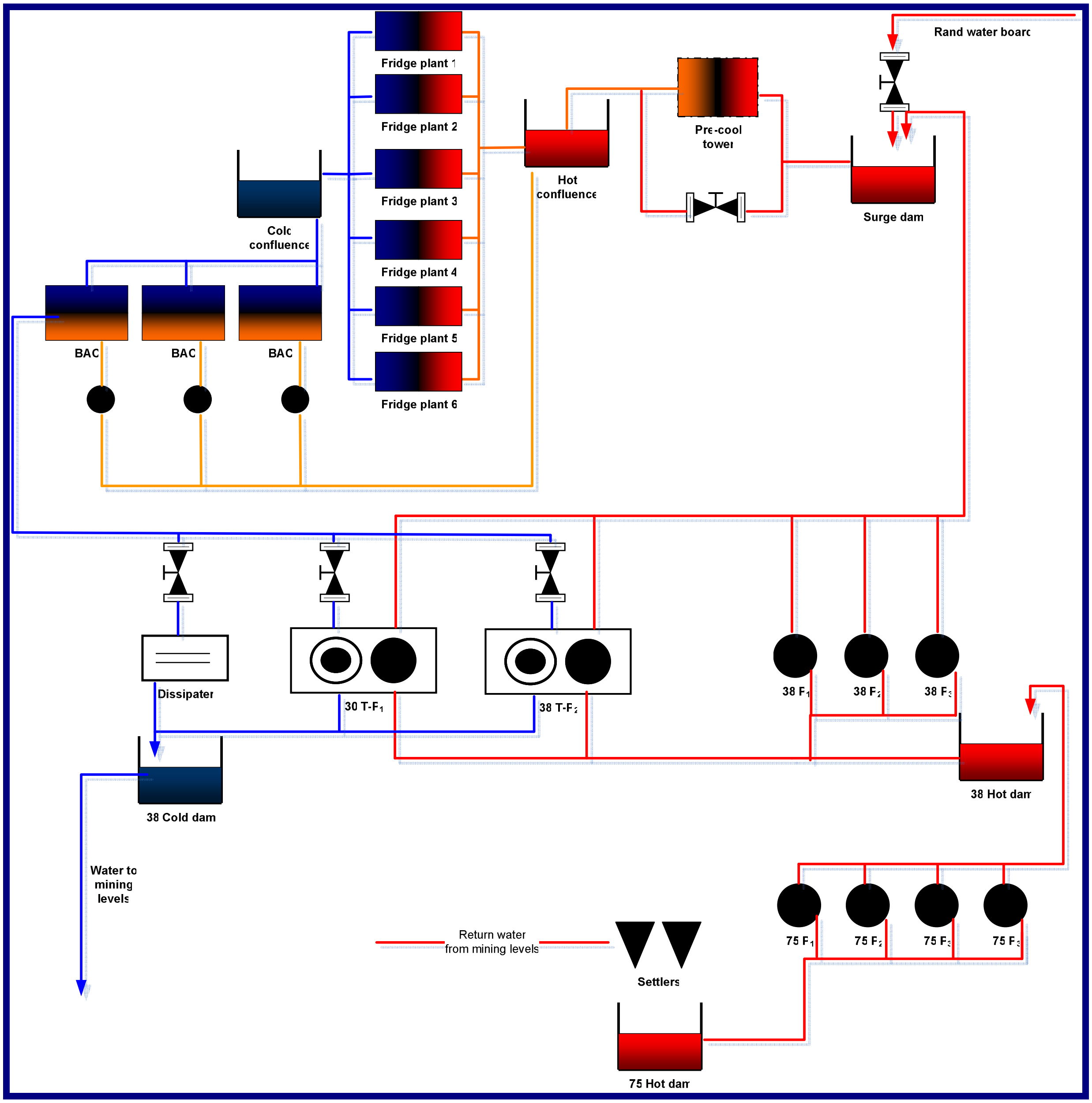

Figure 77: Kopanang total water reticulation layout

Table 18 gives the names and quantities of the electrical water reticulation equipment. The installed capacity of the pumps and refrigeration system is more than 47 MW. This excludes the electrical auxiliaries. They will be excluded in the calculations, due to their relatively small installed capacities.

Table 18: Kopanang water reticulation electrical capacities

Components	Qty	Capacity (kW)	Capacity (kW)
Refrigeration machines	6	5 500	33 000
38 L Pump	3	2 000	6 000
75 L Pump	4	2 000	8 000
Turbine-pump	2	2 000	4 000
			51 000

The water reticulation system at Kopanang is semi-automatically controlled. The refrigeration plant and underground pumps are automatically controlled by the REMS Pump and REMS Fridge plant systems. The two systems were implemented by HVAC International and funded by Eskom DSM. These systems make use of complex computations, inputs from the SCADA system and patented controllers to optimally control and manage the two systems. Load is shifted or reduced during evening and morning peak periods, resulting in electricity cost savings for the mine.

The turbine-pump and underground water level valves are controlled manually via the Kopanang control room. The operator monitors both the 38 cold dam level and the 38 hot dam level to determine the turbine-pumps operational schedule. This link between the underground cold water dam and the refrigeration plant is crucial for the refrigeration plant to shift load. If the turbines are not optimally controlled, the automatic control of the refrigeration plants will be adversely influenced.

The same applies for the underground dewatering system. Before this research the refrigeration plants and underground pumping system were not integrated. The REMS pumping systems only controlled the four pumps on 75 Level and the three pumps on 38 Level. The consequence of not integrating these two systems reduces the daily load shift, and therefore the fully optimised savings will not be attainable.

The following components of the water reticulation system should be integrated to optimise the system control:

- refrigeration system
- underground water supply and turbines

- underground pumping system
- underground mining level water supply

The two turbine-pumps of Kopanang Mine are the most significant energy-saving components in the mine water reticulation system. These components, together with the dewatering pumps, supply the refrigeration plants with underground hot water. They also supply the underground cold water dams with water from the refrigeration plants. It is therefore important to include these two components in the automated water reticulation strategy. They will be controlled correctly to ensure optimal functioning.

Figure 78 represents the integrated flow analysis of the turbine-pump, refrigeration and dewatering systems. From this figure it can be seen how the three systems are linked to complete the water reticulation cycle.

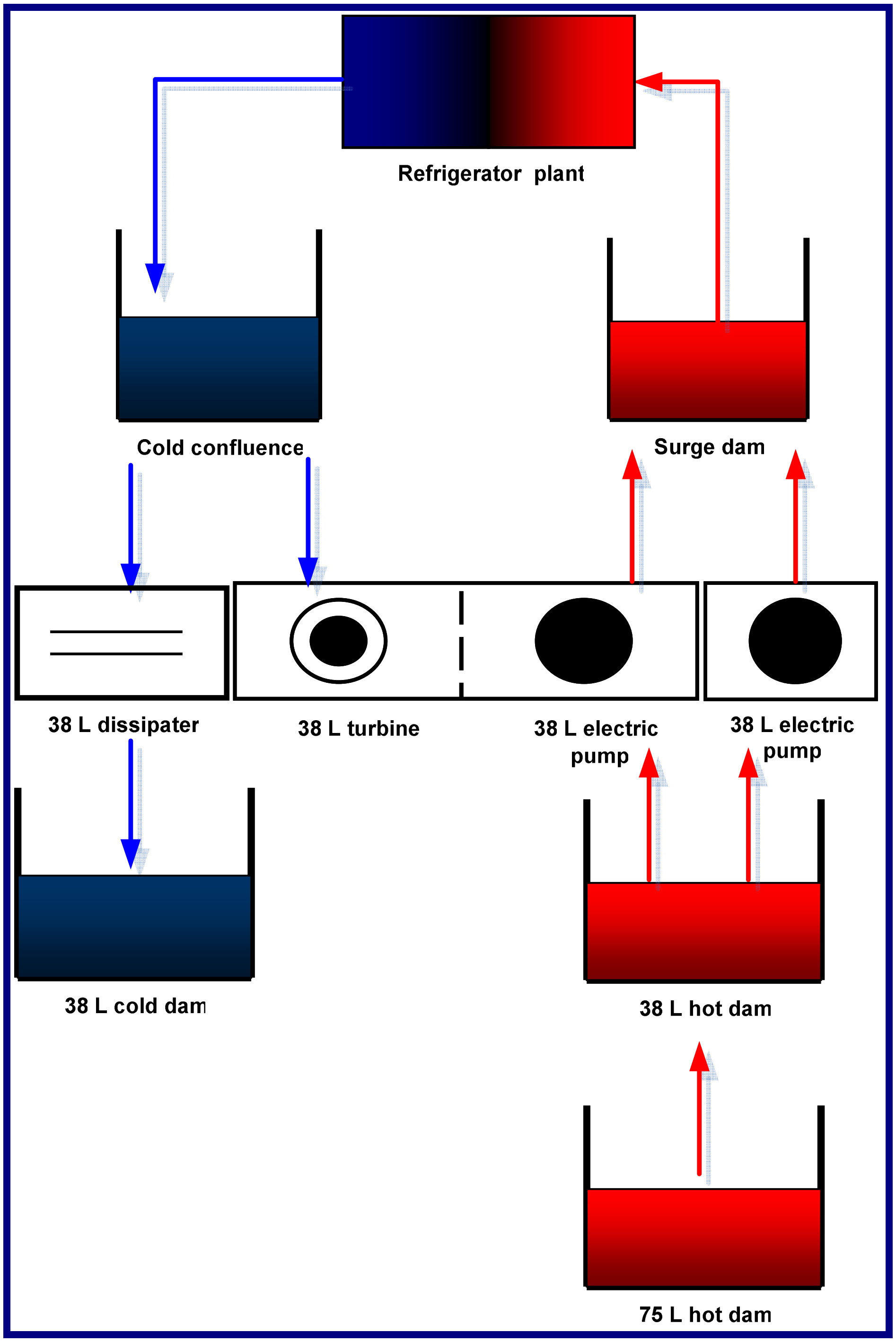

Figure 78: Kopanang turbine-pump, refrigeration and dewatering integration

To integrate the turbine-pump configurations into the complete water reticulation system, the turbine-pumps must first be integrated with the dewatering system. After this is done and a simulation proved that the system would operate within the set constraints, the dewatering and turbine-pump system can be integrated with the refrigeration system.

5.2.3 Underground water supply – dewatering integration

The two turbine-pumps link the dewatering and refrigeration systems. Whenever cold water flows through the turbines, hot underground water will automatically be pumped either to a higher mining level or surface. If the turbine goes off-line, water from the surface will pass through the dissipater to be stored in the underground cold water dam.

Kopanang dewatering constraints are given in Table 19 and Table 20.

Table 19: Dam level constraints

System constraints	Minimum level	Maximum level
Surface cold dam	50%	95%
Surge dam	42%	80%
38 L hot dam	30%	80%
75 L hot dam	30%	80%
38 L cold dam	55%	95%

Table 20: Maximum number of running equipment

System constraints	Maximum number of running equipment
38 L pumps	3
38 L turbines	2
75 L pumps	3

Before the integration of the dewatering pumps and underground water supply, the 75 L dams were forced to pump during Eskom peak times. The reason for this was that the turbine-pump operated during these times, extracting water from the 38L hot dam. In some cases the dam level was reduced to the minimum level. This forced the 75 L pumps to supply 38 L hot dam with water. If the systems were integrated, these missed savings would be eliminated.

The simulation proved that by integrating the turbine-pump and the water reticulation system, the turbine-pumps could now be stopped during peak periods. If for some reason the turbine-pump is required to operate, the water level of the 38 L hot dam should be maintained at a much higher level. In this case enough hot water capacity will be available to the turbine-pumps without having to force the 75 L pumps to supply water.

5.2.4 Underground water supply – refrigeration integration

The cold water delivered underground is controlled by the underground turbine-pump configuration. This configuration is the link between the refrigeration system and the underground cold dams.

Figure 79 is a simulation that shows the effect of the turbines on the refrigeration system. In this figure the effect of increasing the water through the refrigeration system is shown. In this case two turbine-pumps were started just after 13:00. By running two turbines, the outflow from the surface cold water dam will increase to 450 l/s. The refrigeration plant will be forced to cool more water to keep the surface cold dam level above minimum.

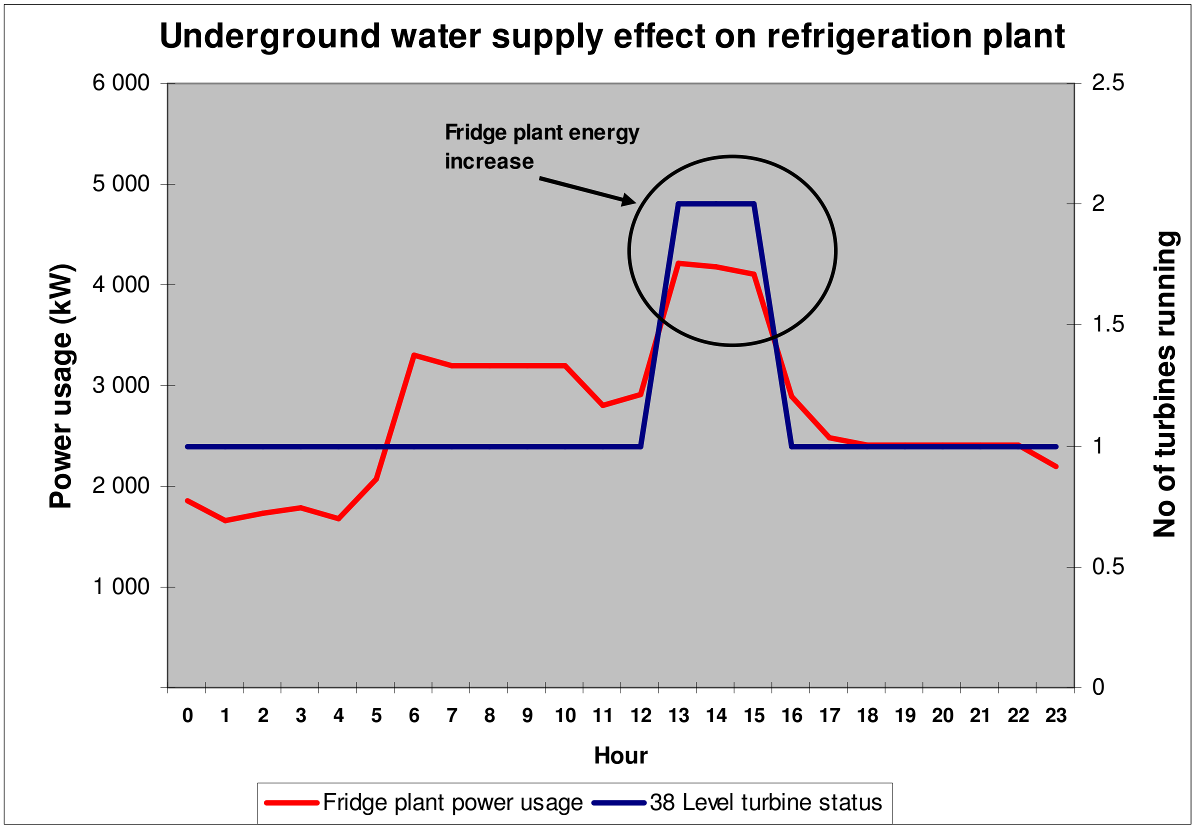

Figure 79: Underground water supply effect on refrigeration plant

After simulations were done, it was noted that the best time for the two turbine-pump configurations to run was between 01:00 and 06:00. During these times the daily ambient temperature is at a minimum. As a result the temperature of the water entering the refrigeration system will also be lower, resulting in less cooling needed.

5.2.5 Novel integrated simulation results

Before implementing a control strategy, a simulation model must be developed and executed. The simulation results will indicate if the new strategy is practical. These results will also give an indication if the new control will enable the components to operate within the system constraints. Damage to equipment and even fatalities can occur if the component constraints are exceeded. Great care should therefore be taken when running these simulations.

Figure 80 shows the simulation flow trends. From this graph it can be seen that the flow to the underground cold water dam at 38 L is increased during the early hours of the morning. By controlling the turbines in this way, the load on the refrigeration plants is increased when the ambient temperature is at its lowest. This strategy forces the refrigeration plants to cool as much water as possible before the start of the drilling shift.

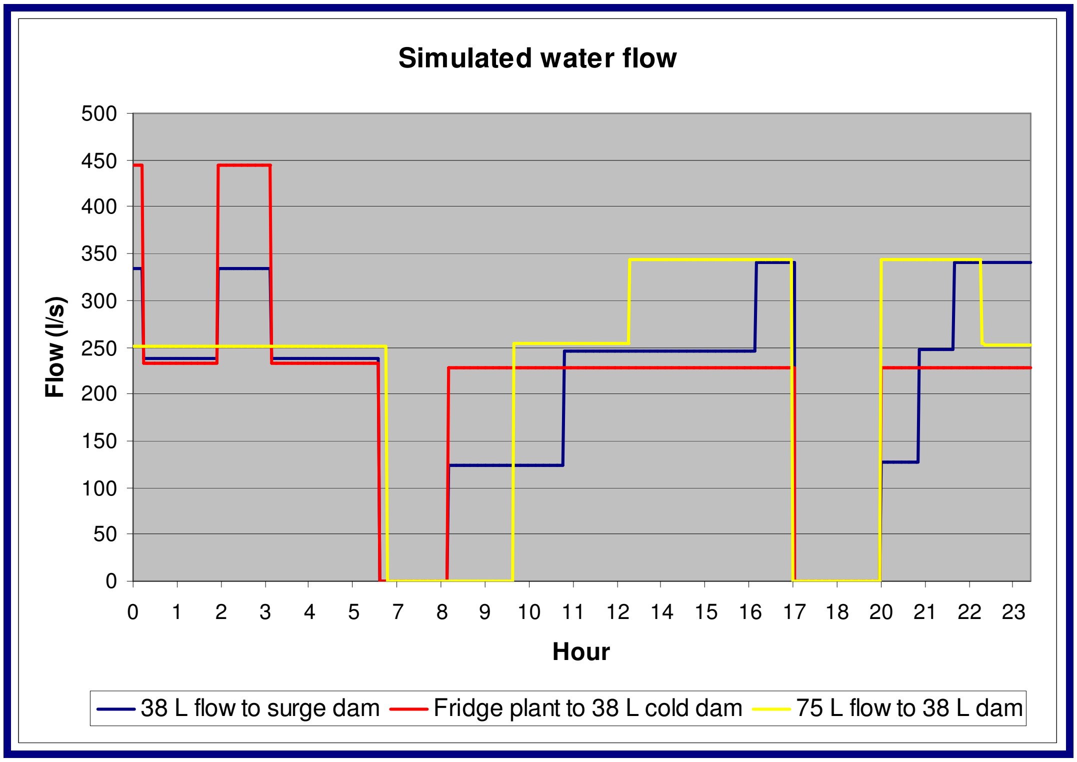

Figure 80: Simulated flow trends of Kopanang Mine

Figure 81 shows the simulated underground dam levels and refrigeration water outlet temperature. 38 Level cold dam is filled to its maximum capacity before the start of the drilling period. During this time the exit temperature of the refrigeration plant increases a fraction. However, during the morning peak period (07:00 - 08:00) when water flow through the refrigeration is a minimum, the water temperature will decrease below the required set point. This will compensate for the high water temperatures before peak time.

From this figure it can also be seen that the high morning underground water demand was also included in the simulation. By controlling the dam Level as full as possible before the start of the drilling shift, the energy load on the refrigeration plant can be reduced throughout the rest of the day.

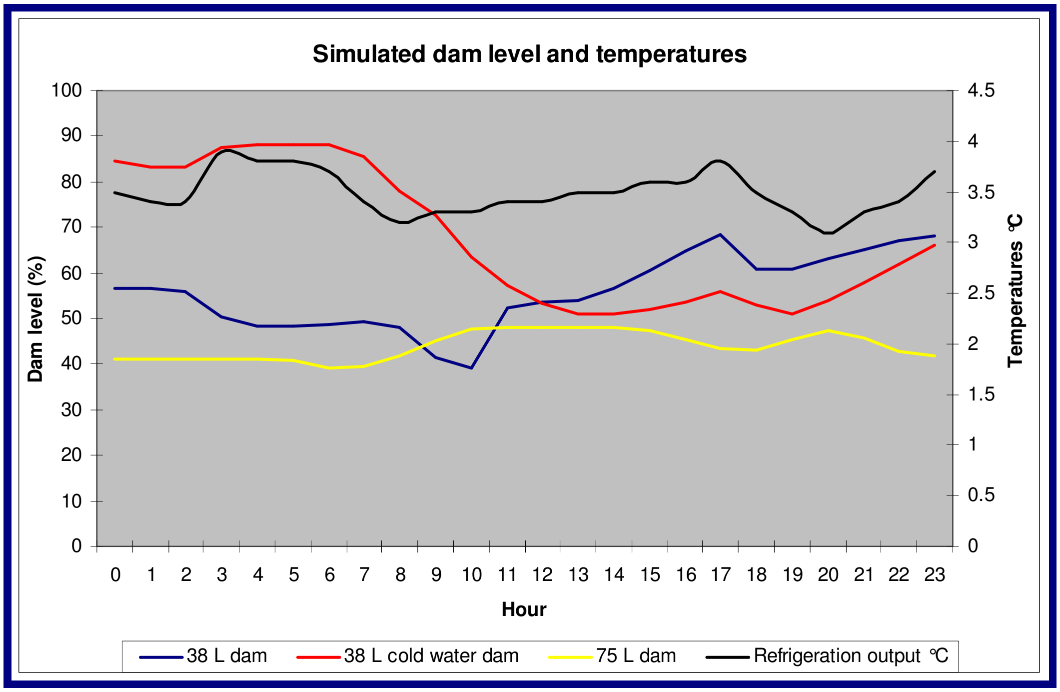

Figure 81: Simulated dam levels

Figure 82 shows the results of the simulated power consumption of both the refrigeration plant and underground pumping system. From this it is clear that the all the dewatering pumps can be stopped during the morning as well as the evening peak period. This energy saving procedure was not possible with the conventional dewatering pumping system.

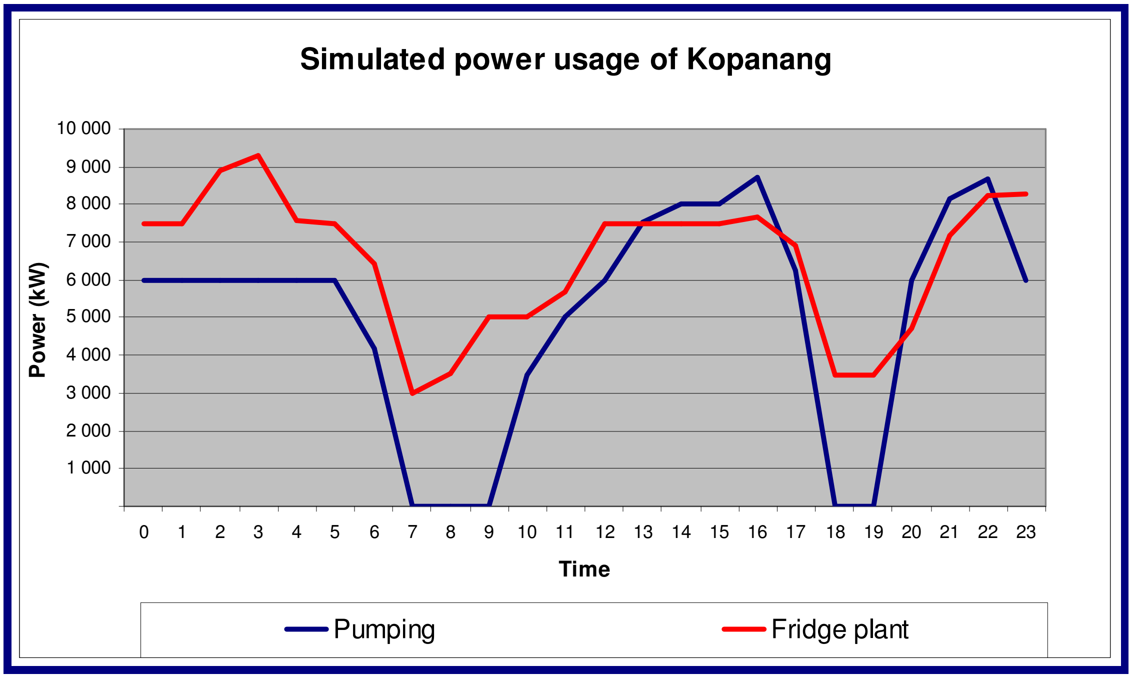

Figure 82: Simulated power profiles

The simulations confirmed that none of the system constraints were violated and indicated that the newly developed control strategy will optimise control and savings. It is therefore evident that the complete water reticulation strategy can be implemented at Kopanang Mine.

5.2.6 **Results**

5.2.6.1 Overview

The complete water reticulation strategy was implemented for 5 days. The control strategy had to be suspended due to scheduled maintenance on the turbine-pump. As soon as the maintenance is completed, the control strategy will be re-activated. This means that no efficiency component will be measured.

5.2.6.2 Dewatering results

To determine the load shift cost savings for the DSM project, the normalisation method was used [66]. In this method, the total energy consumption per day was used to scale the baseline, so that the profiles are energy neutral.

Figure 83 shows the average optimised power consumption profiles of the dewatering system at Kopanang mine. The yellow graph is the baseline of the profile before DSM. The blue graph shows the change in the profile after the automated DSM project was implemented. The red graph shows the result after implementation of the total water reticulation integration strategy.

This figure shows that by optimising the complete water reticulation system, more morning and evening load can be shifted.

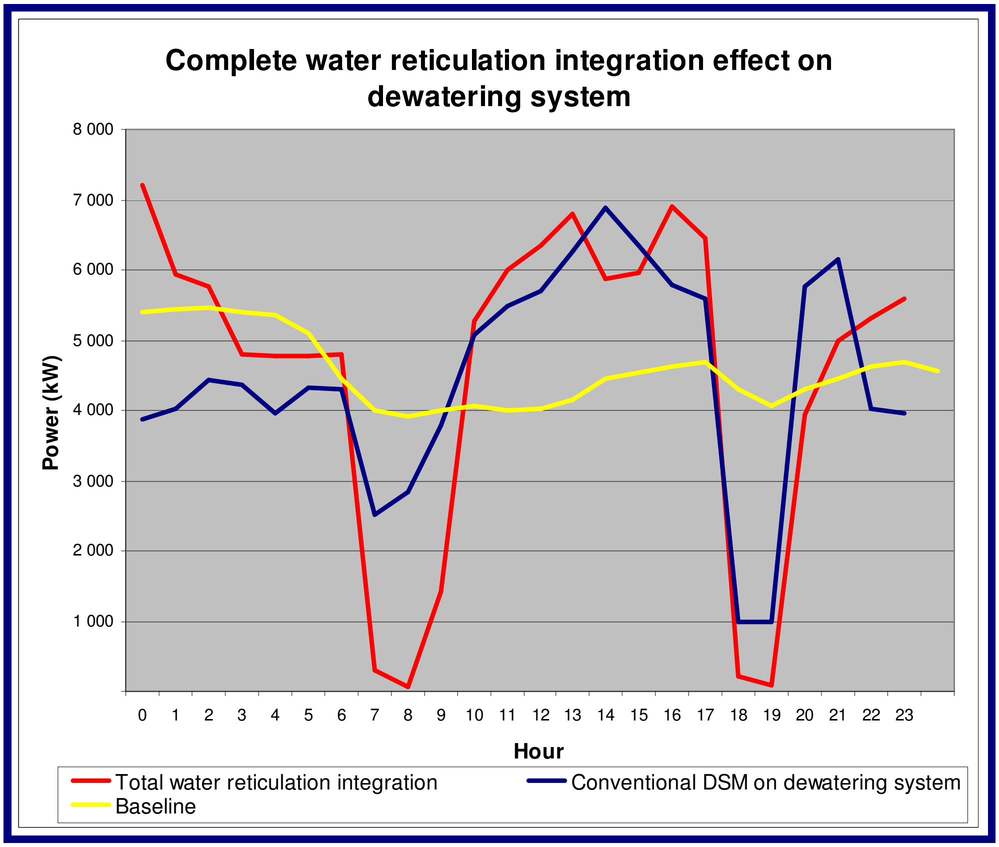

Figure 83: Optimised electricity profile of the dewatering system

Table 21 shows the results of the conventional DSM control against the total system optimisation. From this table it can be seen that by optimising the complete water reticulation system, extra savings can be generated in addition to the conventional DSM-project.

Table 21: Kopanang dewatering system results

Kopanang dewatering results		
	Conventional DSM	Total system integration
Morning load shift (kW)	918	3 373
Evening load shift (kW)	3 187	4 030
Annual savings	R 408 673	R 1 000 055
Average electricity cost (c/kWh)	13.5	12

5.2.6.3 Refrigeration load reduction results

Unlike the pumping system, the refrigeration plant is a load reduction project. Load reduction takes the improvement of energy efficiency and COP of the refrigeration plants into account. The refrigeration plant efficiency is expected to improve if regular maintenance is done. Efficiency will also be improved if the plants are automated and calibrated.

A method was developed to measure the performance of the total system after integration of the refrigeration plants. This method makes use of equation 5-1 that represents the pre-implementation conditions of the refrigeration system. By comparing the ratio between the thermal and electrical energy consumption, an average fitting through these data points can be calculated. Figure 84 represents the amount of energy required to cool the water during the pre-implementation period [67].

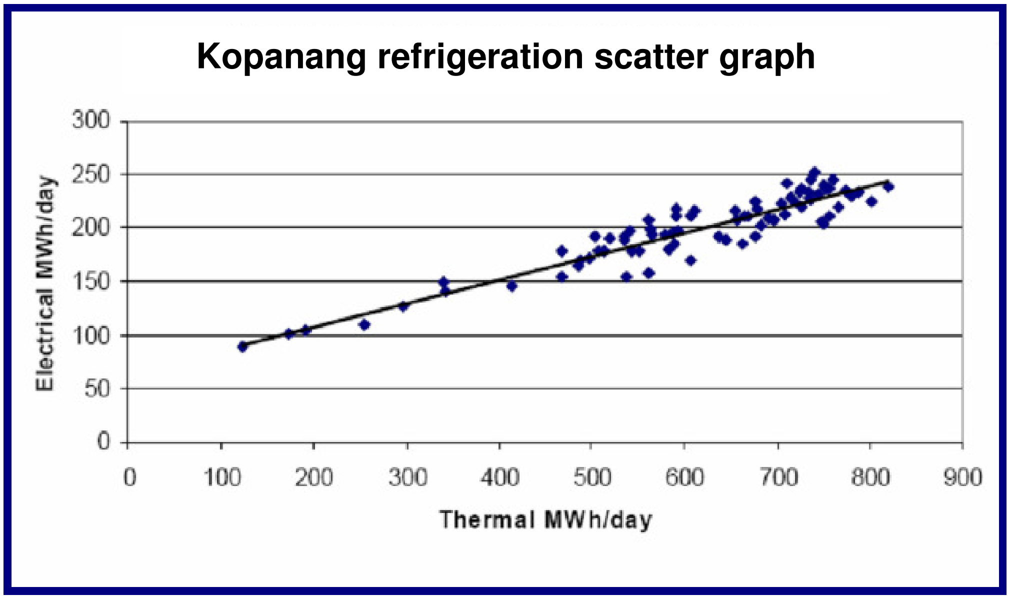

Figure 84: Kopanang thermal and electrical power scatter graph

In this case R^2, the coefficient of determination, is 0.876. It can therefore be assumed that equation 5.1, which represents the fitting, is accurate.

$$y = 0.2184x + 64.657 \qquad (5\text{-}1)$$

Where:

y = electrical energy (MWh/day) usage

x = thermal energy (MWh/day) usage

To scale the baseline, equation 5-1 is used to convert the daily thermal energy usage reading to electrical energy usage. This equation was derived by the least square fitting of the data points in Figure 84. This reading represents the profile before any modifications were made to the system. The thermal data points between 100 kWh and 400 kWh are typical weekdays when the water usage and cooling are reduced.

Figure 85 shows the energy usage profiles of the refrigeration system at Kopanang mine. The yellow graph is the baseline and represents the profile before DSM implementation. This profile was scaled by inserting the daily amount of thermal energy consumed into equation 5-1. The blue line shows the change in the energy profile after the DSM project was implemented. The red graph shows the result on the refrigeration system after the total water reticulation at Kopanang mine was integrated and optimised.

From this figure it can be seen that by integrating and optimising all components of the total water reticulation system, an increased amount of morning and evening load can be shifted.

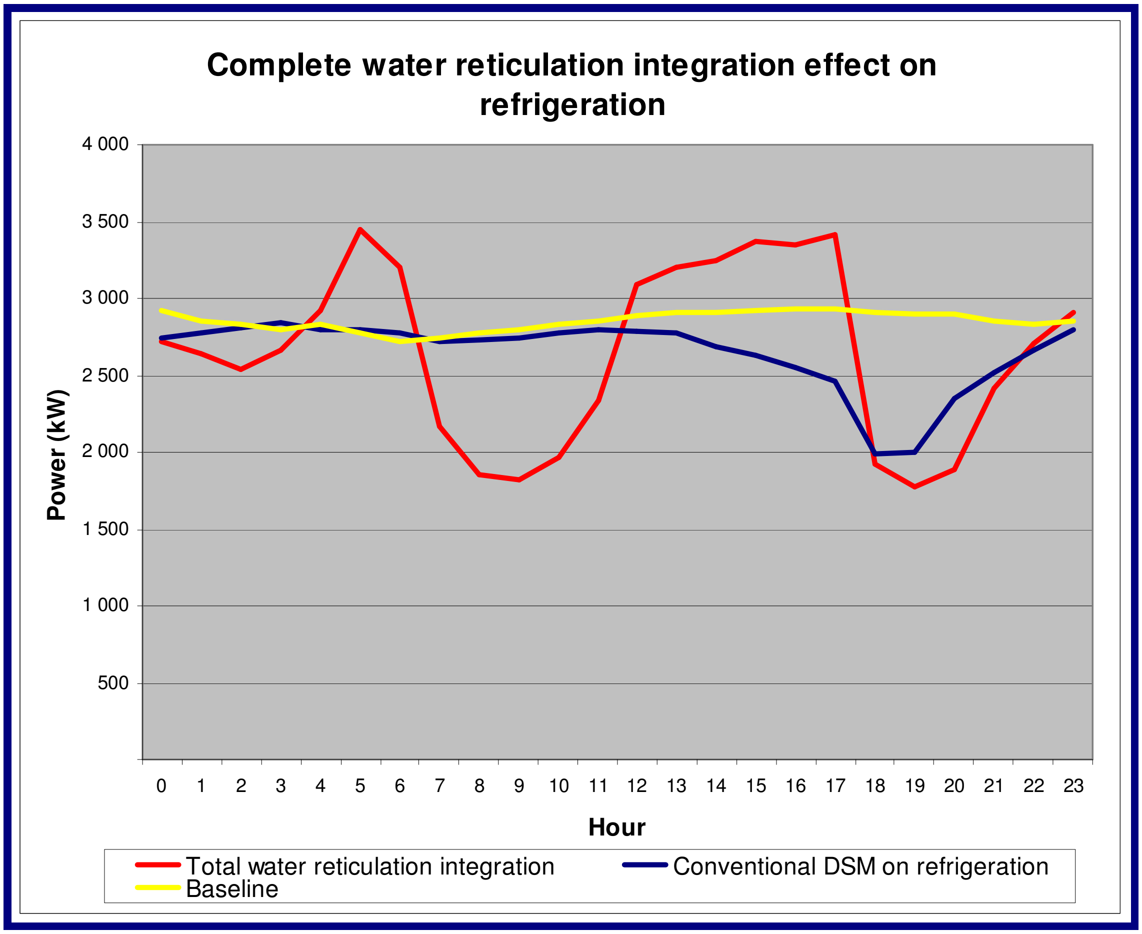

Figure 85: Optimised electricity profile of the refrigeration system (winter)

Table 22 shows the results of the conventional DSM against the total system optimisation. From this table it can be seen that by optimising the complete water reticulation system, extra savings can be generated in addition to the conventional DSM-project.

Table 22: Kopanang refrigeration system results

Kopanang refrigeration results		
	Conventional DSM	Total system integration
Morning load shift (kW)	1 249	3 608
Evening load shift (kW)	3 470	3 914
Total winter savings	143 000	244 000
Total summer savings	420 000	500 000
Annual savings	R 563 000	R 744 000

5.3 Total water reticulation volume

In this study multiple simulations on the complete water reticulation system were conducted on REMS. This was done to determine the optimum water reticulation volume. Each simulation was executed with different amounts of water volumes. The optimum system volume provides the maximum electricity savings for the dewatering system. Figure 86 shows the result of the simulations for Kopanang mine. In this graph the system volume is plotted against the simulated evening load shift.

The reason why the evening peak was simulated, is that Kopanang has a DSM contract with Eskom. This contract states that Kopanang has to shift a minimum of 2.7 MW load during the evening peak period on its dewatering system. By controlling the system according to the optimum system volume, there will be enough water in the system to prepare the dam levels so that maximum load can be shifted during evening peaks.

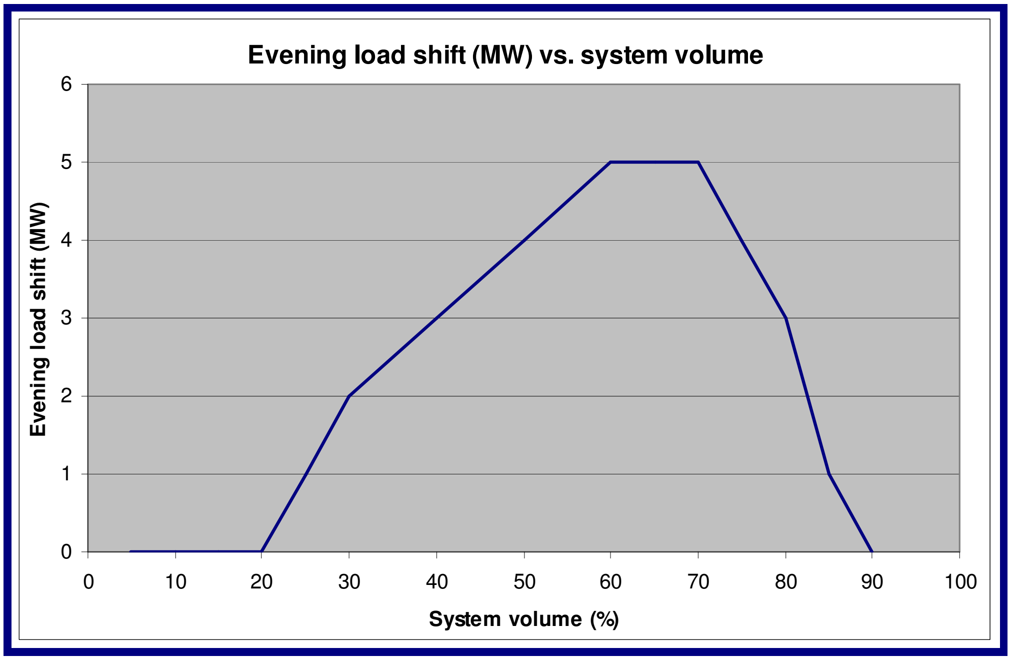

Figure 86: Simulation of evening load shift (MW) against system volume (%)

The results of this simulation indicated that the optimum system volume is between 60% and 70% of the water storage capacity. None of the system constraints were violated during the simulation evaluation.

Figure 87 plots the evening MW load shift against the system water volumes. The red line is a polynomial trend of the water volumes and the blue line is a polynomial trend of the evening load shift. This figure was plotted to prove that the optimum system volume for maximum evening peak load shift is between 60% and 70%. It can be seen that the amount of water in the clear water system has been reduced dramatically, from an average of 60% in August to nearly 40% at the beginning of September. The evening load shift for each day is also indicated on the same graph. From the graph it is clear that the best results were achieved with the system water volume at 60%. It can also be seen that the load shift decreased after the system volume dropped below 50%. From this graph it is evident that the optimum volume simulation can be used to generate maximum savings for the mine.

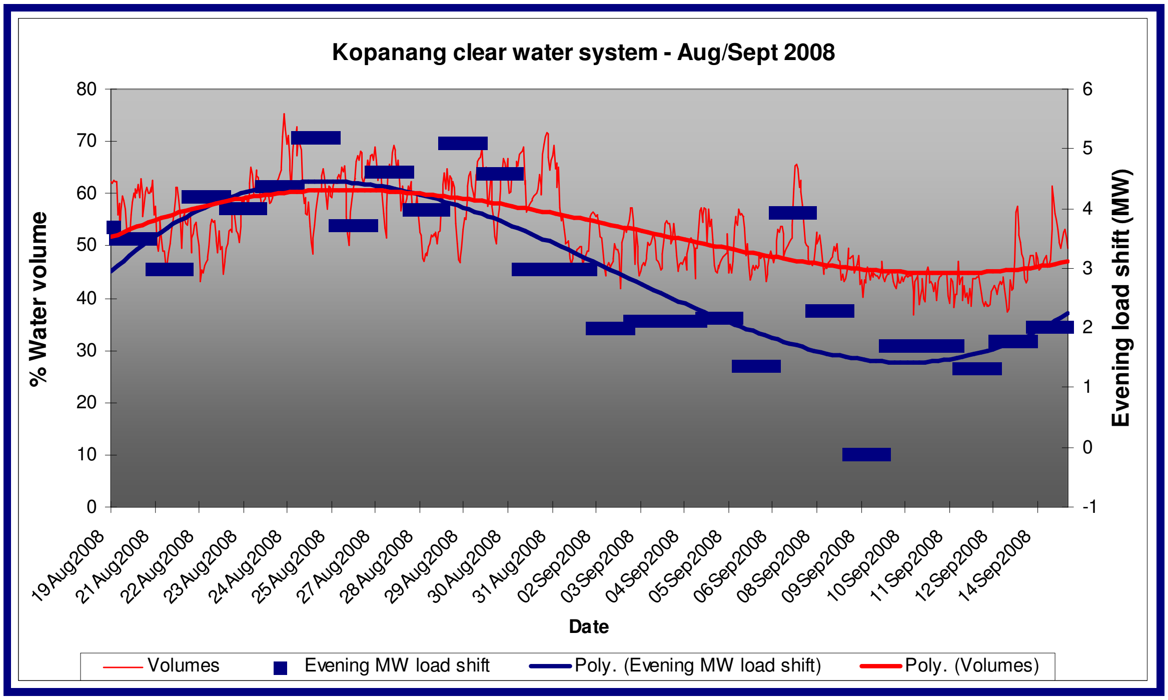

Figure 87: Total water reticulation water volume

5.4 3-CPS integration into a complete water reticulation system

5.4.1 Water reticulation layout

Tshepong mine is a Harmony Mine, situated near Odendaalsrus in the Free State Province of South Africa. Its dewatering system is controlled by the REMS-Pumps system. By optimising the pump schedule according to the Eskom variable tariff structure, cost savings are realised.

After the decision was made to implement a DSM-project on the refrigeration system of the mine, a strategy was developed to combine, simulate and optimise the total water reticulation system. The components to be integrated were the dewatering, 3-CPS and refrigeration systems.

In order to achieve the maximum possible savings, each individual system's optimisation strategy should be analysed and assessed. Once the characteristic of each system is known, a combined optimisation strategy can be developed.

The DSM pumping project at Tshepong was implemented in 2006. Tshepong mine has two pump stations. 66 Level is situated 2 200 m and 45 Level pump station 1 500 m below surface. One 3-CPS is situated on 45 Level pump station, which controls the cold water that is sent down the mine. The 3-CPS is also linked to the 45 Level hot dam. It uses the energy from the cold water that is sent down the shaft to pump water from the underground hot dam to the surface pre-cool dams. The dam level limits are shown in Table 23. These constraints must be adhered to at all times.

Table 23: Dam level constraints

System constraints	Minimum level	Maximum level
Pre-cool dam	42%	100%
Surface cold dam	50%	100%
45 L hot dam	30%	80%
66 L hot dam	30%	80%
45 L cold dam	55%	95%

The used mining and service water flows into 66 L dam. This dam consists of 4 smaller dams, which have a combined capacity of 9 ML. The water is pumped from 66 L to the 45 L dams. From there the water is pumped from either the 45 L pumps or the 3-CPS into the pre-cool towers at surface. The layout is shown in Figure 88.

Water exits the surface pre-cool towers at a temperature of 17°C – 18°C after it is cooled. These pre-cool dams receive water from the pre-cool towers, as well as return water from the bulk air coolers (BACs). The water is then sent to the refrigeration plant. The plant consists of four refrigeration machines with a combined cooling capacity of 29 MW.

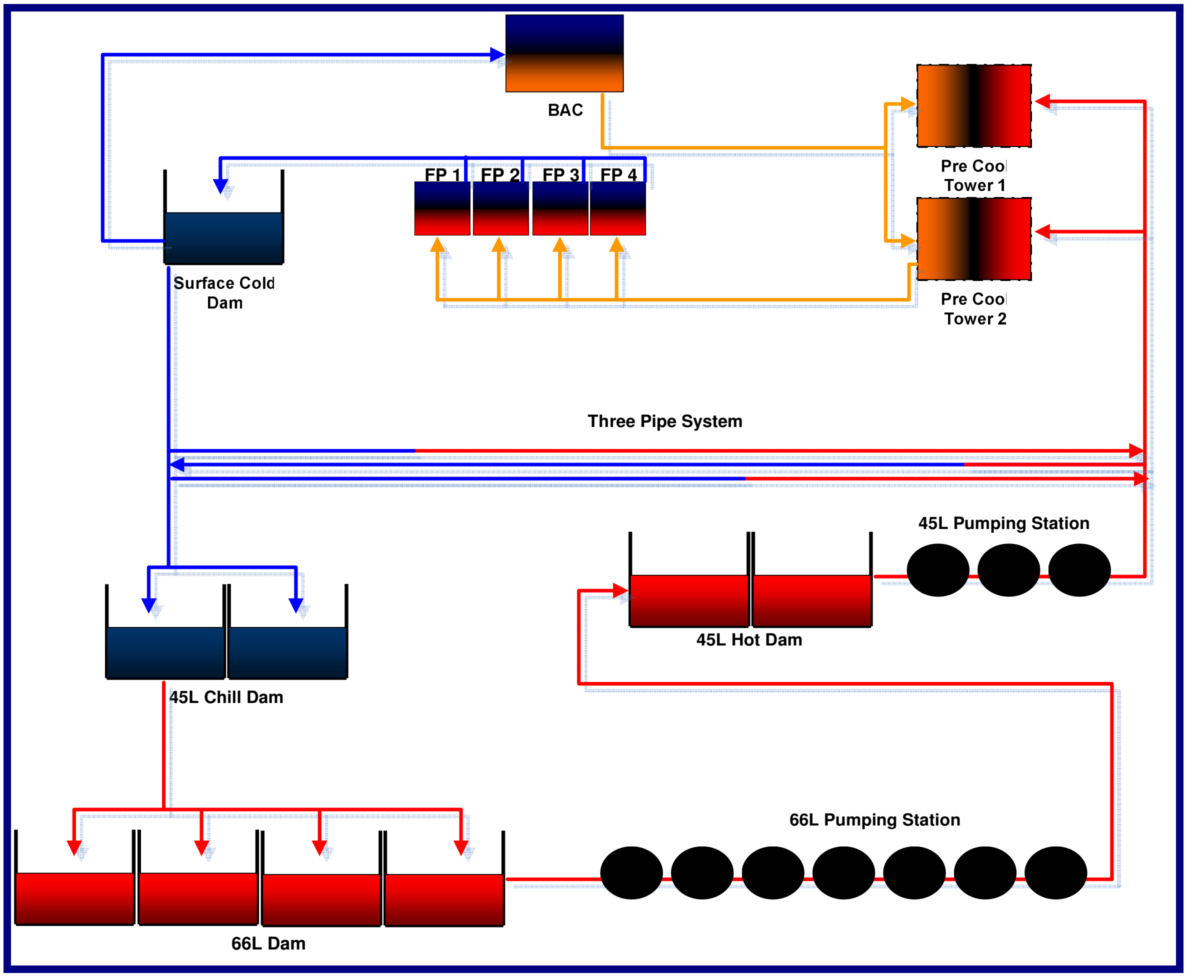

Figure 88: Tshepong 3-CPS, refrigeration and dewatering integration

The combined coefficient of performance (COP) of the refrigeration system is 5.5. After the water enters the refrigeration plant it is pumped through the evaporator to the cold dam at a temperature of between 3.5℃ and 5.5℃. The condenser water is then pumped to the condenser-cooling towers to be cooled. There are three condenser-cooling towers. Each has a flow rate of between 500 l/s and 570 l/s.

The BAC has an average flow rate of 330 l/s and the water exits the BAC at 8℃. The installed capacities of some of the larger water reticulation equipment are listed in Table 24.

Table 24: Tshepong water reticulation electrical capacities

Components	Qty	Electrical capacity (kW)	Total capacity (kW)
Refrigeration machines	4		29 000
45 L pump	3	1 500	4 500
66 L pump	7	1 500	10 500
3-CPS	1	-	3 000
			44 000

5.4.2 Tshepong refrigeration

After the water is cooled, it is sent to a discharge box located on top of cold dam 1 and 2. There are four cold dams that are interlinked. Water from the discharge box is sent directly to the BAC. The surplus of incoming water is stored in the cold dams. The cold dams provide the mining levels with cold water, as can be seen in Figure 89.

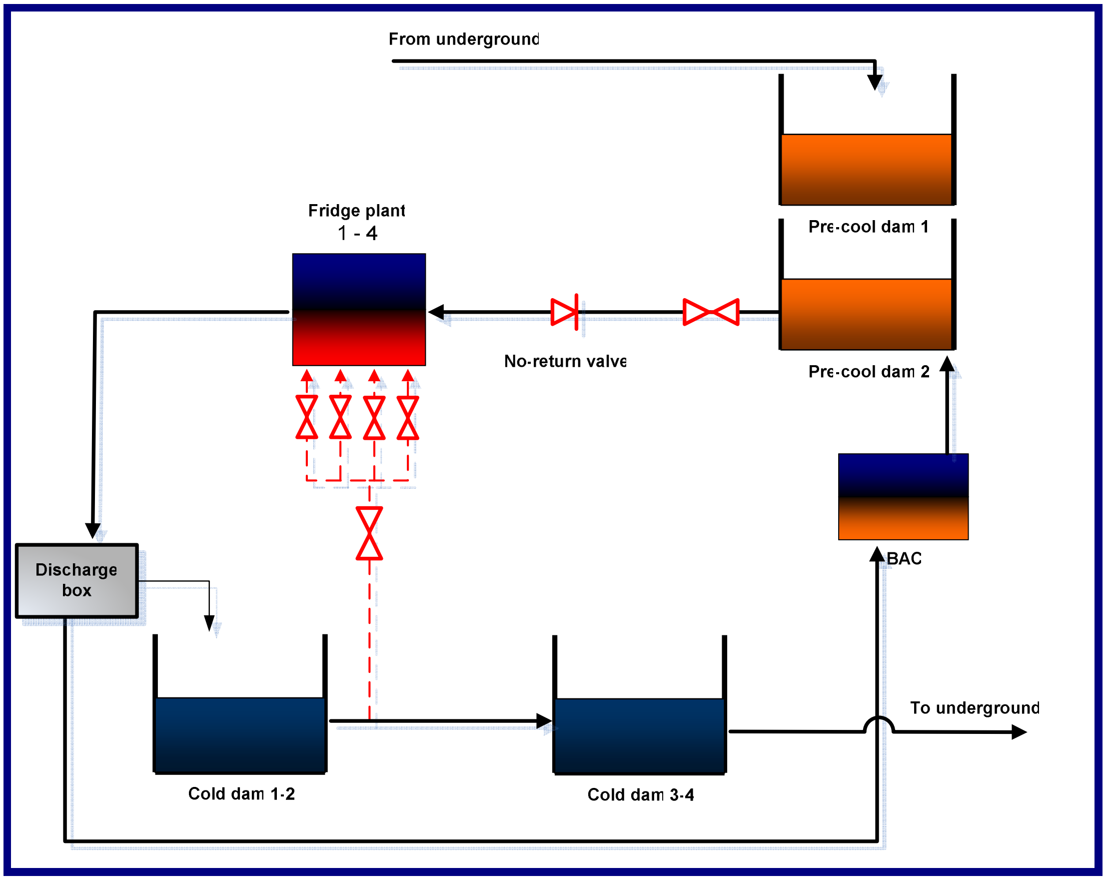

Figure 89: Tshepong gold mine refrigeration system layout prior to the complete system integration

The discharge box is positioned above the level of the cold dams. This allows the water to gravity feed into the BAC, eliminating the requirements of any pumps. The capacity of the discharge box is insufficient to supply the BACs with cold water throughout the peak periods.

Figure 89 also shows the system modifications required to implement a conventional DSM strategy. The additional pipelines and equipment installed are shown in red. To supply the BACs with a constant flow of cold water during the peak periods, the water from the pre-cool tower to the refrigeration machines is stopped. The water from the cold dams is then fed directly into the refrigeration machines. By feeding the refrigeration machines with cold water, the compressor inlet guide vane openings automatically reduce and the refrigeration machines are forced to stopped. The cold water is then fed into the discharge box, which buffers the water that needs to be sent to the BACs, as shown in Figure 90.

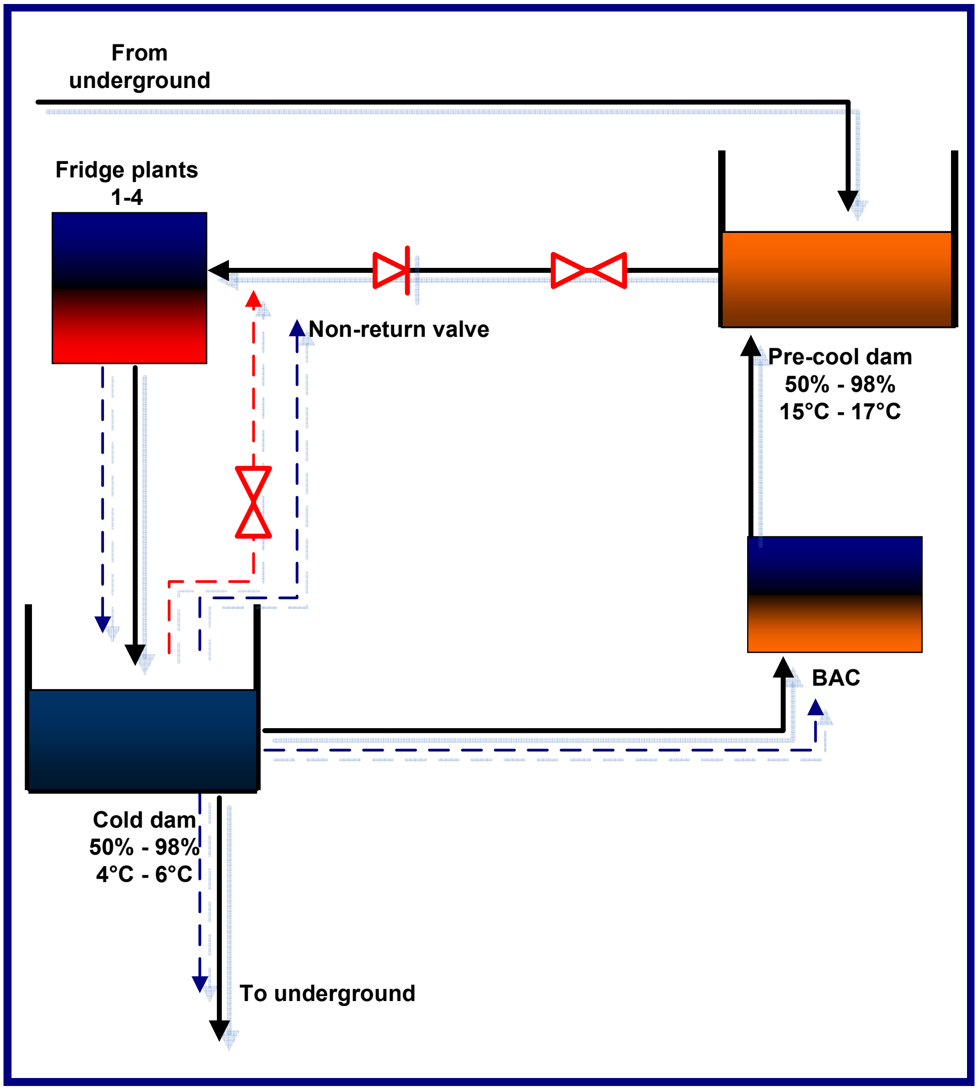

Figure 90: Proposed water balance during peak period.

5.4.2.1 The optimised simulation models for pumping and refrigeration systems

Once the representative simulations and power usage baselines are created, the next step will be to optimise each system. After the separate optimisation strategy of each system has been developed, an integrated strategy can be constructed. For the water reticulation system to be efficient, the 3-CPS operation should be maximised. The refrigeration and dewatering systems should also be controlled so that the minimum electricity is consumed during the Eskom peak periods.

If the constraints do not allow the refrigeration machines to be stopped, the back-pass system will force them to reduce load. The back-pass is used to cool the inlet temperatures of the machines, so that the guide vane openings are reduced and the machines are forced to cut back on power to avoid compressor surges.

The BAC at Tshepong's refrigeration system cannot be stopped due to necessary underground cooling. The pre-cool dam must have sufficient storage capacity to store the incoming water from the BACs. In addition, the cold dam must have enough cold water to provide the BACs with constant cold water feed. There should also be enough water to supply the mining operations, if needed.

To demonstrate the importance of integrating the complete water reticulation, simulations were developed with the refrigeration system in isolation. Through numerous iterations an optimised DSM potential was determined. The optimised power profile simulations of the refrigeration system are shown in Figure 91 and Figure 92 respectively. These simulations were based on conventional DSM methods.

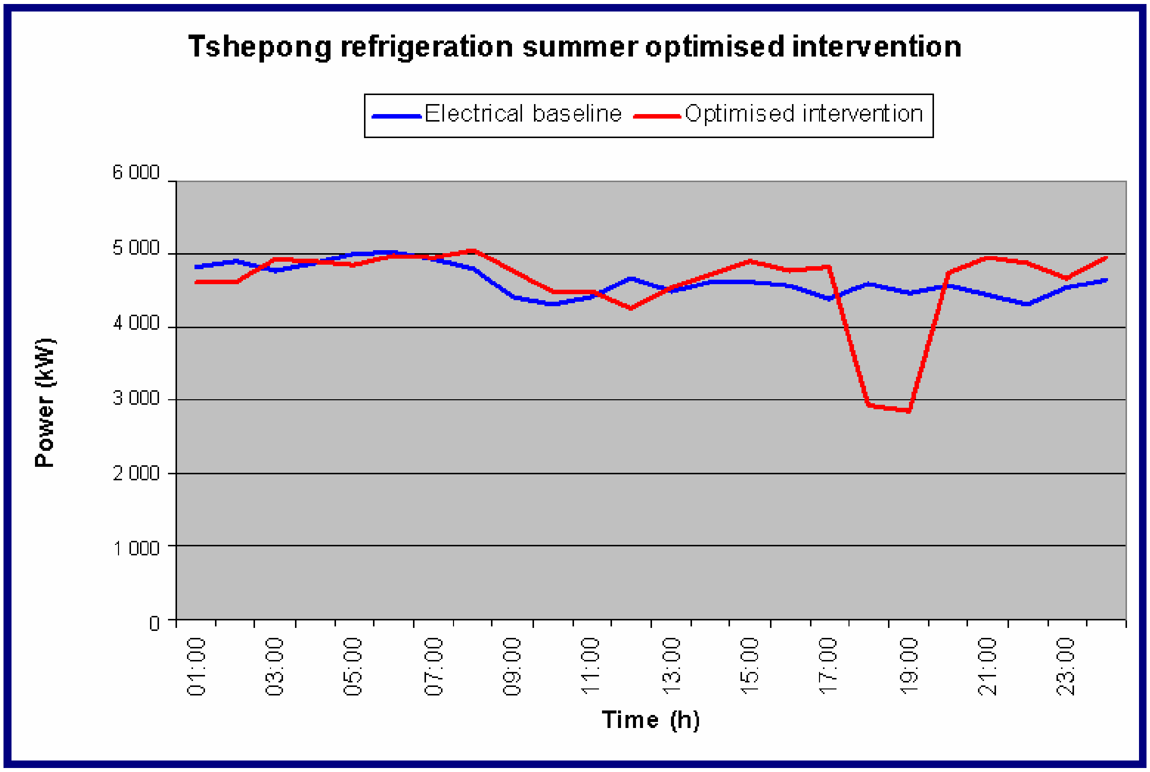

Figure 91: Simulated Tshepong optimised intervention (summer)

Even though the dam levels of the pre-cool dam and chill dam were prepared, the simulation indicated that only a single refrigeration machine can be stopped for the duration of the summer evening peak period. Because of the constant underground water inflow, the remaining two running refrigeration machines cannot be stopped. As a result, the average evening load reduction during the summer peak period is only 800 kW. During the winter period the power consumption of the refrigeration system can be optimised, as seen in Figure 92.

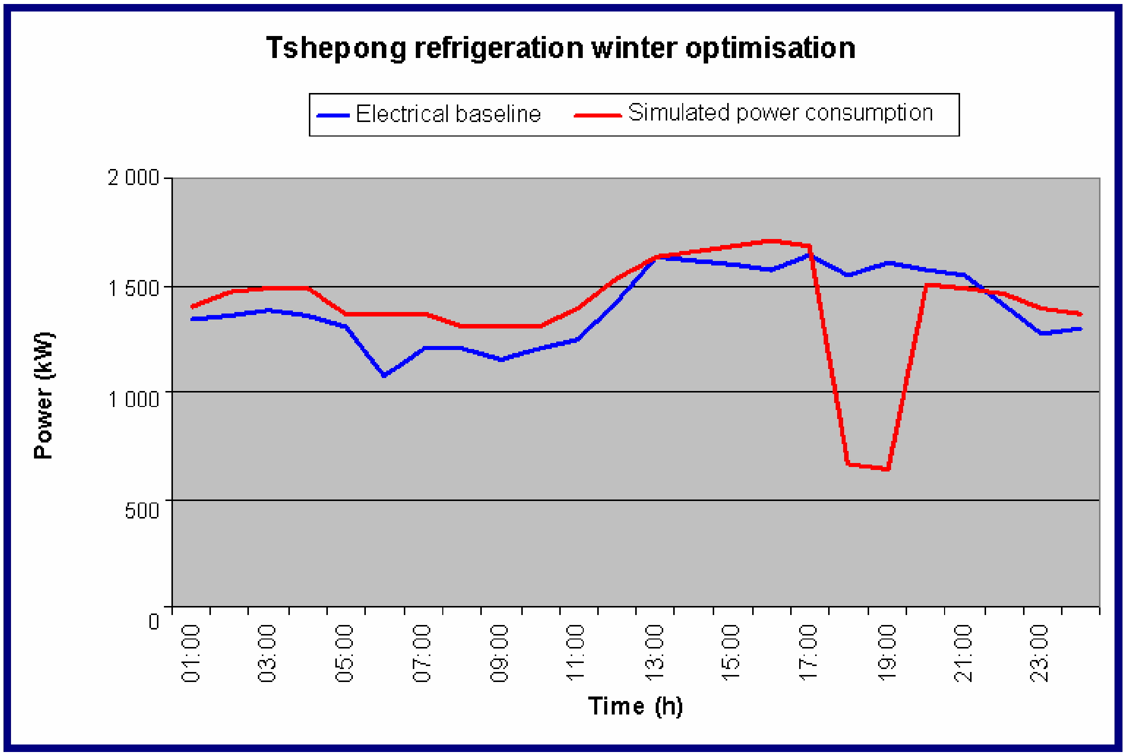

Figure 92: Simulated Tshepong optimised intervention (winter)

From Figure 92 it can be seen that the evening peak load can be reduced by 900 kW. Because of insufficient dam capacity to store the incoming water from the mining levels, some of the refrigeration machines were forced to operate.

From Figure 92 it can also be seen that morning load shift is not possible. The reason is that the 3-CPS operates during the morning peak periods, extracting and adding water to the refrigeration plant. Due to this operation the refrigeration plant must operate on a normal load.

The pumping system was simulated using the existing operational parameters. The dam capacities were found to be large enough to enable significant power savings during the peak period, as illustrated in Figure 93.

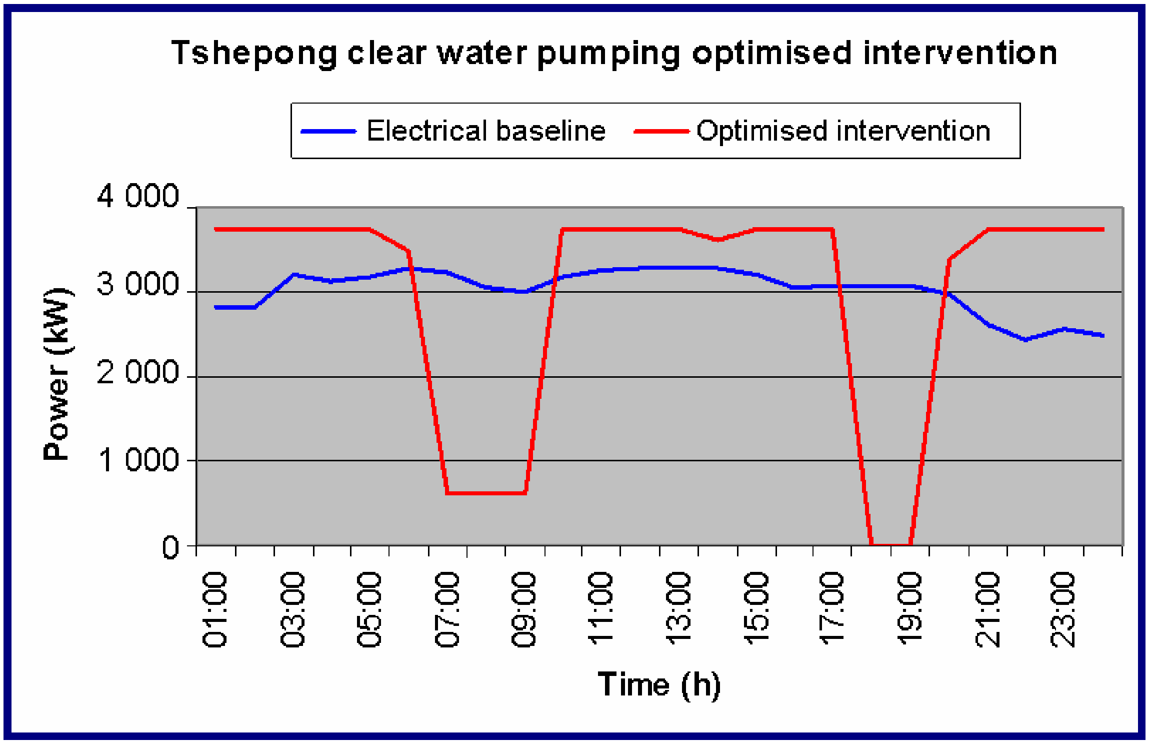

Figure 93: Tshepong pumping optimised intervention

It is clear that there is enough underground dam capacity to store incoming water from 66 L and 45 L during the Eskom morning and evening peak periods. However, due to the need for cold water during the morning peak period, not all pumps can be stopped.

5.4.3 Total system control simulation

As was previously stated, both systems make use of the surface pre-cool dams. Water is stored in the pre-cool dams before it enters the refrigeration machines. In order to reduce energy consumption during the peak periods, the utilisation of the pre-cool dam must be optimally controlled so that both systems benefit from its capacity. In order to stop the maximum number of refrigeration machines during the summer and winter peak periods, the water entering and exiting the refrigeration plants must be reduced. This effect can be seen in Figure 94. Therefore the 3-CPS, as well as the dewatering systems, must be included in the system control strategy.

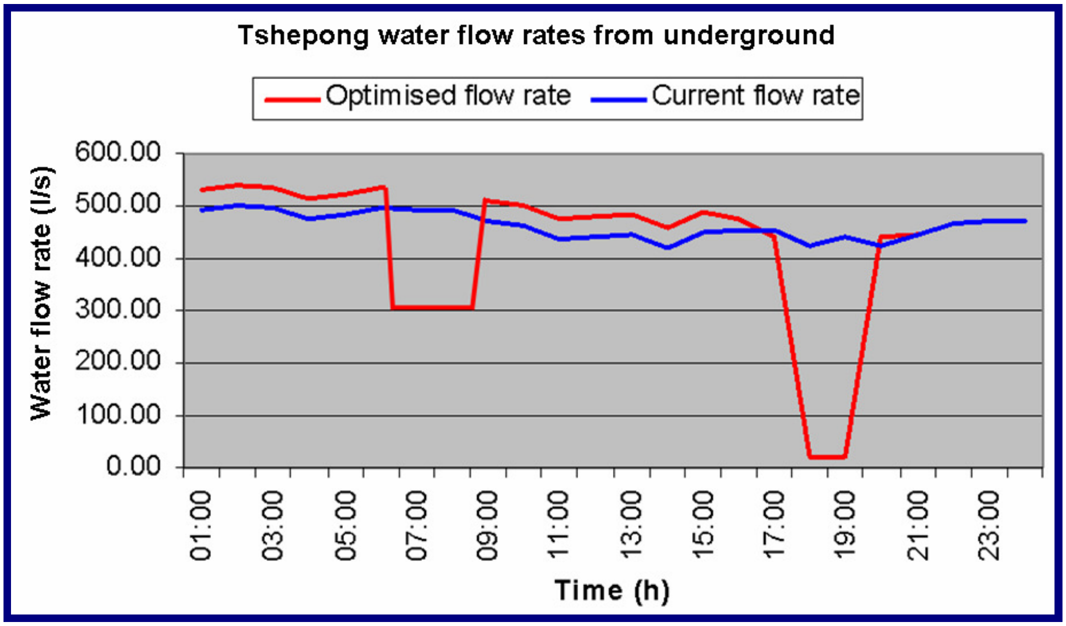

Figure 94: Optimum water flow rates from underground

It is indicated in Figure 94 that the underground water flow to surface must be reduced during the peak periods. It is therefore essential that the pumping system be controlled to accommodate the DSM strategies of the refrigeration system. This figure also shows that the water flow can be reduced, but not completely stopped during the morning peak period. Similar to Kopanang, the underground water demand during this period is very high.

The optimised power usage for this strategy is illustrated in Figure 95 and Figure 96 for the summer and winter periods respectively.

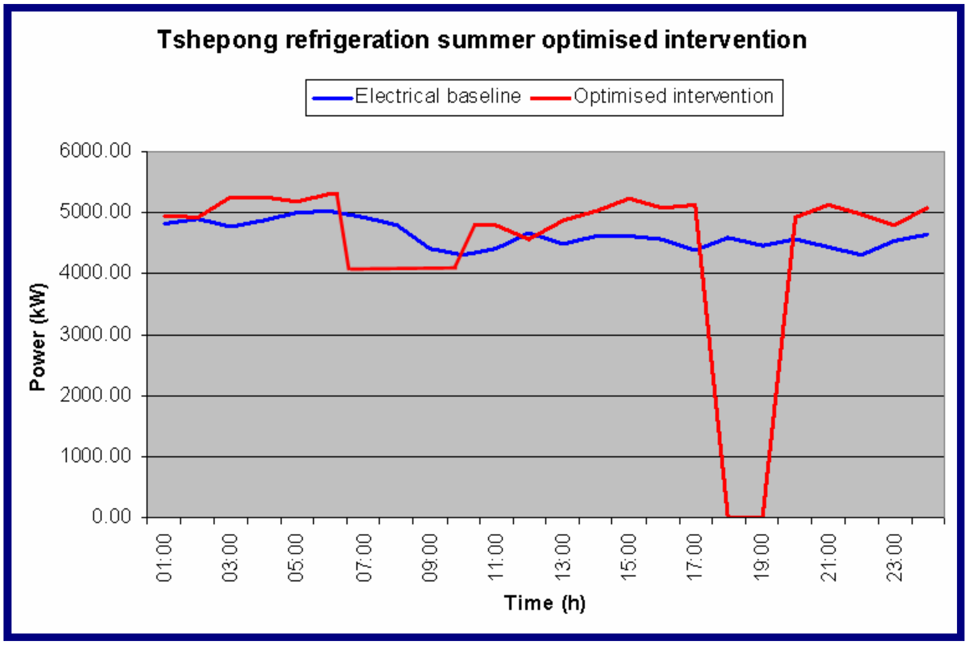

Figure 95: New Tshepong refrigeration optimised intervention (summer)

With sufficient dam preparations, all the refrigeration machines can be stopped during the evening peak period. This will result in an average daily load reduction of 4.5 MW during the weekdays in summer. Because of the high flow rate underground and to the BACs for mine ventilation cooling during the morning peak period, it will not be possible to stop the refrigeration machines. However, by reducing the in- and outflow of the refrigeration plants during the morning peak times, load could be reduced. This makes a small saving possible.

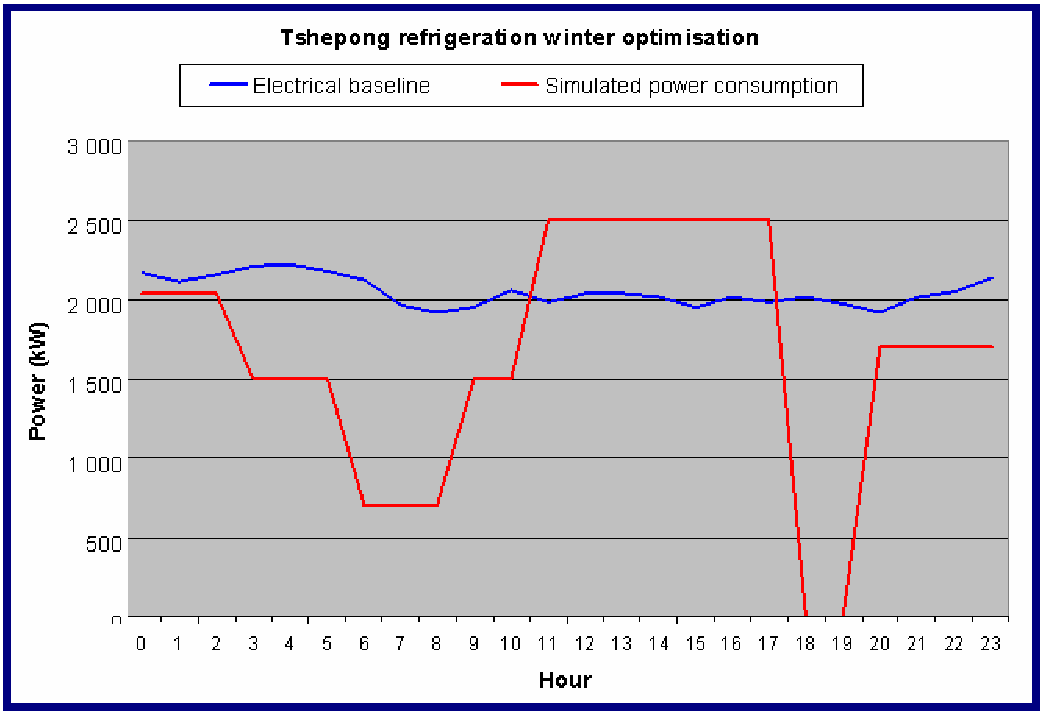

Figure 96: New Tshepong refrigeration optimised intervention (winter)

As seen from Figure 96, it is possible to stop all the machines during the winter evening peak period. However, only a limited number of the machines can be stopped during the morning peak period. The total reduction during the winter period was calculated at 1.9 MW for the evening peak period and 1.2 MW during the morning peak. In order to accomplish this saving, both underground cold water and pre-cool surface dams must be prepared before the peak periods. Due to the relatively low BAC water consumption during the winter peak periods, some of the refrigeration machines will be able to cut back or stopped during the morning peak.

Figure 97 shows the optimum refrigeration dam levels required to achieve savings during the summer and winter periods.

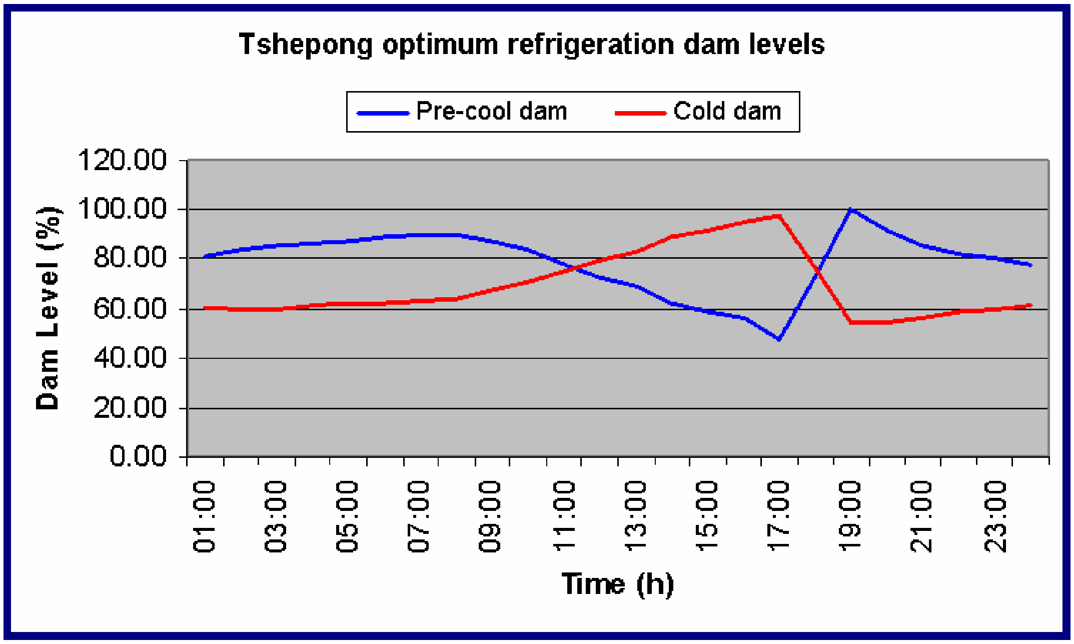

Figure 97: Tshepong optimum refrigeration dam levels

From Figure 97, it is clear that the Pre-cool dam must be at a minimum level and the Cold dam at a maximum level before the evening peak time. This can be done by integrating the refrigeration, 3-CPS and pumping system. By doing so maximum savings can be generated.

5.4.4 Refrigeration results

If the refrigeration system had not been included in the complete water reticulation control strategy, it would not have been possible to stop all the refrigeration machines during the peak periods. The importance of implementing a complete water reticulation strategy is highlighted in this section.

To determine the amount of savings during the weekdays, the baseline has to be scaled according to the thermal energy prior to implementation. Figure 98 shows a scatter plot of the thermal and electrical data points. The values obtained during weekdays were used. The thermal kWh energy values were plotted against the electrical kWh energy values.

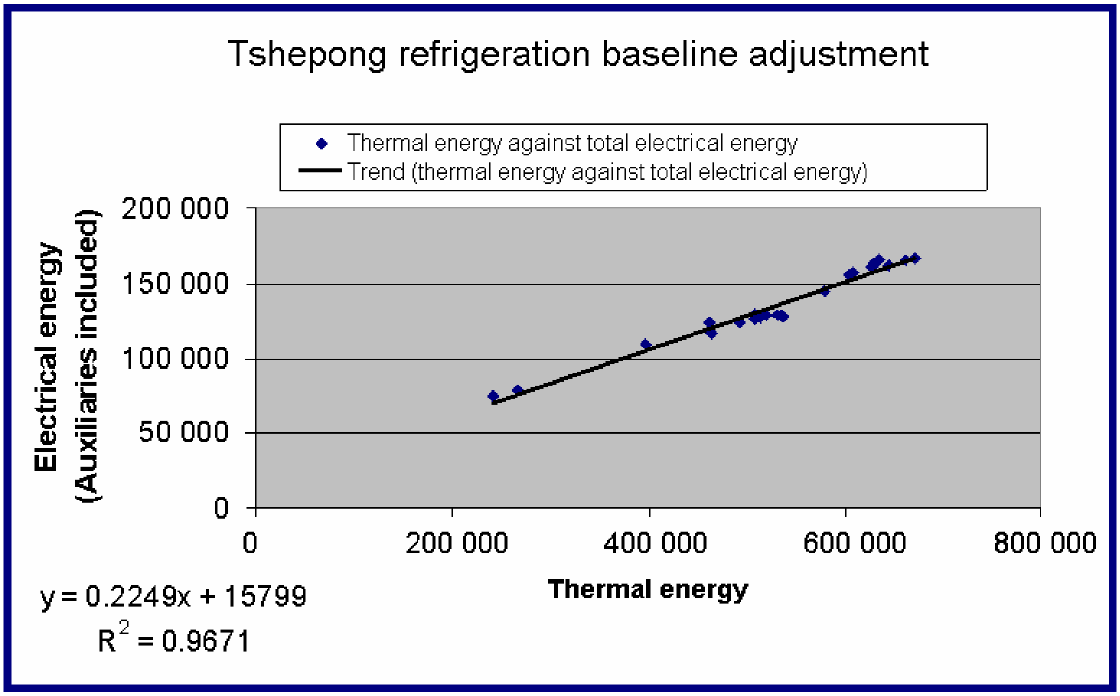

Figure 98: Total system thermal energy against total system electrical energy

The equation of the fitting is as follows [68]:

$$Y = 0.2249x + 15799 \qquad (5\text{-}2)$$

Where:

Y = electrical energy (kWh/day)

x = thermal energy (kWh/day)

Equation 5-3 is used to scale the baseline according to the thermal parameters. This is done so that efficiency of the refrigeration machines can be included in the saving. By using this equation, the new optimised profile can be compared to the inefficient baseline, as seen in Figure 99 and Figure 100.

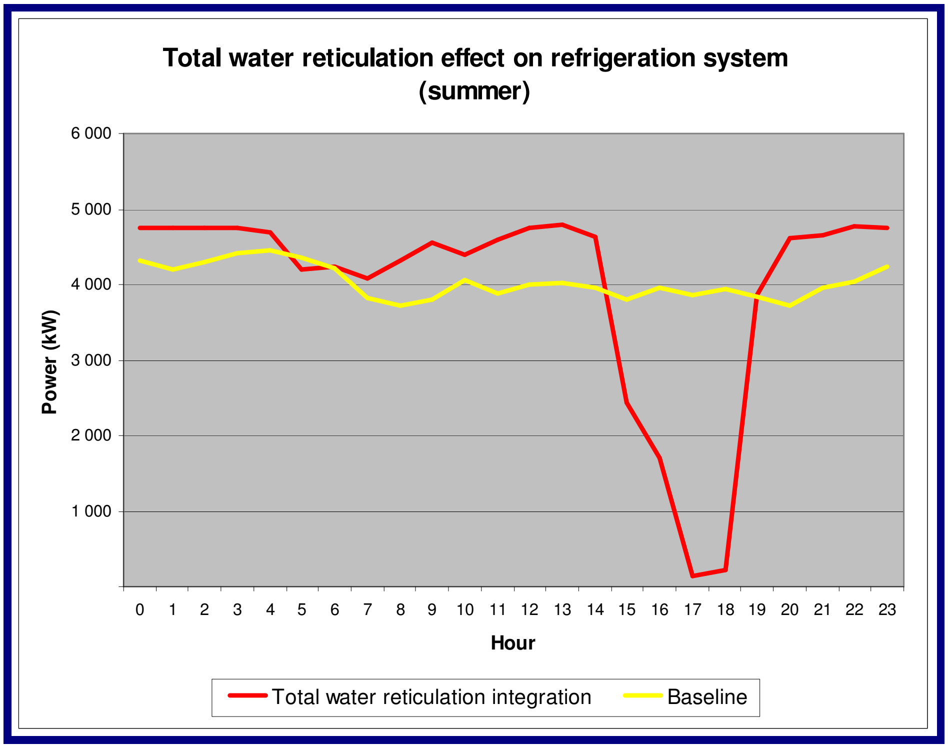

Figure 99: Tshepong refrigeration results (summer)

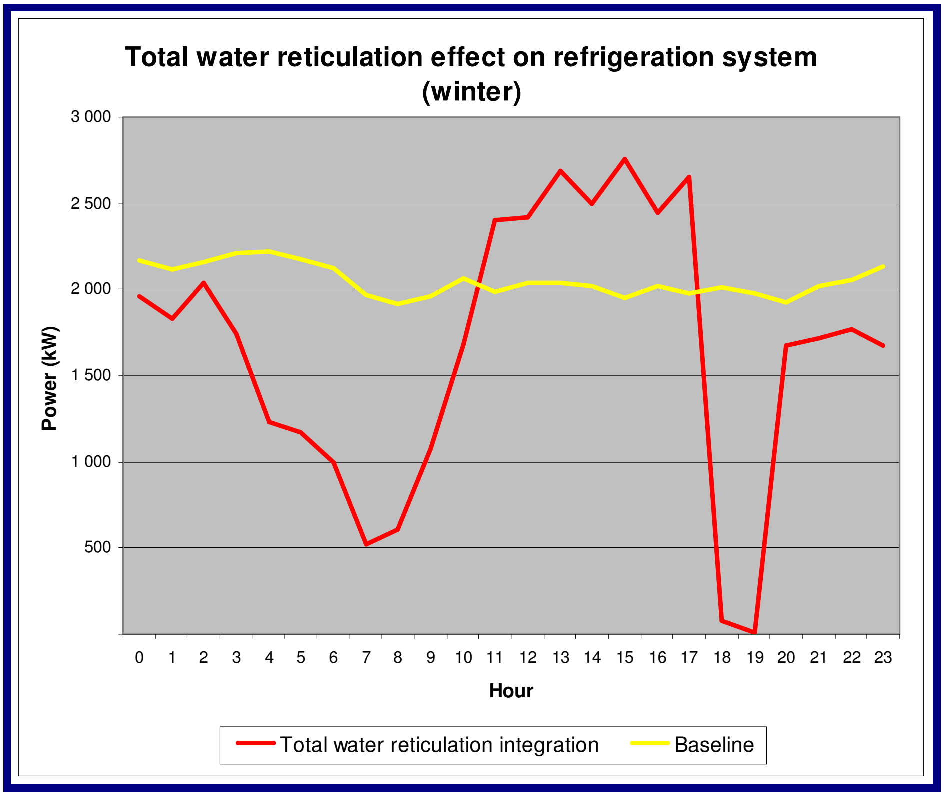

Figure 100: Tshepong refrigeration results (winter)

The new optimised profile clearly indicates that, by integrating the complete water reticulation system, energy consumption can be reduced during the Eskom evening periods. From this figure it can also be seen that due to the implementation of the back-pass system, load can also be reduced during the morning peak period.

The savings associated with this reduction is shown in Table 25.

Table 25: Summary of implemented intervention

Tshepong refrigeration results	
Summer morning load reduction (kW)	0
Summer evening load reduction (kW)	5 300
Winter morning load reduction (kW)	1 215
Summer evening load reduction (kW)	1 947
Total winter savings	R 137 871
Total summer savings	R 286 513
Annual savings	R 424 384

5.4.5 Dewatering results

The performance of the dewatering system was also measured to evaluate the effect of the complete water reticulation integration on this system. To measure the performance of the integrated dewatering and 3-CPS, the electrical power baseline is scaled according to the daily amount of water pumped.

The following equation was used to scale the baseline of the 3-CPS and 45 L dewatering baseline [69].

$$Y = 0.904x \tag{5-3}$$

Where:

Y = Electrical power consumption (kWh/day)
x = Amount of water pumped (kl/day)

The 66 L electrical baseline was scaled according to equation (5-4) [69].

$$Y = 3.0974x + 26949 \qquad (5\text{-}4)$$

Where:

Y = Electrical power consumption (kWh/day)
x = Amount of water pumped (kl/day)

By using the above equations, the baseline can be compared with the optimised results of the total water reticulation integration. These equations were found to be a reasonable representation of the dewatering operation prior to the complete system integration.

In Figure 101 the red line represents the power consumption after the complete water reticulation integration strategy was implemented. The blue line represents the conventional DSM power profile prior to the study, and the yellow line baseline prior to the REMS-pumps installation. This figure shows that more load is shifted during the evening and morning peak periods and that an energy efficiency component has been introduced.

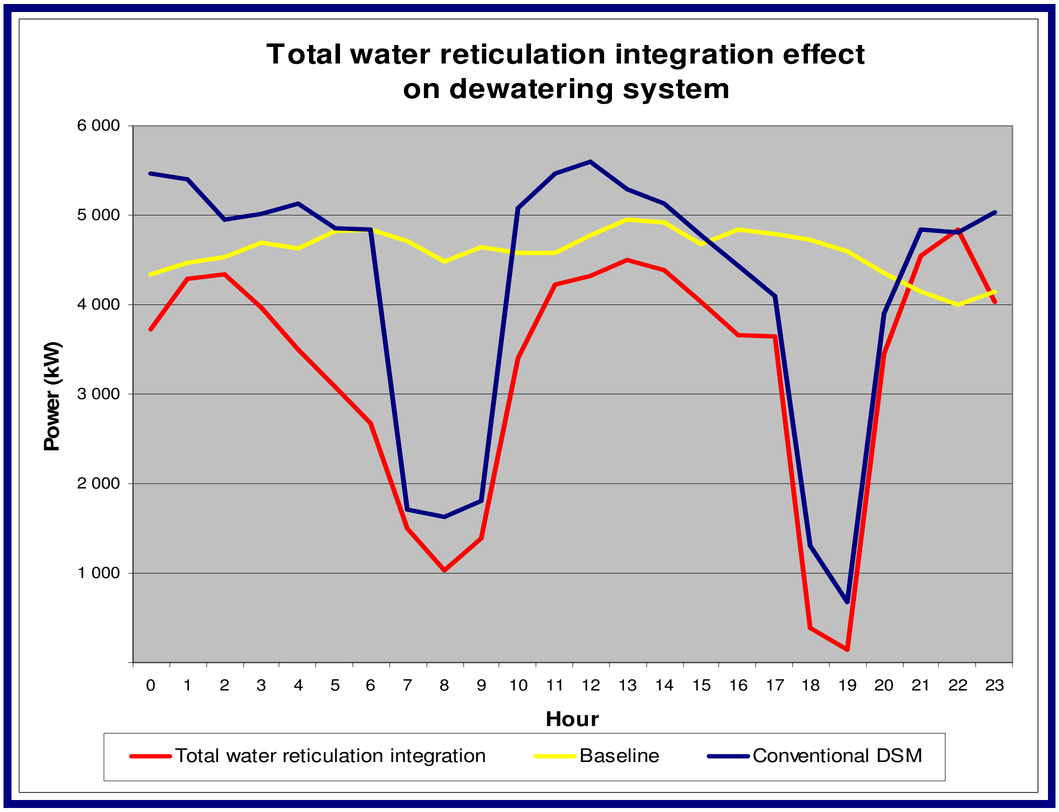

Figure 101: Tshepong dewatering results

The result of the total water reticulation integration on the dewatering system is shown in Table 26. From this table it can be seen that an energy efficiency component of 1 MW, a morning load shift of 3.2 MW and an evening load reduction of 4.9 MW was realised. The efficiency was introduced due to the more effective operation of the 3-CPS.

Table 26: Summary of implemented intervention

Tshepong dewatering results		
	Conventional DSM	Total system integration
Morning load shift (kW)	2 900	3 237
Evening load shift (kW)	740	4 950
Daily energy efficiency (kW)		1 000
Annual savings	R 800 000	R 2 100 000
Average electricity cost (c/kWh)	13.6	12.1

The average evening peak savings for the pumping project are seen in Figure 102. From this figure it can be seen that from Oct 2005 to May 2007, the average evening load shift of Tshepong's dewatering system was 3.7 MW. After the complete water reticulation system was integrated, the evening load reduction were increased to 5 MW. It is clear that the integrated water reticulation control strategy resulted in additional savings for the mine.

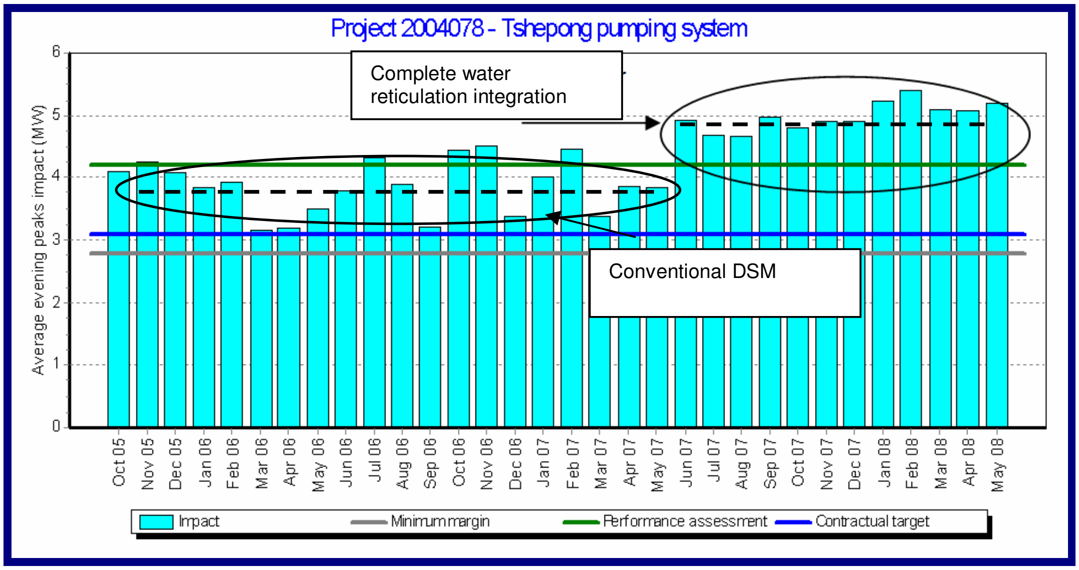

Figure 102: Historic evening peak load shifting of Tshepong pumping system

5.5 Expanding this research to other mines

In section 5.2 it was shown that by implementing an integrated control strategy on the total water reticulation system, the average electricity tariff could be reduced to 12c/kWh. If this strategy is implemented on the dewatering systems shown in Table 27, an estimated annual saving of R17.7-million for the mining industry can be expected.

Table 27: Estimated annual savings for electricity tariff at 12c/kWh

Mine	Running capacity (MW)	Current average electricity costs (c/kWh)	Annual electricity saving at 12c/kWh
South Deep	10.7	12.98	R 918 573.60
Beatrix1,2,3	7	12.8	R 490 560.00
Cooke1#	2.8	12.6	R 147 168.00
Grootvlei	10	15	R 2 628 000.00
Mponeng	10.7	12.72	R 674 870.40
Kopanang	4.6	13.5	R 604 440.00
Tshepong	3.5	13.6	R 490 560.00
Kloof 8#	5	16.8	R 2 102 400.00
Kloof 10#	6.8	15.6	R 2 144 448.00
Tau Tona	14	14.4	R 2 943 360.00
Harmony 3#	5	13.9	R 832 200.00
Evander 7#	4.5	14.1	R 827 820.00
Kloof 7#	17	14	R 2 978 400.00
Total annual saving			R 17 782 800.00

5.6 Conclusion

In this chapter the successes of integrating a water reticulation system were shown. In addition to the conventional DSM strategies, extra savings can be generated by making use of the newly developed integrated optimisation techniques.

Total system integration of Kopanang's turbine-pump, dewatering and refrigeration systems resulted in extra savings for the mine. By implementing the complete control strategy, the load shift on the pumping system, as well as load reduction on the refrigeration plants were increased. In addition to conventional DSM savings, an annual saving of R 800 000 was realised.

An optimum water volume simulator was also developed, as described in Chapter 5. To prove that this simulator works, it was applied on the dewatering system of Kopanang. The simulation indicated that the total system water volume of Kopanang should be more than 60% to generate maximum evening load shift. Logged water volumes from August 2008 to September 2008 showed that with the water volume above 60%, the system could shift a maximum of 5 MW from the evening peak. It was indicated that if the volume dropped below 60%, load shift reduced dramatically. Therefore by optimising the water volume in this system, more sustainable load shift will be achieved.

It was also concluded that by integrating Tshepong mine’s 3-CPS, refrigeration and dewatering systems into a complete optimised strategy, load reduction on the mine would increase. The evening load on the refrigeration system was reduced by 5.3 MW during the summer and 1.9 MW during winter. Due to the system integration, the evening peak load on the dewatering system was further reduced by 1.2 MW. In addition to the conventional DSM projects, 1 MW energy efficiency was also introduced due to the optimisation of the 3-CPS.

Finally, the mining sector can benefit from an annual saving of R 17.7-million by implementing the newly optimised strategies on a number of other South African mines.

5.7 References

[66] den Heijer, W., “Baseline report: Kopanang Mine Cold Water System Project”, Project number: 2003007, Measurement and Verification Team, North-West University, PO Box 19139, Noordbrug, Potchefstroom, 2522, August 2004.

[67] Britt, I., “Measurement and Verification, Anglo Gold - Kopanang Fridge Plant system”, Baseline Draft, Corporate Division, Corporate Technical Audit Department, Report number 0509 V1R0, North-West University, September 2005.

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CHAPTER 6: Conclusion and recommendations

This chapter concludes the complete thesis and ends with several suggestions for further work in this field.

6.1 Conclusion

The South African energy and in particular its electricity demand is rapidly increasing. During the past few years the electricity demand has grown by 1 200 MW per year. This increase in demand has put a lot of strain on the electricity grid of Eskom.

In January 2008 the reserve supply margin of 8% was proven to be insufficient. During this period, the maximum demand threatened to exceed the maximum available supply. Operations, such as gold mining, were forced to be shut down. After the situation was stabilised, the mining and industrial electricity consumers needed to reduce their electricity consumption by 10% to prevent similar occurrences. If not, the surplus of energy above the allocated target could be charged at more than 18 times the average energy cost.

In this thesis new energy efficiency and optimisation models were developed to identify inefficient dewatering systems. Other than conventional efficiency models, the new models assessed the dewatering energy efficiency, water efficiency and electricity tariff rates. These components are independent of each other, and to realise the true performance of a dewatering system, the mine should be evaluated by all three these models.

If a system is identified to be less efficient than other mines, an energy efficiency optimised model could be used to improve the inefficiencies. The unique optimised models could assist the user in identifying and resolving common mine dewatering inefficiencies. These inefficiencies could be reduced by means of short- or long-term solutions. Payback periods of different systems were also estimated and compared.

These newly developed models were applied to a number of dewatering systems. The models indicated that the dewatering system of Beatrix 1 Shaft was operated inefficiently. After the system was processed through the energy efficiency optimisation models, an energy efficiency improvement of 14.4 MWh per day was identified. Presently the mine saves an estimated R 2 500 000 per annum due to the implementation of the REMS system.

A new underground level water controller was developed and implemented on the underground level valves at Kopanang mine. This controller enables the mine to reduce water wastages in periods when the minimum amount of water is consumed. By making use of these novel water reduction techniques, the water consumption on Kopanang was reduced by 1.3 Ml per day to realise a total energy efficiency of 700 kW.

A number of DSM projects were done on mine dewatering, as well as refrigeration systems. These systems were also implemented with great success. However, the importance of integrating all components of the water reticulation system into one complete system was highlighted. The integrated system should include components such as turbines, dissipaters, 3-CPSs, refrigeration systems and dewatering systems. Newly developed simulations and optimised strategies that can be integrated to form a complete water reticulation system were developed. By integrating these systems into a complete optimised control strategy, extra savings can be generated in addition to conventional DSM-projects.

New simulations that can calculate the optimum water volume for maximum cost savings were developed. By controlling the system water volume according to the optimum volume, maximum sustainable cost savings will be realised.

Total system integration of Kopanang's turbine-pump, dewatering and refrigeration systems resulted in extra savings for the mine. In addition to conventional DSM-projects, the load shifts on the pumping, as well as load reduction on the refrigeration system were increased. This intervention increased the annual savings by R 800 000.

It was also concluded that by integrating Tshepong mine's 3-CPS, refrigeration and dewatering systems into a complete optimised strategy, load reduction potential on the mine is increased. By implementing the complete water reticulation strategy on the mine, evening load reduction on the refrigeration system increased to 5.3 MW during summer and 1.9 MW during winter. The effect on the dewatering could also be seen with a morning load shift of 3.2 MW and an evening load shift of 3.8 MW.

The new models proved to be effective and should be used on all deep level mines to optimise energy consumption on water reticulation systems. By implementing this, the mining sector can save more than R 20-million annually.

6.2 Recommendations

In this section a number of recommendations for further studies are discussed.

6.2.1 New complete water reticulation integration concept

The new complete water reticulation integration control needs to be implemented and tested on systems that include underground refrigeration plants. This will test the compatibility of the new concept.

The system also needs to be implemented and tested on other type of mines like platinum, copper and diamond mines. If these tests are successful, the application for new concept can be expanded and the mining sector will benefit even more.

6.2.2 Maximum demand control

Mines are billed according to electricity pricing profiles that penalise the user according to a maximum demand value within a given period. This motivates the mine to monitor and manage their maximum power demand.

Since REMS was developed to control the dewatering and refrigeration systems of a mine, it also has a profound impact on the electricity usage of that mine and could influence the maximum demand. A suggestion is to develop REMS further in order to reduce the maximum demand of a typical mine. Should the maximum demand reach critical levels, REMS could stop equipment in order to lower the demand.

Due to the nature of load shift, the electricity demand after the Eskom peak periods increases. I future it might happen that the peak demand period will shift and a “new” peak demand might be created. It could therefore be useful if the system could be developed to accommodate variable peak demand periods.

6.2.3 Include mine ventilation in the integrated control

Since the BACs form part of the mine ventilation, it is proposed that the effects of implementing load reduction on the BACs be investigated. The BACs, as well as the mine ventilation fans should be integrated into the new water reticulation system to further enhance the performance of the system.

APPENDIX A: Details about mine water reticulation

A.1. Mine dewatering pump system

To ensure a safe and comfortable underground working environment, the mines use ventilation, refrigeration plants and underground pumping systems. These components contribute in the order of 30% of the electricity used in underground mines [70]. The industrial sector contributes up to 52% of Eskom's peak demand. The contribution of pumping systems alone is 13% and is responsible for approximately 2 300 MW to 34 000 MW of the electricity peak in South Africa [70]. Figure 103 shows the various industrial sectors and their contributions to Eskom's peak demand.

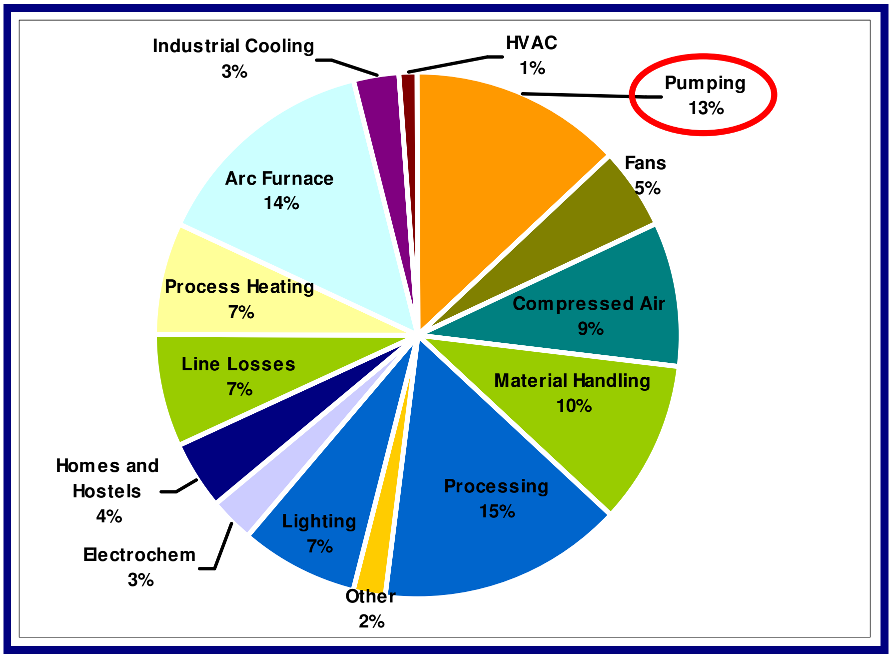


Figure 103: Contribution by process in the industrial sector to Eskom's peak demand [71]

3.4 MW of power is required to pump a volume of 1 megalitre (Ml) from a depth of 1 km in one hour. This is at an efficiency of 80% with a well-maintained pump [70]. Some mines in South Africa operate at depths of 4 km and pump more than 20 Ml of water from the mine on a daily basis.

It is evident that the clear water mine pumping and dewatering system is a very necessary and complex system to control efficiently.

The pumping system supplies water to a number of refrigeration plants and cooling towers on surface [26]. Underground refrigeration plants have been constructed and installed in certain deep level mines [23].

Figure 104 [72] illustrates a typical layout of a mine pump station with the key description for this figure given in Table 28.

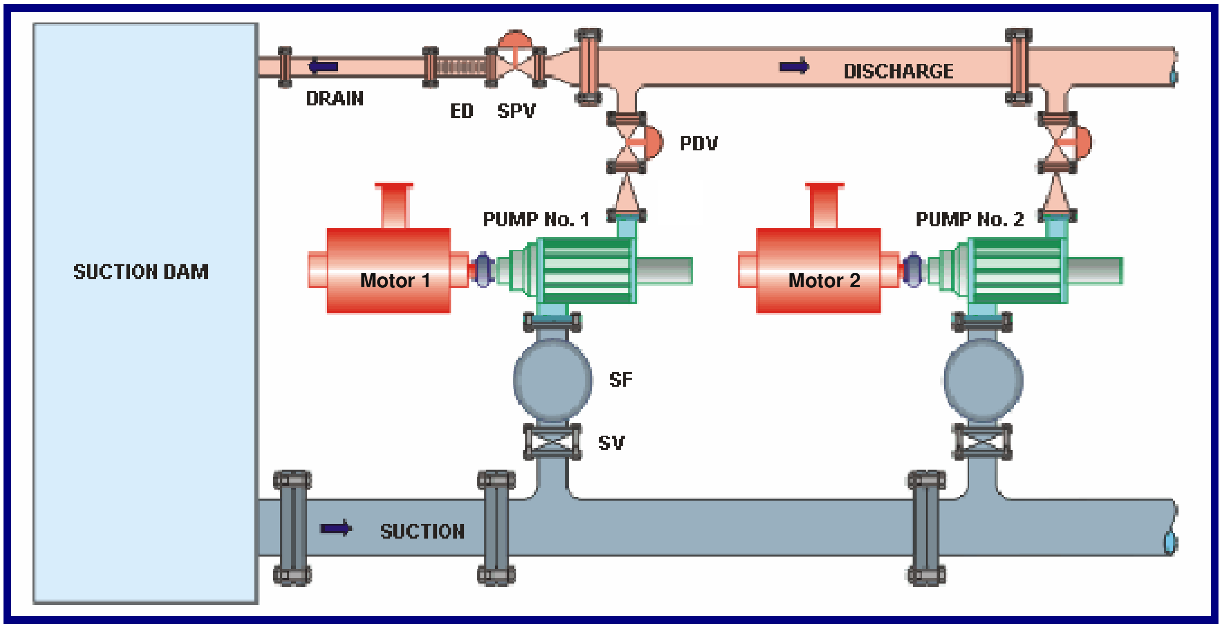


Figure 104: Layout of a typical pump station

Table 28: Key description for Figure 104

Key	Description
ED	Energy dissipater
SPV	Shock prevention valve
PDV	Pump discharge valve
SF	Suction filter
SV	Suction valve

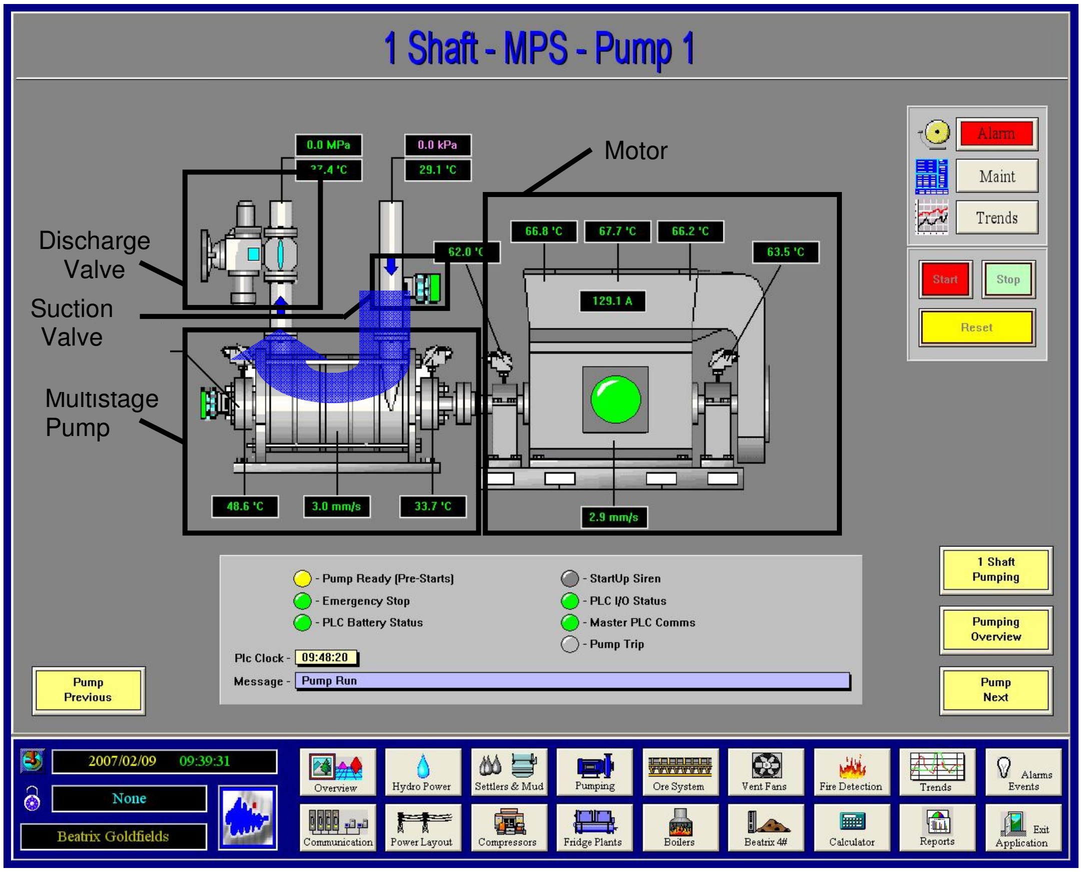
- The shock prevention valve prevents water hammer. This is achieved by providing an instantaneous alternate flow passage if the water flow direction suddenly changes. This valve prevents the sudden stop of water flow. The valve is designed to open instantaneously on a pump trip occurrence and will then close at a controlled rate after a short time delay.

- The energy dissipater works in conjunction with the shock prevention valve and absorbs the remaining energy in the column.

- The suction filter prevents large particles that might damage the internal components of the pump from entering the pump casing.

A.2 High-pressure valves, multi stage pumps and high tension motors

Figure 105 shows a detailed layout of typical elements required for a deep level mine dewatering system.



1 Shaft - MPS - Pump 1

🟡 - Pump Ready (Pre-Starts)
🟢 - Emergency Stop
🟢 - PLC Battery Status
● - StartUp Siren
🟢 - PLC I/O Status
🟢 - Master PLC Comms
○ - Pump Trip

Plc Clock - 09:48:20
Message - Pump Run

2007/02/09 09:39:31
None
Beatrix Goldfields

Figure 105: Typical pump SCADA of a typical dewatering system

Figure 105 is a Supervisory Control And Data Acquisition (SCADA) drawing of Pump 1 at Harmony 3 Shaft mine. This picture represents the underground pump, motor and valve conditions and is displayed in the surface control room. It is however a common practice in the mining environment to install the pumps below the level of the suction dam. The positive pressure on the pump will minimise the effect of cavitations and water-vortexes [73].

Important elements of dewatering pumps include:

- Suction valves
- Discharge valves
- Multistage pumps
- High-tension (HT) motors
- Soft-starters
- Variable speed drives

A.2.1 Pump control valves

The **suction valve** is used to isolate the pump from the dam. This valve is usually open, except during maintenance when it is closed to prevent water from running through the pump. This valve operates under medium water pressures (30 kPa – 300 kPa), because the level of the water in the dam is usually not more than 30 m above the level of the pump.

The **discharge valve,** often called the control valve, is used to isolate the pump from the discharge column and could operate at pressures as high as 15 MPa. This valve is critical for underground pumping, as it has to be controlled in such a way that the differential water pressure in the column is kept to a minimum.

This valve must also ensure that the column is kept filled with water, even when the pumps are stopped. During pump start-up, the valve must be opened slowly in order to keep a positive flow through the pump. If the pump stops unexpectedly, the valve should close as quickly as possible to minimise water loss in the columns.

Figure 106 to Figure 108 show different types of valves commonly used in the mining environment, including:

- Ball valves
- Butterfly valves
- Gate valves

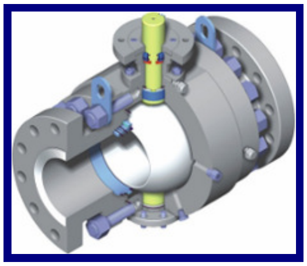


Figure 106: Ball valve

Figure 107: Butterfly valve

Figure 108: Gate valve

A.2.2 Single and multistage pumps

A single-stage centrifugal pump has a single impeller and is used to deliver low to moderate pumping heads. This pump is usually used for relatively high volumes and low pumping heads. For static heads above 75 m, multistage pumps as shown in Figure 109 are used.

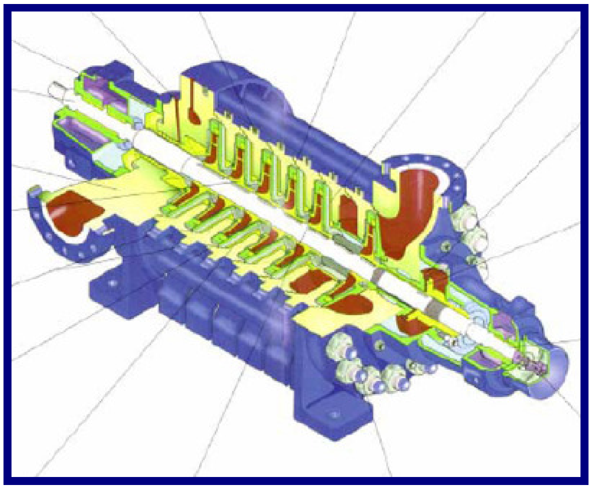


Figure 109: Crosscut of a typical multistage centrifugal pump

A multistage pump can consist of up to 12 stages, and is possible to deliver a flow at heads of up to 1000 m. These pumps are specifically designed for mine dewatering applications. Their robust construction is designed to combat the highly abrasive environment in which they operate. Extensive use of replaceable wear surfaces (such as the balancing disk) ensures that the pumps can be maintained in a good as new condition without requiring extensive replacement of essential parts [74].

A.2.3 High tension motors

Due to the high volumes of water that must be pumped great heights, large electrical motors must be used to drive the multistage dewatering pumps. Both induction and synchronous motors are generally used in the mining environment.

The three-phase induction motor is widely used in industrial and mining applications. No excitation is required. A well maintained induction pump usually has a power factor rating of more than 0.8 [46].

Synchronous motors provide constant speed operation, power factor control, high efficiency control and are used in a wide range of applications. These motors are ideal for dewatering in the mining environment. Synchronous motors are however more expensive and complex than induction motors. This is because of the excitation of the field current that needs to be set [46].

Due to high electrical costs, as well as extensive maintenance on both multistage pumps and large motors, soft-starters and variable speed drives have been developed to reduce wear and lower electricity costs.

A.2.4 Background on soft starters

Soft starters are designed to provide controlled starting and stopping of Alternating Current (AC) electric motors. This is done by gradually increasing the supplied current to the motor. This reduces the sudden inrush current and high torque problems associated with the startup.

Figure 110 illustrates how making use of soft starters dampens the voltage amplitude and strain.

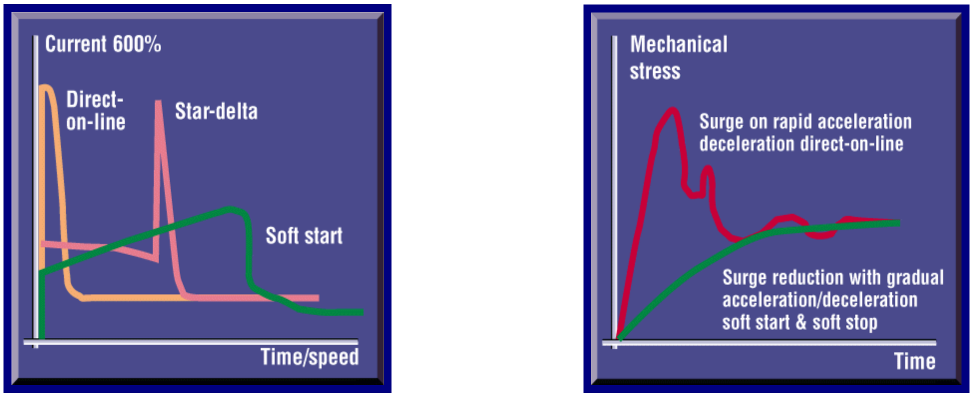


Figure 110: Effect of soft start on the current and stress of a motor [75]

In pumping applications, damage to pipe work as a result of the adverse effects of water hammer can be prevented. Soft start and stopping is particularly useful when pumping fluids at high torques, which often cause water hammer effects.

Advantages and disadvantages of using soft starting/stopping:

Advantages:

- Protects pumps and motors from being damaged.
- Reduces the risk of rupturing pipes and couplings.

Disadvantages:

- High cost.
- Extensive wear on the balancing disk of multistage pumps.

Soft starters are a very expensive solution to reduce maintenance on pumping systems. It is not commonly used in the mining environment and the replacement costs of the balancing disk might reduce savings from other benefits.

A.2.5 Variable speed drives

Variable speed drives are becoming very popular in pumping applications. This drive acts as a soft starter, but can also vary the speed of the motor during normal operations. This characteristic enables the pump to operate at its best efficiency point.

However, due to the great depth of a typical mine pump station, the static head is exceptionally high. In systems with high static heads, the system curve does not start from the zero point y-axis. It begins at some non-zero value on the y-axis that corresponds to the static head. Therefore the system curve is also relatively flat as shown in Figure 111.

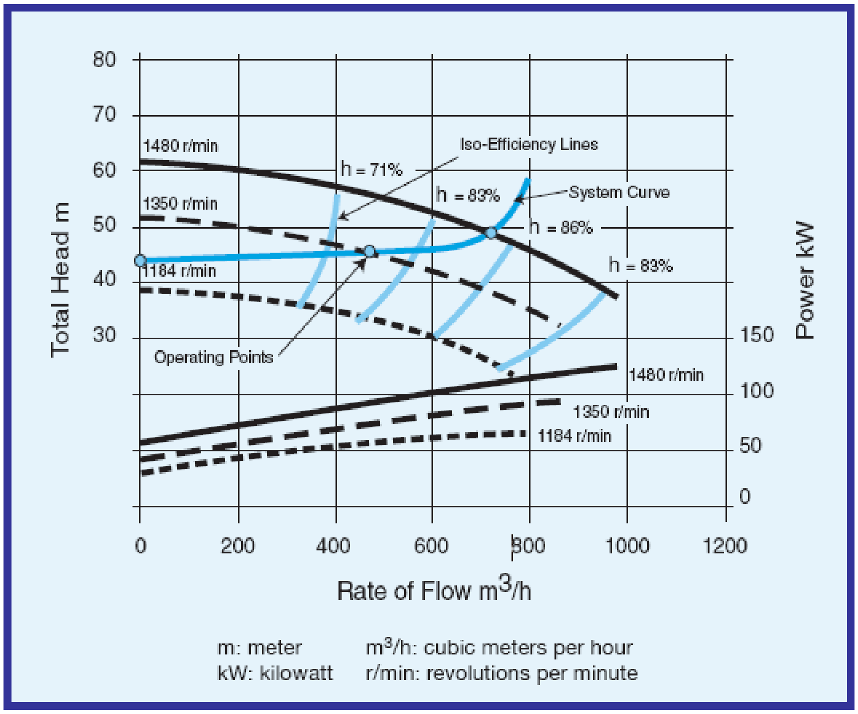


Figure 111: Pump speed change in a high static head application [76]

The reduction in flow is no longer proportional to the speed of the impellers. A small decline in speed greatly reduces flow rate and pump efficiency. This therefore explains that the use of variable speed drives on extraordinary high static heads does not have the same energy savings effect than on high dynamic head applications. Therefore variable speed pumping should not be included in deep mine dewatering.

A.3 Pump system automation

Pump system automation is becoming more acceptable in the mining environment. Reasons are:

- Labour cost savings
- Condition monitoring
- Improved safety
- Better energy management

Several critical instrumentation components are required for pump automation. In this section the most critical components are discussed, which will reduce the cost of automation.

There are a few differences regarding the set standards and minimal requirements before underground pumping systems can be automated. The requirements discussed in this section have been tested and shown to be successful.

Table 29 gives a summary of mine dewatering systems, their running capacity and automation cost. This table shows that the average cost to automate a mine pumping system is R 458 000 per MW.

Table 29: Average dewatering automation costs

Mine	Running capacity (MW)	Automation infrastructure costs	Automation costs per running MW
South Deep	10.7	R 4 300 000	R 401 869.16
Target	1.2	R 500 000	R 416 666.67
Beatrix1,2,3	7	R 4 900 000	R 700 000.00
Cooke1#	2.8	R 900 000	R 321 428.57
Grootvlei	10	R 4 200 000	R 420 000.00
Kloof 8#	5	R 3 000 000	R 600 000.00
Kloof 10#	6.8	R 2 400 000	R 352 941.18
Average automation cost per running MW			R 458 986.51

A.3.1 Communication

One of the necessities for optimum pump automation is reliable communication from the underground pumping station to the surface. This link allows the operation to be monitored from the surface.

Common underground communication mediums are:

- Leaky feeder
- Fibre optic cable
- Telephone lines

The leaky feeder communication is widely used in the underground mining environment. It makes use of a cable that emits and receives radio signals similar to a normal antenna. Underground conditions limit the line of sight range when using wireless communication. Therefore the leaky feeder comes in handy. But due to its limited bandwidth and slow speed it is not recommended for real-time management systems.

The best solution for underground communication is the fibre optic cable. This is cheaper than the copper cables used for telephone lines. Figure 112 shows a typical fibre communication layout connecting the underground levels with the surface control room.

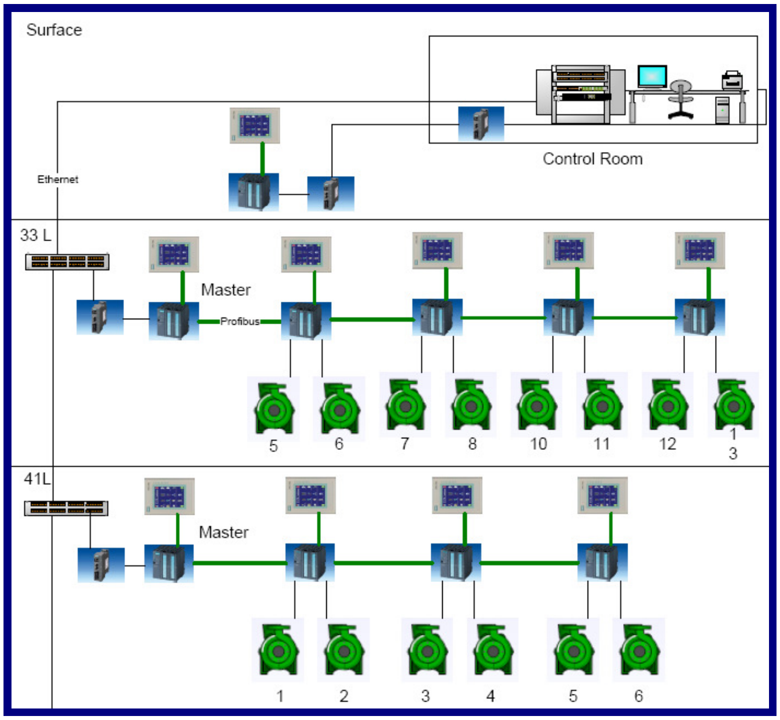


Figure 112: Typical fibre optic network layout

A.3.2 Field instrumentation

Field instrumentation refers to the metering of, for example temperatures and pressures, at specific locations of each component of a dewatering system. These measurements must conform to certain restrictions for the system to operate successfully.

Figure 113 indicates where these measurements are located.

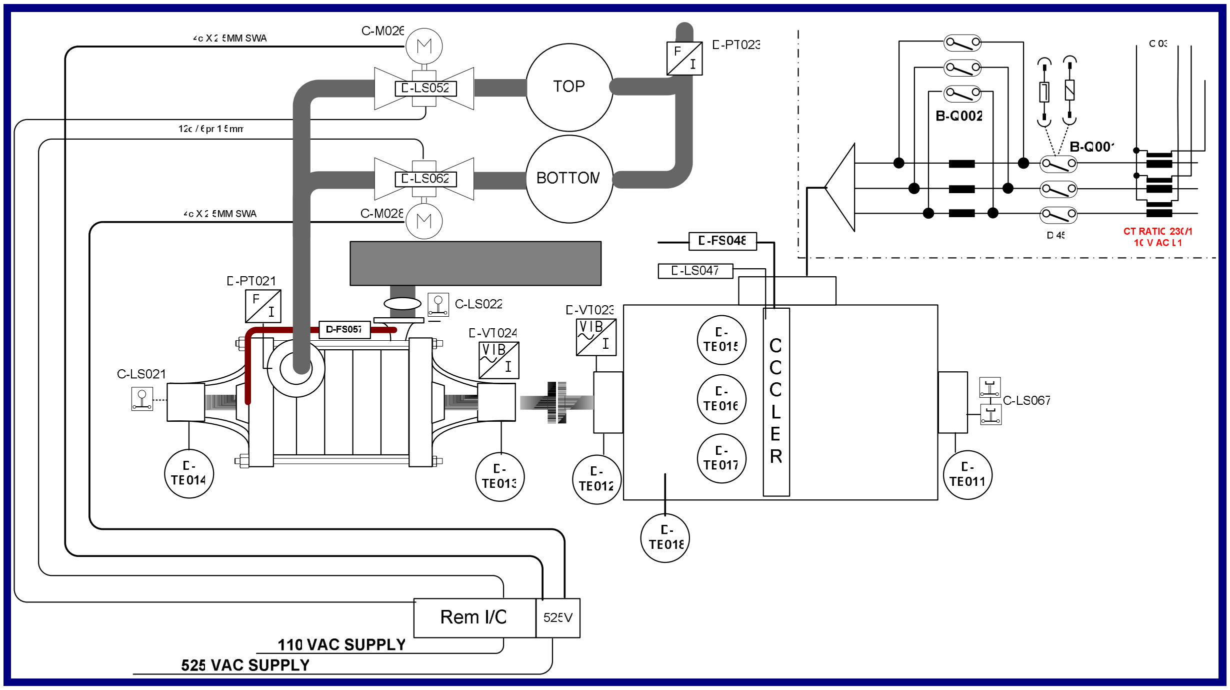


Figure 113: Instrumentation layout of a pump

- The non drive end motor bearing temperature- (TE011), drive end motor bearing temperature- (TE012), non drive end pump bearing temperature- (TE014), and drive end pump bearing temperature (TE013) sensors could indicate worn bearing or shaft misalignments.
- Three motor winding temperatures (TE015, TE016 andTE017) could indicate an overheating motor.
- Pump vibration (VT024) and motor vibration (VT023) could identify possible pump or motor failures.
- Suction valve open/close switch (LS022) indicates the status of the valve.
- Proximity switch on discharge valve (LS052) (LS062) indicates position of valve.
- Discharge column pressure (PT023).
- Balancing disk switch (LS021) indicates worn disk.
- Oil/Water cooling flow (LS047) indicates whether cooling fluid is circulating.
- Switch gear healthy.

A.3.3 Control philosophy

Figure 114 is a flow diagram indicating the typical sequence checks that must be met, and controls required before a pump can be stopped or started. These actions are usually programmed into a Programmable Logic Converter (PLC). If for some reason one of the actions cannot be executed, the complete programme sequence is aborted and the pump stopped. This is done to prevent or limit any further damage.

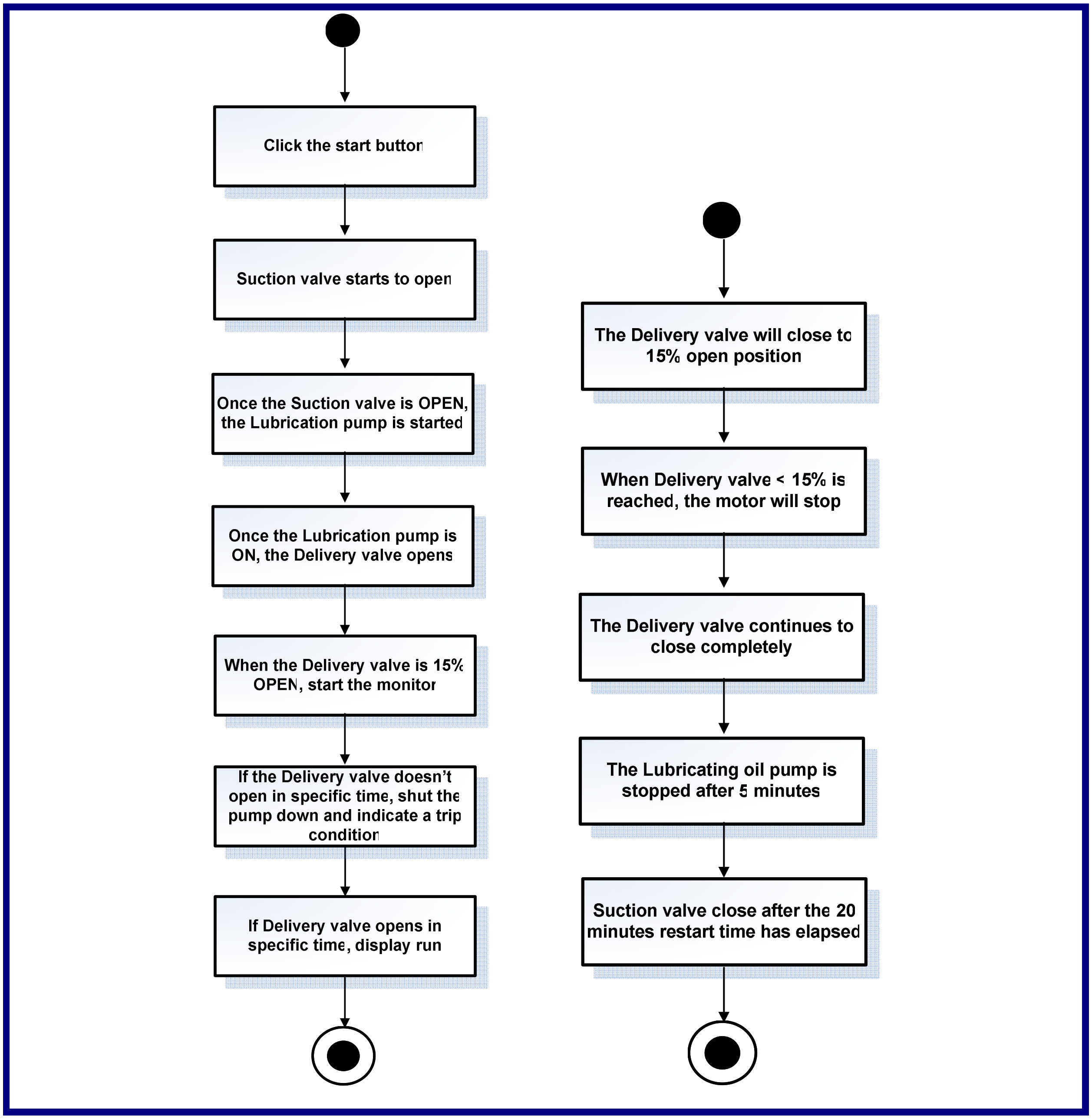


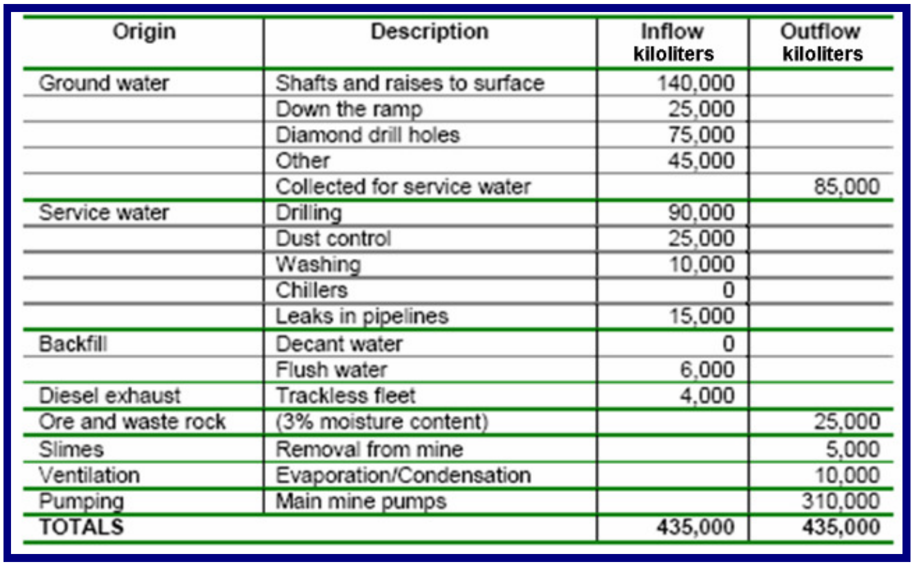
Figure 114: Start and Stop sequence of a typical mine automated dewatering pump

A.4 Underground mine water supply

Table 30 gives the information required for an underground water table. Setting up a water balance table is an essential task that must be performed so that water sources and the amount of underground water usage can be defined. In some regions it might be that less water is pumped during the winter months due to the annual rainfall pattern. This requires that two separate balances must be compiled.

The main water source in the water reticulation system is ground water. Service water that is used for drilling, dust suppression and washing also adds to the volume. Table 30 shows how a typical water balance can be set up.

Table 30: Underground mine water balance



Origin	Description	Inflow kiloliters	Outflow kiloliters
Ground water	Shafts and raises to surface	140,000	
	Down the ramp	25,000	
	Diamond drill holes	75,000	
	Other	45,000	
	Collected for service water		85,000
Service water	Drilling	90,000	
	Dust control	25,000	
	Washing	10,000	
	Chillers	0	
	Leaks in pipelines	15,000	
Backfill	Decant water	0	
	Flush water	6,000	
Diesel exhaust	Trackless fleet	4,000	
Ore and waste rock	(3% moisture content)		25,000
Slimes	Removal from mine		5,000
Ventilation	Evaporation/Condensation		10,000
Pumping	Main mine pumps		310,000
TOTALS		**435,000**	**435,000**

A.4.1 Pressure Reducing Stations or dissipaters [24]

Some deep level mines reach depths of up to 4000 m below surface. High pressures are created with these depths. The shaft column pressure must be reduced before water is used for services or cooling as seen in Figure 115.

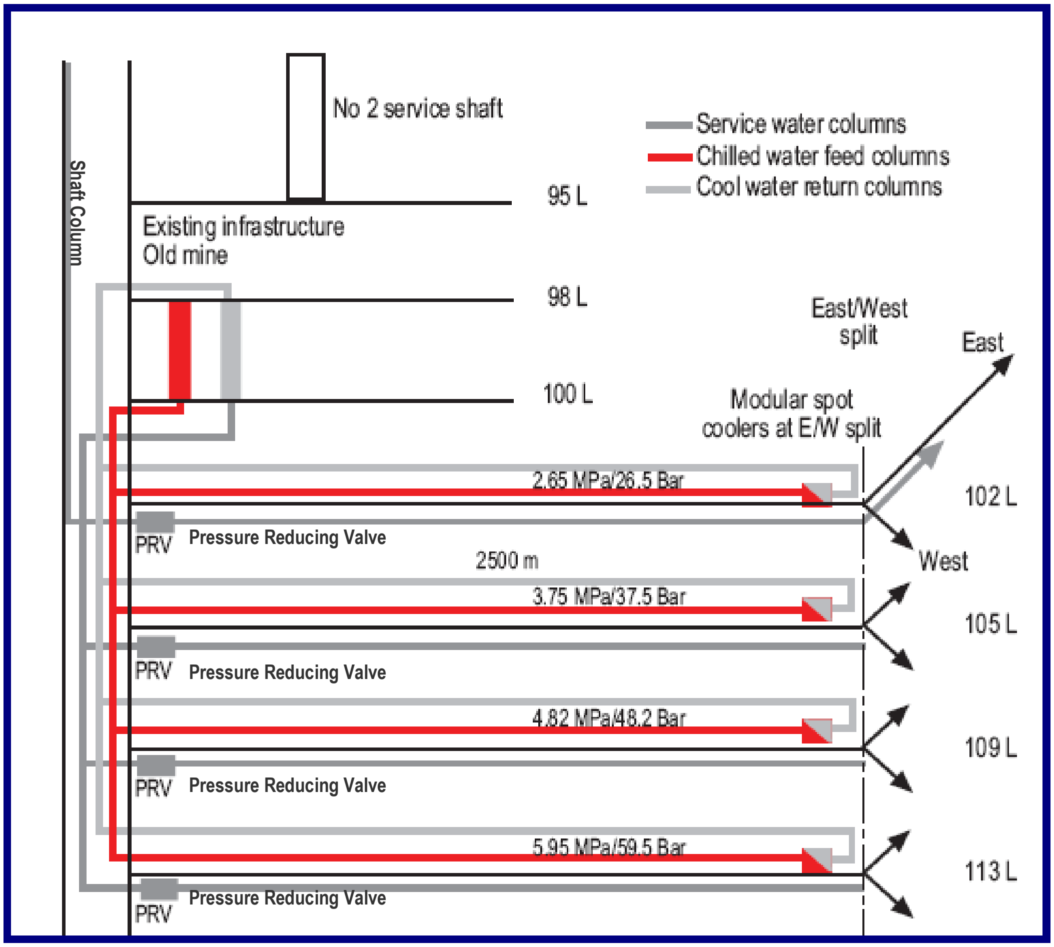


Figure 115: Mine water layout of the "New Mine" at Elandsrand

A dissipater or pressure reducing station is installed on each main section and reduces the upstream pressure of a particular station to the required downstream pressure. This is done irrespective of the flow rate through the station. A main pressure reducing station consists of a running leg and a standby leg, as shown in Figure 116.

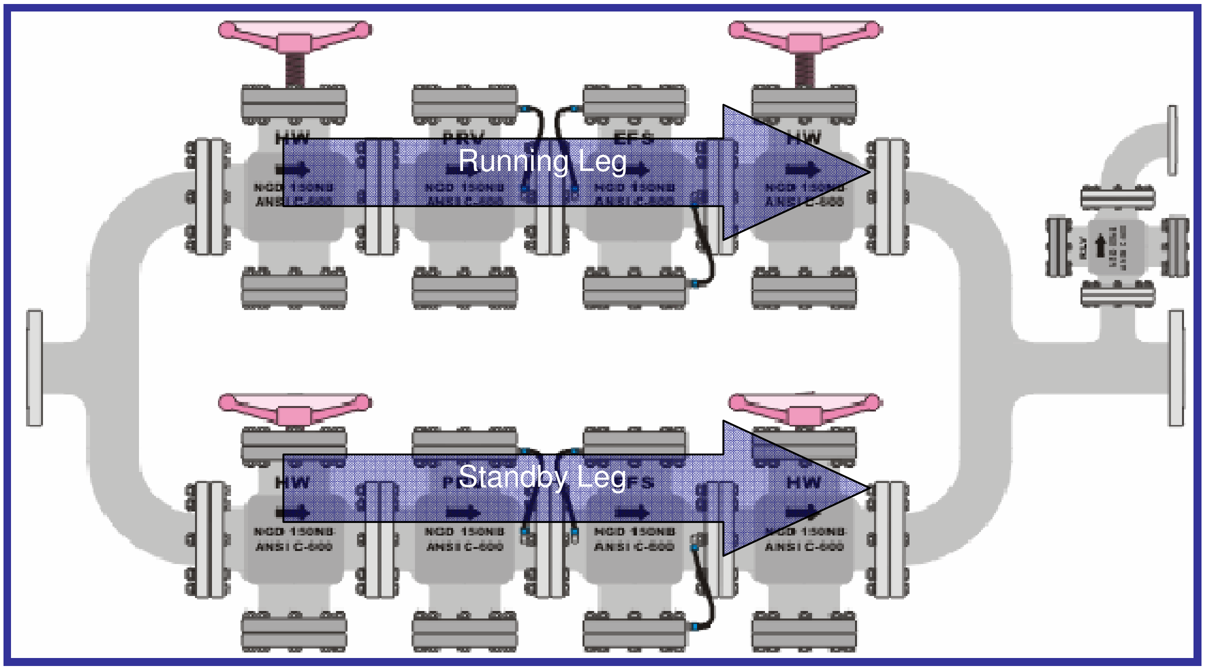


Figure 116: Typical configuration of a pressure reducing station

To reduce the high column pressure, the pressure reducing stations reduce the high water pressure by converting the gravitational potential energy into thermal energy. This would result in an increase in the underground temperature in the vicinity of the pressure reducing station. Therefore, a more efficient solution was required. This system is more complex and will be described in the following section.

A.4.2 Turbines

As previously explained, cold water is fed underground for cooling and daily services. The water is gravity fed to the various underground levels. However, the energy cost to pump this water out of the mine is very expensive. Fortunately the potential energy of this water can be partially recovered and used to power other equipment [57].

If no work is performed on the water that is fed underground, the major part of the potential energy is converted to heat. Therefore the water that is primarily used for cooling is now being heated.

Recovery of potential energy through hydropower principles is well known. Hydroturbines, such as an impulse turbine, can produce a significant amount of energy. Up to 85% of the potential energy can be recovered to perform useful shaft work. [77].

The equipment should also be located near the cold water reservoir, as this position will realize the maximum potential energy. This system must be provided with a bypass pipeline so that the turbine can be taken off-line without influencing the mining operation.

Turbines can be used in different types of generator configurations. The turbine-generator configuration shown in Figure 117 is one of the simplest configurations of energy recovery.

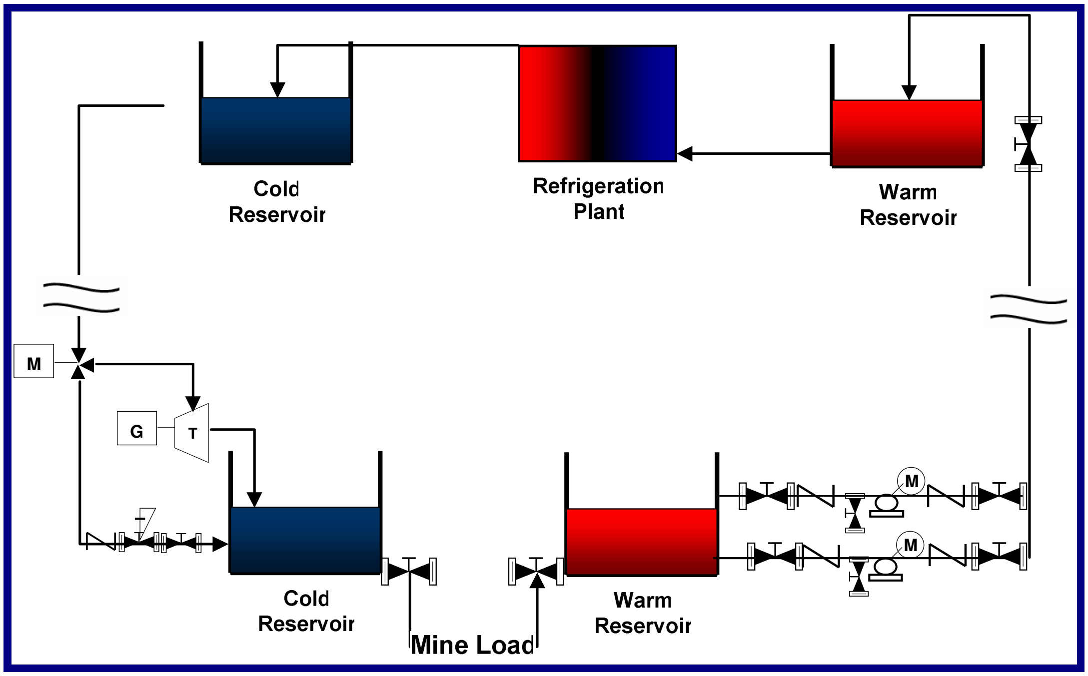


Figure 117: Turbine-generator configuration

The electricity produced from the turbine driven generator can be fed back into the Eskom electricity grid. Special equipment must however be installed to regulate the energy recovered and returned to the grid. This might seem as the simplest solution, but due to the penalties imposed by Eskom on the client for regenerating electricity back into the grid, this might not always be economical. If electricity is regenerated into the national grid, it is seldom done without a slight phase difference from the national grid. This therefore influences the harmonics and quality of the national grid. Another turbine application is the turbine-pump system, shown in Figure 118.

The turbine drives a pump that is connected to the underground hot water dam. This dam is more or less on the same elevation as the cold water dam. In effect the turbine converts the energy from the lower head, or return a lower flow rate all the way back to the surface.

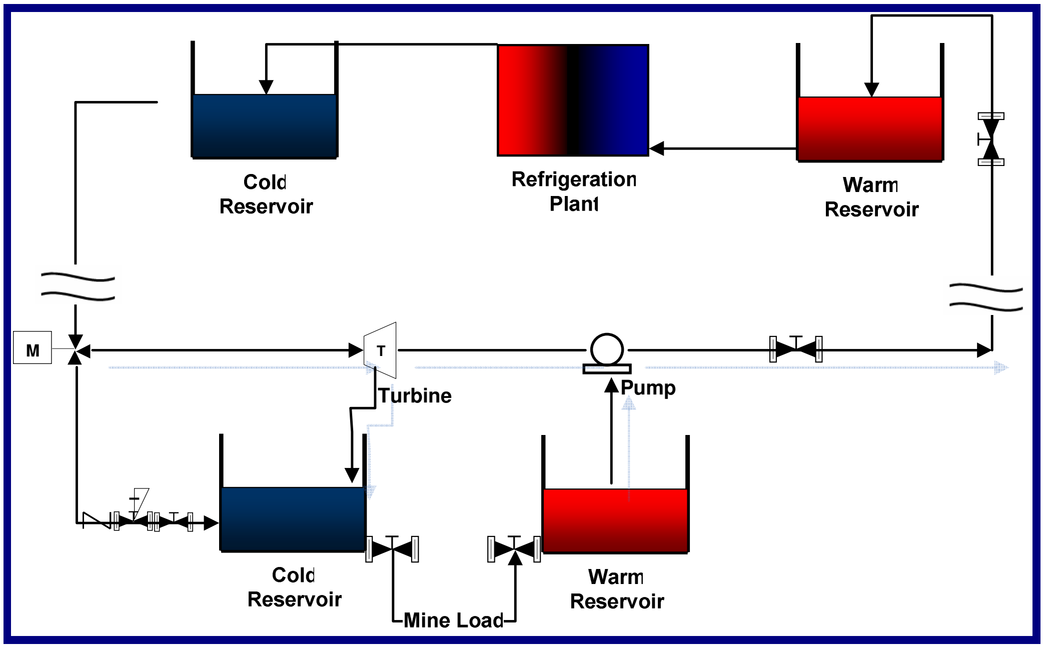


Figure 118: Turbine-pump configuration

A.4.3 Three Chamber Pipe System (3-CPS) [12]

The three-chamber pipe system (3-CPS) or 3-pipe system was introduced to South Africa in the early 1990's when it was installed at Tshepong Gold Mine in the Free-State. Initially the mine experienced serious maintenance problems. These problems have been overcome and the system is presently operating at an availability of more than 90%.

A hydropower equipment company is presently implementing the 3-CPS. This is being done in conjunction with Eskom through its DSM-programme at three mining sites. These projects have the potential to save about 157 GWh a year.

Mining companies have only recently come to realise what benefits the 3-CPS can provide. The system is however better suited to mines with pumping depths of at least 600 m. The deeper the mine pumps are situated and the greater the pump volumes, the greater the cost savings will be.

The three-chamber system uses the principle of conservation of mechanical energy. It makes use of the energy generated by the cold water that is fed underground to displace the warm water out of the mine. This principle is illustrated in Figure 119.

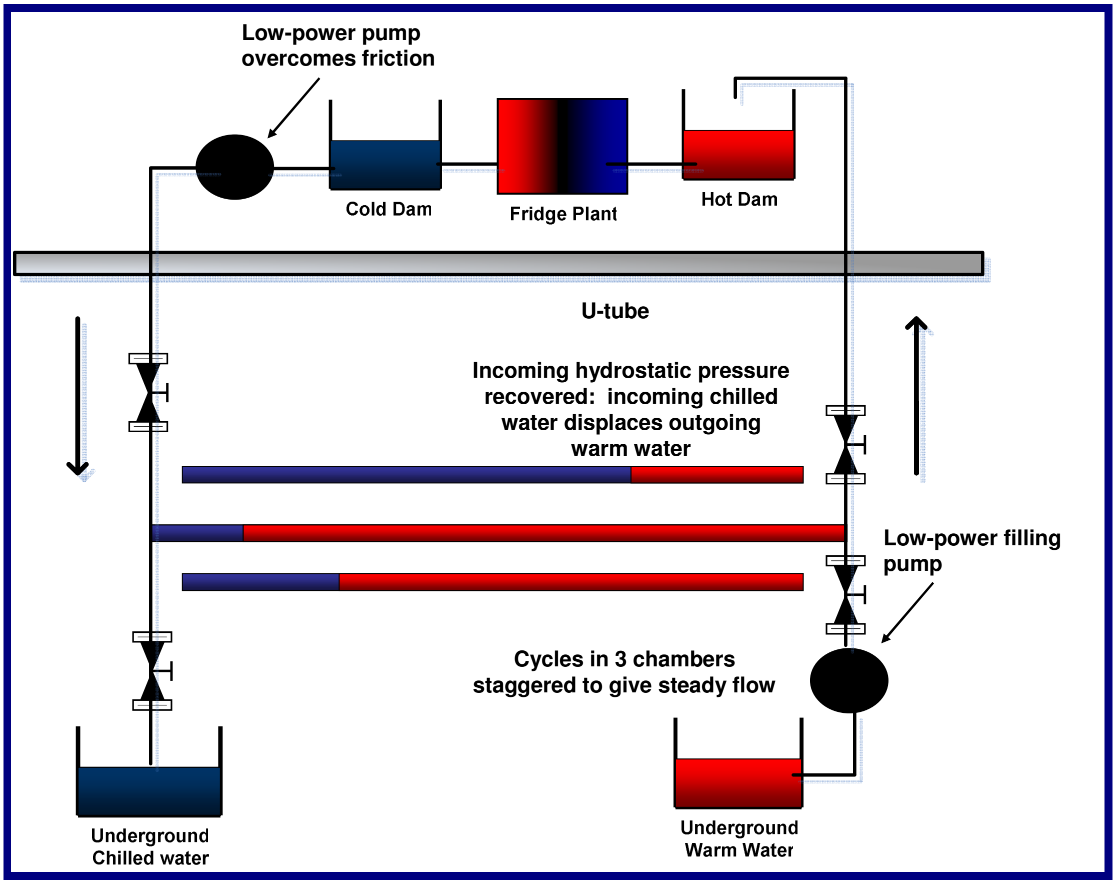


Figure 119: Three-chamber pipe feeder system

This system should complement a conventional pumping system and should be used to reduce the electricity consumption of a conventional pumping system. The 3-CPS results in a significant electrical load reduction on the motors, which also reduces the total electrical pumping cost.

One of the disadvantages of the 3-CPS is that it requires regular maintenance on the valves due to the forces resulting from the 90º change in momentum through the valves. This will increase the operational costs of the system, which is not always taken into account. Another limitation to the system is that the 3-CPS is only operational while water is being delivered from surface to underground levels. Therefore conventional electrical dewatering pumps have to be installed as a backup.

If the 3-CPS is not properly managed and the system does not take other components into consideration, energy could be wasted. A common mistake is to operate the 3-CPS to dewater hot dams when no cold water is needed underground. In this case the energy consumed by the refrigeration plant to cool the water that is fed underground, is wasted.

A.5 Refrigeration system

The manmade heat loads from mining activities which involve vehicles, power system losses and blasting increases the temperature of the underground environment. The depth below ground level is also responsible for the increase in the underground temperature due to adiabatic heating of the air. Factors that add to the high temperatures include:

- Geothermal gradient.
- Hot fissure water in-flow.
- Auto-compression temperature increase of descending ventilation air
- Heating of service and cooling water.

These heat sources combine to create a hot, humid, and unhealthy work environment. In order to maintain a cool, comfortable work environment, these deep mines must be kept cool by artificial means. This is accomplished through refrigeration and the cooling of water that is sent down the mine.

The refrigeration system of a mine is used to reduce the water temperature to a pre-determined set temperature. It also plays an important role in mining, as it has a major influence on the production of the mine. The higher the underground temperature, the less efficient miners work. It is therefore important to provide an overview of the refrigeration component, which forms part of the water reticulation system of a mine.

A.5.1 Background on refrigeration

A schematic representation of a typical water-cooled refrigeration plant is illustrated in Figure 120. The compressed refrigerant enters the evaporator at a temperature T_{ei} in a liquid and vapour state. Here heat transfer takes place and the temperature of the mine water is reduced. The refrigerant exits the evaporator at a temperature of T_{eo} and T_{ci} is entering the condenser as vapour. The condenser towers are installed to transfer the required heat to the refrigerant so that the needed refrigerant temperature (T_{co}) exits the condenser as a liquid.

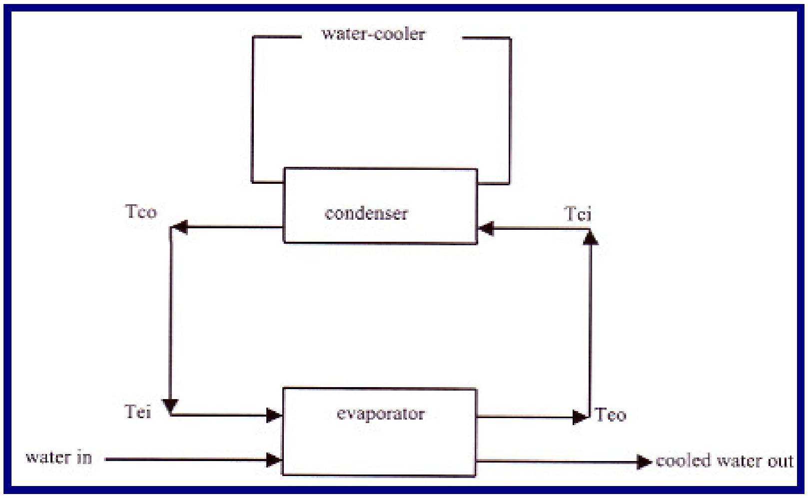


Figure 120: Schematic layout of a water-cooled refrigeration plant [78]

Expansion valves and other equipment like compressors control the pressure and phase state of the refrigerant. The equipment is controlled in such a way that the refrigeration plant supplies the needed outlet water temperature.

Figure 121 illustrates the heat transfer and the equipment associated with the refrigeration process.

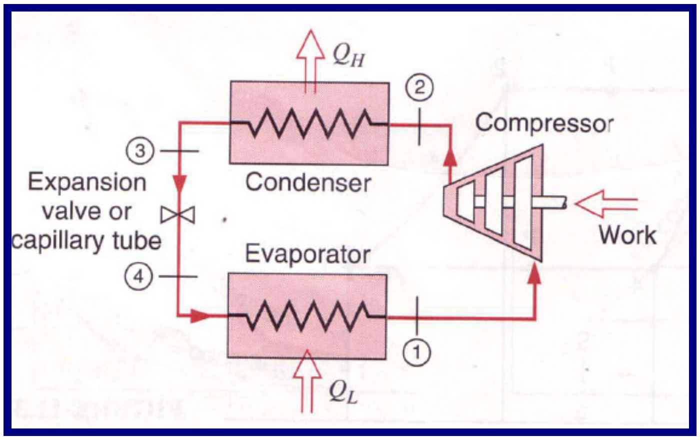


Figure 121: The compression refrigeration cycle [79]

Power is therefore conserved so that:

$$Q_H = Q_L + W \qquad \text{(A1-1)}$$

Where:

Q_L = Incoming heat (kW)
Q_H = Outgoing heat (kW)
W = Work done by compressor (kW)

With the COP defined as:

$$COP = \frac{Q_L}{W} \qquad \text{(A1-2)}$$

The COP determines the efficiency of the refrigeration cycle. A high COP represents an efficient operation. The biggest factor that influences the COP or heat transfer is the type of refrigerant and the condition of the refrigeration plant.

A.6 References

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APPENDIX B: Beatrix mine layout

B.1 Beatrix mine layout