The integrated effect of DSM on mine chilled water systems

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ABSTRACT

Title: The integrated effect of DSM on mine chilled water systems

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The national electricity utility in South Africa, Eskom, is currently under pressure to supply the increasing demand for electricity on a national level. To address this problem in the short term, Eskom partially funds load management and energy efficiency projects.

In the meantime, Eskom is also increasing their generation capacity through the erection of new power stations. To finance these capital projects, sharp tariff increases, higher than inflation, are levied, resulting in higher operating expenditures for the consumers. These increased tariffs are especially affecting industrial institutions. Large industries are therefore willing participants in the partially Eskom funded electricity savings programme that hold benefits for both parties.

One of these large industries is the Mining Sector. This sector is an energy intensive group and consumes up to 15% of Eskom's total output. The refrigeration and pumping systems used in the sectors are two of the major electricity consumers. As part of Eskom's Demand Side Management (DSM) initiative, an electrical energy savings project was implemented in the deep mines' chilled water systems.

The cooling system is optimally controlled to ensure less underground water usage. This ensures that less water is pumped out by the dewatering system, reducing electrical energy usage.

A variety of components, such as refrigeration and energy recovery depend on chilled water to function properly. Every relevant component was simulated and the verification of results was done through correlations with process data obtained from the mine. The simulation results showed acceptable error margins that would not influence accuracy.

Two sites where a water supply optimisations project was implemented were selected as case studies. In both case studies, thermal results of the refrigeration and cooling system showed a reduction in cooling effectiveness. In case study A, the energy recovery components showed negative results. All of the results were converted to electrical energy costs to enable comparison.

Constraints were evident during deep mine water supply optimisation. These were determined and the thermal effects were simulated. This study enabled basic quantifications of environmental impact and also determining project cost savings.

The studies showed that positive and negative effects can be brought on in the mining systems with the reduction in chilled water use. In some cases the cooling system components showed a decrease in cooling effectiveness, but exhibited electrical energy savings. This impact was during periods where no personnel were underground in the working area.

In conclusion the study also showed that cost savings resulting from the reduced chilled water are substantially higher than negative financial losses seen on the other components.

Keywords *: Chillled water, Reduction, Intervention, Deep mining, Cost, Demand Side Management, Simulation*

SAMEVATTING

Titel: Die geïntegreerde impak van DSM op mynwater retikulasiestelsels

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Promotor: Professor M. Kleingeld

Graad: Magistergraad in Ingenieurswese (Elektries)

Eskom, die nasionale elektrisiteitvoorsiener, is tans onder druk om genoeg elektrisiteit te genereer wat die stygende nasionale aanvraag kan bevredig. Om dié probleem in die kort termyn aan te spreek, finansier Eskom gedeeltelik lasskuif sowel as energiebesparingsprojekte.

Terselfde tyd is Eskom ook besig om hul opwekkingskapasiteit drasties te verhoog deur die oprig van nuwe kragsentrales. Om dié groot kapitaalprojekte te finansier is elektrisiteitstariewe skerp verhoog. Die verhoging in elektrisiteitskoste affekteer veral groot nywerheidsinstansies se operasionele kostes. Groot nywerhede neem graag deel aan die Eskom gefinansierde energiebesparingsprojekte wat vir beide partye voordelig is.

Een van dié groot nywerhede is mynbou. Die mynbousektor is ‘n energie intensiewe groep wat tot 15% van Eskom se totale uitset gebruik. Twee van die grootste elektrisiteitsverbuikers is verkoeling- en pompstelsels. As deel van die Eskom DSM inisiatief, is daar energiebesparingsprojekte in diep myne se ondergrondse kouewater retikulasiestelsels geimplementeer.

Die kouewater retikulasiestelsel word optimaal beheer sodat minder water vermors word. Dit veroorsaak dat minder water in die warmwaterstelsel versamel en na grondvlak gepomp word, wat weer tot energiebesparing lei.

Daar is ‘n verskeidenheid komponente wat funksioneel afhanklik is van koue water, soos die turbine- en verkoelingstelsel. Elke toepaslike komponent is gesimuleer en die verifiëring van resultate is gedoen deur vergelykings met data wat vanaf die myn ontvang is. Die simulasieresultate het foutfaktore gewys wat klein genoeg is om nie die akkuraatheid te beïnvloed nie.

Twee intervensies is geïdentifiseer waar ‘n waterbesparingsprojek op die kouewater retikulasiestelsel van die myn geïmplementeer is. Die twee projekte vorm deel van die gevallestudies. Die studies het getoon dat daar ‘n verlaging in die effektiewe verkoeling van sekere komponente plaasgevind het. In Gevallestudie A het die turbine negatiewe resultate gelewer. Al die resultate is omgeskakel na elektriese energiekostes om die vergelyking te vergemaklik.

Daar is van nature beperkinge op die waterbesparingsprojek en met die studie is die beperkinge asook die termiese impak, bepaal. Dit het gely tot die kwantifisering van die omgewingsimpak en die bepaling van kostebesparings.

Die studie het bewys dat negatiewe sowel as positiewe effekte veroorsaak kan word deur die vermindering van koue water op ‘n waterbesparingsprojek. In sekere gevalle het die verkoelingskomponente minder verkoeling gelewer. Dié impak was gedurende die periodes wanneer geen personeel ondergrond in die werk area was nie.

Die gevolgtrekking is dat dit meer ekonomies is om die koue water optimaal te beheer omdat die besparing meer is as die negatiewe impak op die ander komponente.

Sleutelwoorde : *Koue water, Vermindering, Intervensie, Diepmyn, Koste, Aanvraagkantbestuur, Simulasie*

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- If there are any omissions of authors or sources, I apologise. Please inform me in order for me to rectify.

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ABBREVIATIONS

3CPFS	Three Chamber Pump Feeder System
ACP	Air Cooling Power
BAC	Bulk Air Cooler
CA	Cooling Auxiliaries
COP	Coefficient of Performance
CWC	Chilled Water Car
CWC	Cooling Water Car
DSM	Demand Side Management
EE	Energy Efficiency
EEDSM	Energy Efficiency Demand Side Management
ESCO	Energy Services Company
IDM	Integrated Demand Management
IPC	Intermediate Pump Chamber
kl	kilo litre
M&V	Independent Measurement and Verification
NERSA	National Energy Regulator of South Africa
PA	Performance Assessment
PAT	Pump as Turbine
pH	The scale measures how acidic or basic a substance is
PRV	Pressure Reduction Valve
RAW	Return Airways
SCADA	Supervisory Control and Data Acquisition System
VRT	Virgin Rock Temperature
WSO	Water Supply Optimisation

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CHAPTER 1: BACKGROUND

Hydro powered Sibanye Ikamva shaft surface headgear [Photo taken in February 2013]

The use of chilled water on a typical South African gold mine is presented. A discussion on legislation and the environmental management plan is put forward together with previous energy efficiency initiatives on mine chilled water.

1.1 Introduction

In 2013, the National Energy Regulator of South Africa (NERSA) granted the state owned electricity utility, Eskom, an average price increase of 8% per annum over the next 5 years [1]. This will increase the current average price of 61 c/kWh in the 2013 financial year to 83.53 c/kWh in 2016/17 financial year [2]. As a result, South African industries, in particular gold mining's operating expenditure, will increase at a rate greater than inflation. This will exert more cost pressure on an already declining mining sector.

Gold mining in South Africa has always been a very important economic activity [3]. The South Africa economy is highly dependent on mineral resources. Mining exports contribute approximately 50% of the total export earnings [4]. Some 518 000 people are directly employed in the mining and quarrying industry.

Gold mining has seen a steady decrease in production output over the last 30 years. Arguably, the steady decrease in production can be attributed to the increase in operating expenditure due to mining at increasing depths of more than 3000m below surface. As a result, the energy use necessary to mine also increased fourfold from 1970 to 2001 [5].

Gold mining is an energy intensive process consisting of various operations to enable gold extraction from the ore bodies situated underground. Mining services are supplied electricity underground to ensure these operations can be conducted. In a typical gold mine, services such as ventilation and cooling as also dewatering are some of the highest electrical energy consumers. These can contribute as much as 46% of the total average electricity consumption on a typical mine [6]. A breakdown of the large electrical energy consumers is given in *Figure 1* in a typical mine.

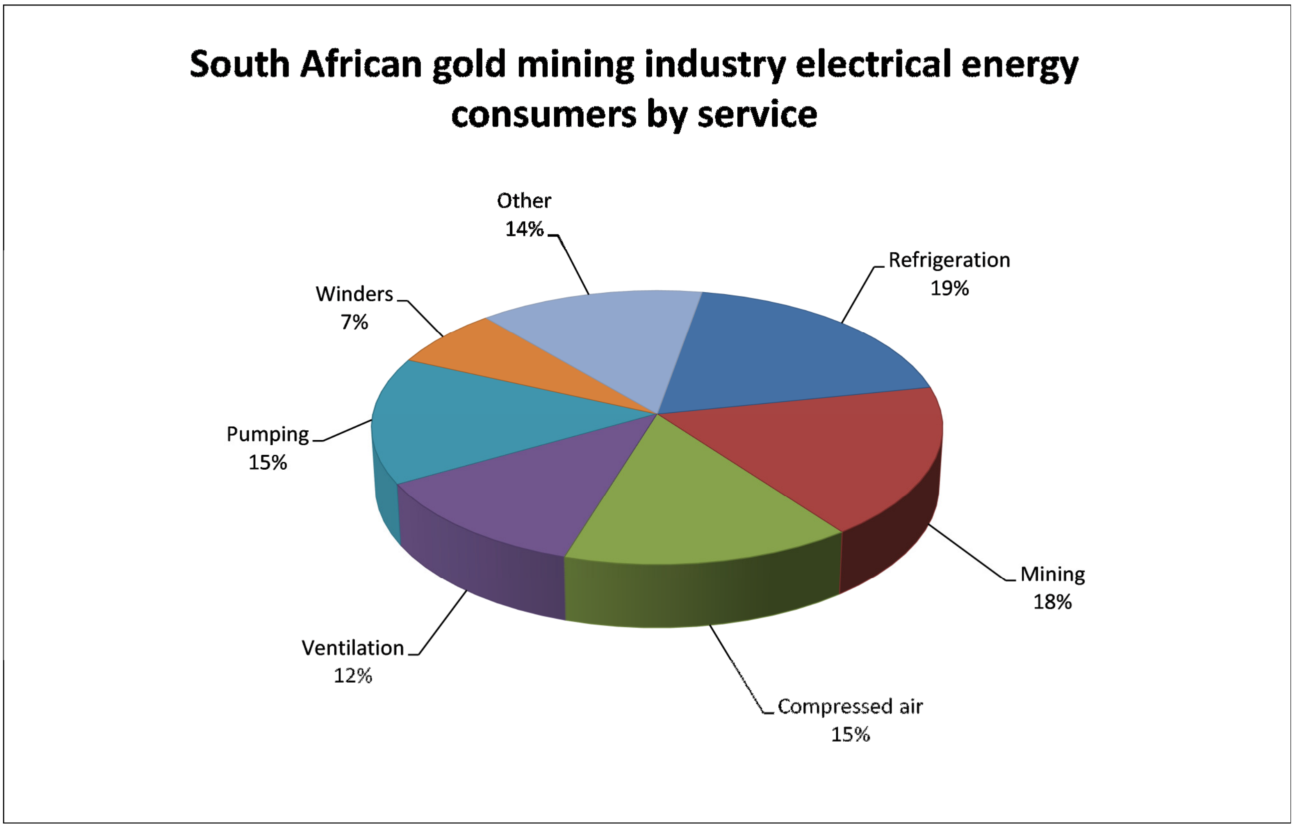


Figure 1: Typical ultra-deep gold mine electricity consumers given by service [6]

Due to their high electricity usage, ventilation, refrigeration and pumping are the main focus points of energy and energy cost savings initiatives. A significant number of Demand Side Management (DSM) projects have been implemented on these services by the state-owned national utility, Eskom. DSM initiatives ensure loads can be predicted and energy/cost savings realised by ensuring electrical energy are consumed in a predictable, yet efficient manner [7].

DSM programs began modestly in the United States of America more than 40 years ago [8]. In South Africa DSM programs were initiated by Eskom in 1992. DSM interventions most commonly used in South Africa can be classified onto three categories, namely:

- **Peak clipping** - Reducing electricity demand during the Eskom peak periods.
- **Load shifting** - Partly shifting demand to less expensive periods.
- **Energy efficiency** – Decreasing electrical energy consumption.

Energy Efficiency Demand Side Management (EEDSM) projects have only recently started to enjoy higher priority [9]. It can be argued that Eskom's current capacity constraint is the reason for the preference and not only a peak demand problem.

Usually, Energy Services Companies (ESCOs) are contracted to implement energy initiatives on client sites and processes. As the name states, ESCOs provide a service to a customer that ultimately reduces electricity demand or at least electricity costs. ESCO services usually include development, design, installation, maintenance, and measurement and monitoring of typical energy projects [10].

One such Energy Efficiency (EE) intervention focusses on optimising the electrical energy usage of a deep mine chilled water system. Chilled water has various uses and numerous mining services depend on chilled water to function. Water is usually cooled by means of a refrigeration plant, either on surface or underground. Thereafter the water is transported in piping reticulation systems to the underground consumers [11].

After the chilled water is used, transportation back to the refrigeration system is required for the cooling cycle to continue. If the total amount of water sent underground is reduced, the amount of water transported to surface is also reduced. This results in positive financial and environmental results [12]. With the reduction in water used underground, savings and incentives can also include:

- Water cost savings.
- Savings associated with treatment of contaminated water.
- Electrical energy cost savings.
- Cost savings due to reduced frequency of equipment usage therefore reducing maintenance.
- Complementing the client's water resource management plan.

Chilled water directly influences operations such as mining, refrigeration, cooling, ventilation, dewatering and even energy recovery systems. Therefore, a reduction in chilled water can only be achieved if it does not affect operations negatively.

Subsequently, a reduction in the amount of chilled water used will not only reduce the operating costs but may in turn compliment the current water resource management plan. These plans are enforced to reduce water wastage and contamination.

As a result of a reduction in electricity demand due to DSM interventions, less pressure is experienced by the national electricity system. This will buy Eskom the essential needed time to increase the electrical output capacity. With the implementation of this type of EE project, careful consideration must be given to the effect on the other water dependant systems. This study aims to determine the impact of a reduction in chilled water on all mining services and operations including energy recovery, ventilation and cooling.

1.2 Water regulations and management in South African mines

In South Africa, the availability of natural freshwater is highly variable and changes with rainfall and season [13]. With relatively low rainfall and high evaporation rates, South Africa is rated within the twenty most water stressed countries in the world [14]. A large amount of South Africa's available freshwater resources had already been allocated to different users. The largest consumer, 62% of the total, is the agricultural sector and more specifically irrigation [15]. A breakdown of the total South African fresh water resource usage by industry is given in *Figure 2*.

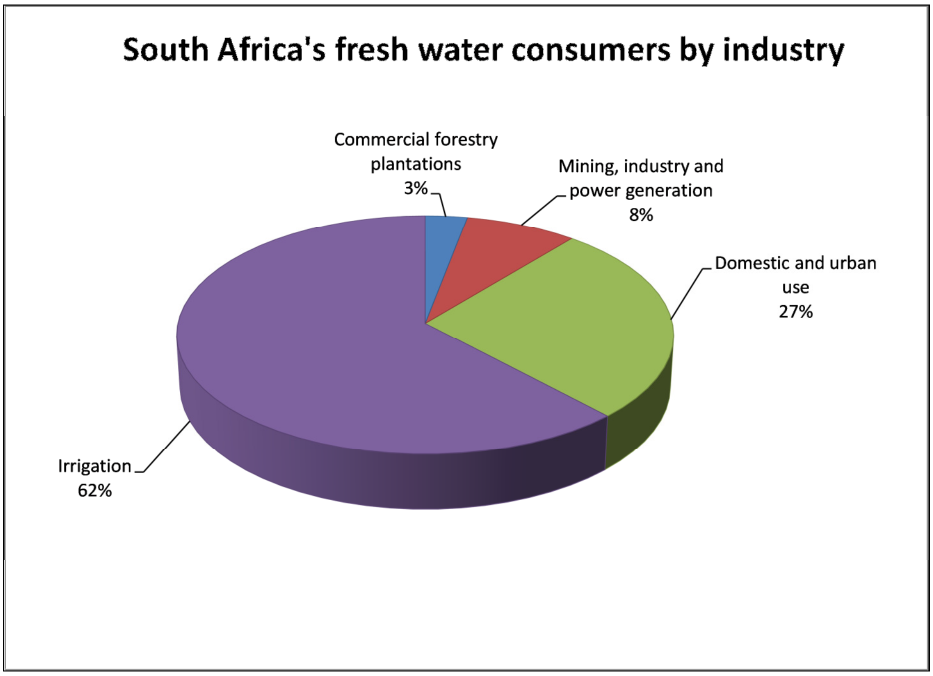


Figure 2: Fresh water usage in South Africa by industry [15]

With regards to mining, a typical deep gold mine in South Africa uses between 2.4 and 4.15 kl of service water to mine one ton of rock [16]. This high demand, with extreme mining depths, contributes to the challenges faced in underground mine water management.

One of the biggest concerns of water management is wastewater. Water used within the Mining Sector is highly susceptible to pollution. Fundamentally water management is governed by the National Water Act and the Water Services Act. The National Water Act (36 of 1998) and the Water Services Act (108 of 1997) deal with water resources and services respectively.

In the past, it can be argued that the laws relating to water resources were discriminatory and not in the best interests of all South Africans. However, this changed largely, with the implementation of the National Water Act (No. 36 of 1998). Major advancements were made in water management, protection, development, conservation and control as management of water resources was transferred to the South African state [17].

With regards to deep mines, the Department of Water Affairs and Forestry (DWAF) developed a series of best practice guidelines pertaining to water for deep mines with a focus on sustainability [12].

Water management in underground mines can be seen as planning, designing, constructing and operating the mine to ensure minimal water usage, maximising water reuse and reduced impact on the water resource. Thus, a typical DSM project that aims to reduce the amount of chilled water consumed underground may be incorporated into the environmental management plant and can result in secondary benefits such as conforming to accreditation or legislation.

1.3 Water utilisation and efficiency improvement

According to world trends, the cost of water and electricity is increasing at an alarming rate, in most cases exceeding inflation by a large margin [18]. In South Africa, this state of affairs coincides with world trends and is further demonstrated by the recent electricity tariff increases approved by the National Energy Regulator of South Africa.

One major industry affected by this increase is the Gold Mining Industry. During the last couple of years, various initiatives were conducted to find efficient ways to mine gold as deep as 5000m with the increasing depth of the gold bearing reefs [19].

Two of the biggest contributors towards electrical energy usage in deep mines are refrigeration and dewatering [20]. These processes are directly affected by the amount of water circulated in the mine. If the amount of water circulated throughout the mine can be reduced, there will be a reduction in electrical energy costs [20]. With the approval of the recent electricity tariff increases, innovative ideas and old technologies have been emphasised as they become more viable. In the following section some of these technologies are discussed.

1.3.1 Energy recovery

One energy recovery device currently in use on deep gold mines throughout South Africa is the Three Chamber Pipe Feeder System (3CPFS). The 3CPFS uses chilled water sent down the shaft to displace the hot used water back to surface [21]. Thus, the potential pressure energy of the chilled water is harvested and used to pump the hot water. The 3CPFS, if utilised, can reduce the electrical energy consumption of the clear water pumping system. This can be attributed to less electrical energy needed due to less operating hours on the pump motors to pump a lesser amount of water to surface.

3CPFS usually has an effectiveness of between 50% and 80% [22]. The effectiveness can be described as the sum of the system efficiencies, availability and utilisation combined to represent the overall system effectiveness. A sustained effectiveness in the order of 80% is difficult to achieve [22]. Nevertheless, in future, the use of a 3CPFS will become more favourable due to the increase in electricity costs.

1.3.2 Energy regeneration

A turbine or pump coupled in reverse, are some of the most common energy regeneration systems found in the South African Mining Sector. The most favourable turbine used in the industry is the Pelton turbine, due to its high efficiency controllability and simplicity [23].

If a turbine is used instead of a pressure reducing valve, the possibility exists for potential savings on the refrigeration system as well. Studies have shown that with chilled water sent down a shaft with a head of 1000m, an average chilled water temperature increase of approximately 2.3℃ can be expected if no energy recovery system is used [24].

If an energy recovery turbine with an efficiency of approximately 70% is used, the temperature will only increase by 0.86℃ [24]. However, the efficiency of a typical turbine is usually much lower. Another problem the Mining Industry faces with regards to large Pelton turbine installations and operations is the lack of support in South Africa.

1.3.3 Ice technology

Usually deep mines use water as the main cooling interface between the surface refrigeration plant and the underground workings [25]. In the cooling system, water is used to absorb heat from various underground heat loads and collected in hot water holding dams. This water is then pumped to the surface to be cooled and reused.

The increasing mining depth increases the pumping delivery head, which in turn increases the amount of electrical energy necessary to transfer hot water to the surface [26]. Thus, if the amount of water sent down can be reduced, the amount that must be pumped to surface is automatically reduced.

This is where the advantage of ice lies over chilled water. Ice or ice slurries has more cooling capacity than chilled water, and can provide the same cooling capacity with less water being used [27]. This reduction in the total amount of water used can result in savings of up to 80% on pumping cost due to less water pumped to the surface. However, one disadvantage of ice compared to chilled water sent down a shaft is the inability of ice to power an energy recovery system such as a turbine.

1.3.4 Ventilation or Cooling on Demand (COD)

With the flexibility of cooling on demand, cooling and ventilation can be increased in areas where mining or development takes place and reduced in other areas where no mining occurs. This potential arises due to conventional mine cooling operation where most mines are cooled using the entire ventilation and cooling system’s capacity all the time [28].

Cooling flexibility ensures more ventilation and cooling can be introduced to certain areas where it will be efficiently consumed. With cooling only taking place on demand, potential cost savings realised can be as high as 10% of the total operating expenditure [18]. Many DSM interventions originate from this basic concept of matching supply with demand.

1.3.5 Recirculation of underground water

Conventionally, in a deep mine, the refrigeration plant is installed on surface. This provides easy accessibility and maintainability as well as heat rejection directly to the atmosphere increasing the coefficient of performance (COP) [29]. The COP of a refrigeration system is a measure of its performance. For simplification, it can be described as the refrigeration effect divided by the rate of compression [30].

However, with the increase in distance from where the water is cooled to the actual point of use, there is a natural decrease in the cooling system effectiveness due to thermal losses. This is commonly known as positional efficiency. As a result, secondary cooling is required in deeper operations and is achieved by installing a refrigeration plant in closer proximity to the point of use, usually underground.

Underground refrigeration plants operate in a unique environment when compared to the surface installations. With underground fridge plant installations, the ambient temperature is mostly higher than surface ambient temperature. This reduces the ability of heat rejection to the return airways (RAW), resulting in a plant COP decrease, and increasing the amount of electrical energy necessary to deliver the same cooling capacity as a plant located on the surface [29].

Refrigeration systems installed underground are usually operated in a closed loop configuration with reduced addition of required “make up” water. Water is cooled underground and sent to strategic positions, used, and then returned to the refrigeration plant for cooling [31]. The result is less water pumped to the surface and a reduction in pumping costs, but capital costs and complexity are added when compared to the traditional refrigeration plant situated on the surface.

1.3.6 Water Supply Optimisation (WSO)

Using water as cooling medium to transfer cold heat to deep underground areas in a gold mine is common practice [11]. Chilled water is transferred to the appropriate users using steel piping, pressure reducing valves, and chilled water holding dams [11].

A Water Supply Optimisation (WSO) DSM intervention can be explained as a reduction in the amount of chilled water sent underground. This is accomplished in periods when no mining takes place. Utilising control valves installed on each mining level's chilled water piping, the water pressure is reduced. This reduces the amount of water flowing into the level in turn reducing the chilled water consumption.

It can only be accomplished in periods when no mining crews require water for production. During a typical mining week, each day consists of either a production or non-production day. The typical mining days are categorised as follows [32]:

- Weekday (normal mining production).
- "Off Saturday" (no mining production takes place).
- "On Saturday" (mining takes place with one shift).
- Sunday (no mining production takes place).

Usually a weekday schedule consists of drilling, blasting, non-entry and cleaning periods in pre-determined times throughout the day. This schedule is mostly used on deep gold mines throughout South Africa. A typical mining schedule over a 24 hour weekday period is shown in *Figure 3*.

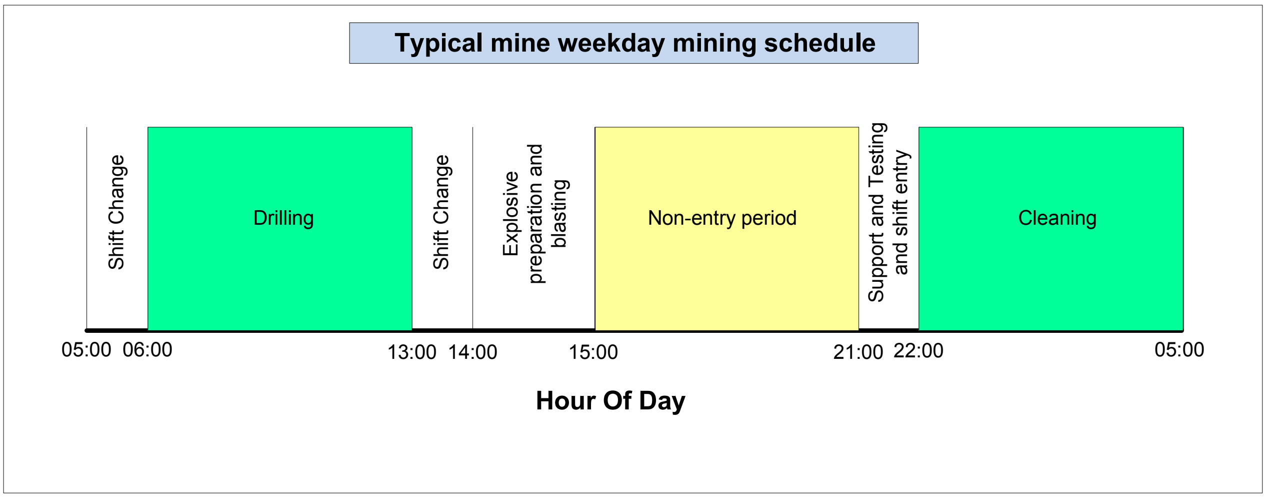


Figure 3: Typical deep mine daily operational schedule

Starting at 06:00 the schedule consist of the drilling shift where mining personnel drill holes in the rock face for the placing of explosives. The drilling shift clears the work area and the explosives preparation teams insert the explosive onto the planned detonation areas. The shaft is cleared and the explosives are discharged. The non-entry period is used to ensure dust settling and suppression before the support team assesses and secures the areas according to standards. The sweeping crews clean and remove the broken rock.

This presents an opportunity to reduce the chilled water during certain periods of the schedule, namely the shift change and more substantially the non-entry periods. During the six hour non-entry period mine personnel will be cleared from the workings and only minimal cooling is necessary [33]. The result is less water demand and less water can be sent to the underground workings.

For simplification, when analysing a typical mining levels flow demand profile, water users can be classified into two groups, namely static or dynamic users. Typical static demand users include Bulk Air Coolers (BAC) and localised cooling units designed to use a fairly constant flow. Chilled water leaks can also be classified as a static demand user due to a constant leakage, depending on the size of the hole and the water pressure in the pipe.

The flow demand of dynamic demand users fluctuates and includes hydro powered drills and cleaning or sweeping crews. Water requirements for these users will vary during the drilling and cleaning periods. This depends also on the type of mining operation and number of crews underground.

Chilled water is supplied from surface to underground via piping and pressure reduction, or pressure control stations situated on each applicable level. These stations can be controlled to reduce the amount of flow supplied during pre-specified periods of the day.

A Pressure Reduction Valve (PRV) station can be used to reduce the pressure during the no entry period. The result is reduction in the flow during this period shown in Figure 4. Note the optimised profile showing a decrease in flow from 16:00 to 22:00.

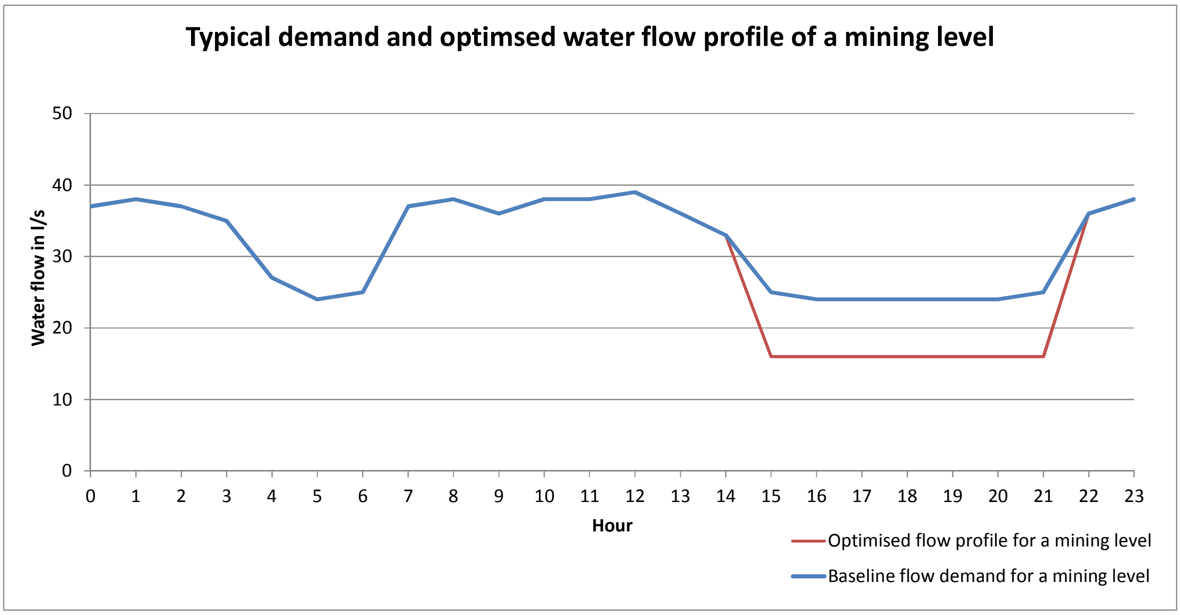


Figure 4: Typical mining level average demand and optimised flow profiles

The optimised flow profile, if implemented, results in less water finding its way into the dewatering system. This in turn ensures less electrical energy is used by the dewatering system to pump this water. One of the main reasons for dewatering the shaft is to prevent used chilled and fissure water from flooding the shaft area [5].

On the mines analysed as part of this study, it was mostly found that production and development takes place on the deeper levels within the mine. It is therefore assumed this is where most of the services such as chilled water are consumed. Most of the chilled water collects on the deepest pump stations and is pumped in a cascade configuration from here to the next pump station until it ultimately reaches the surface. A typical cascade dewatering system on a deep mine is shown in *Figure 5*.

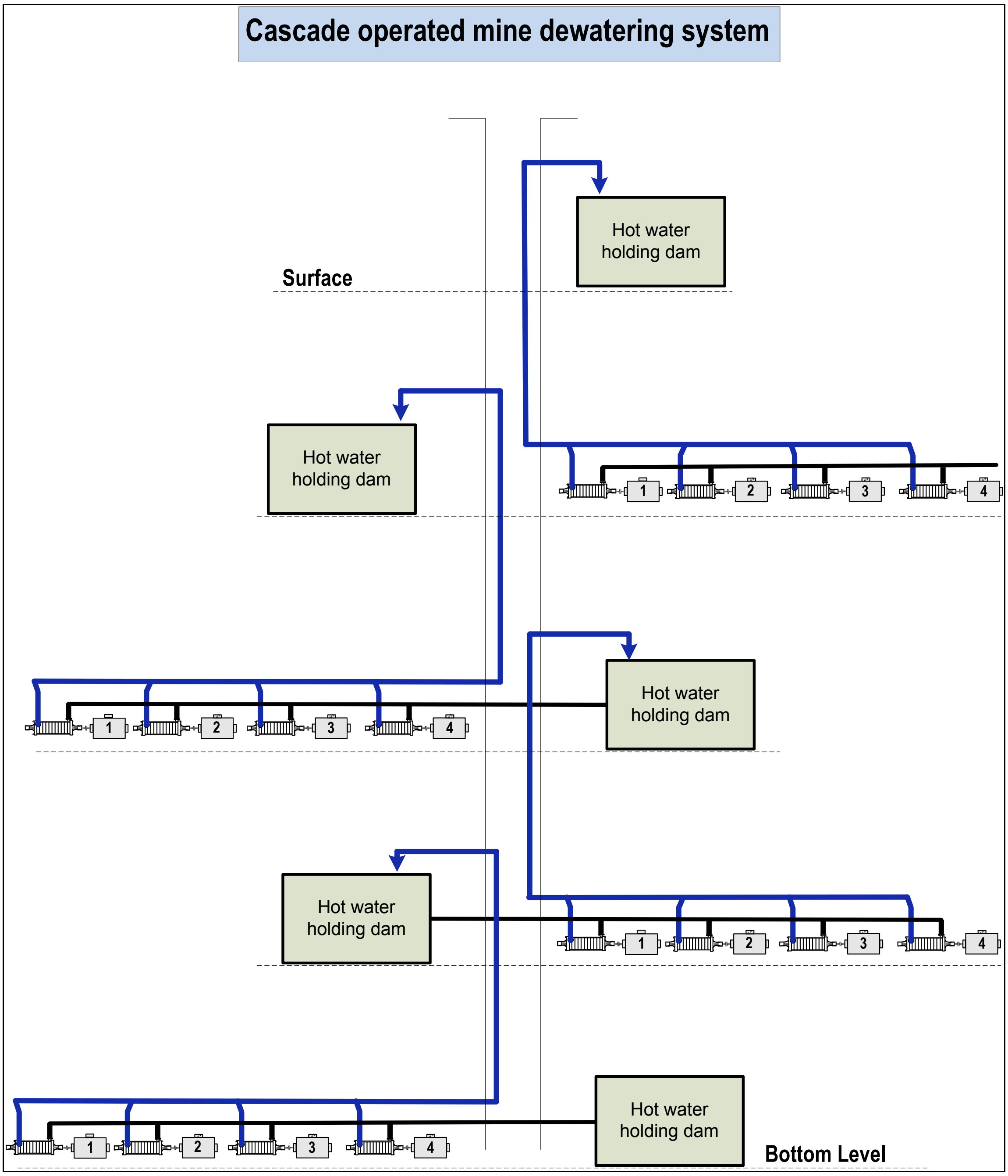


Figure 5: Typical cascade operated mine dewatering system

Another strategy forming part of a typical WSO project intervention is reducing the water leakage on chilled water piping systems. Mines can have chilled water reticulation systems that are highly complex and extensive. Within the workings they are not always well documented. An example of a complex water reticulation system for a single level is shown in *Figure 6*.

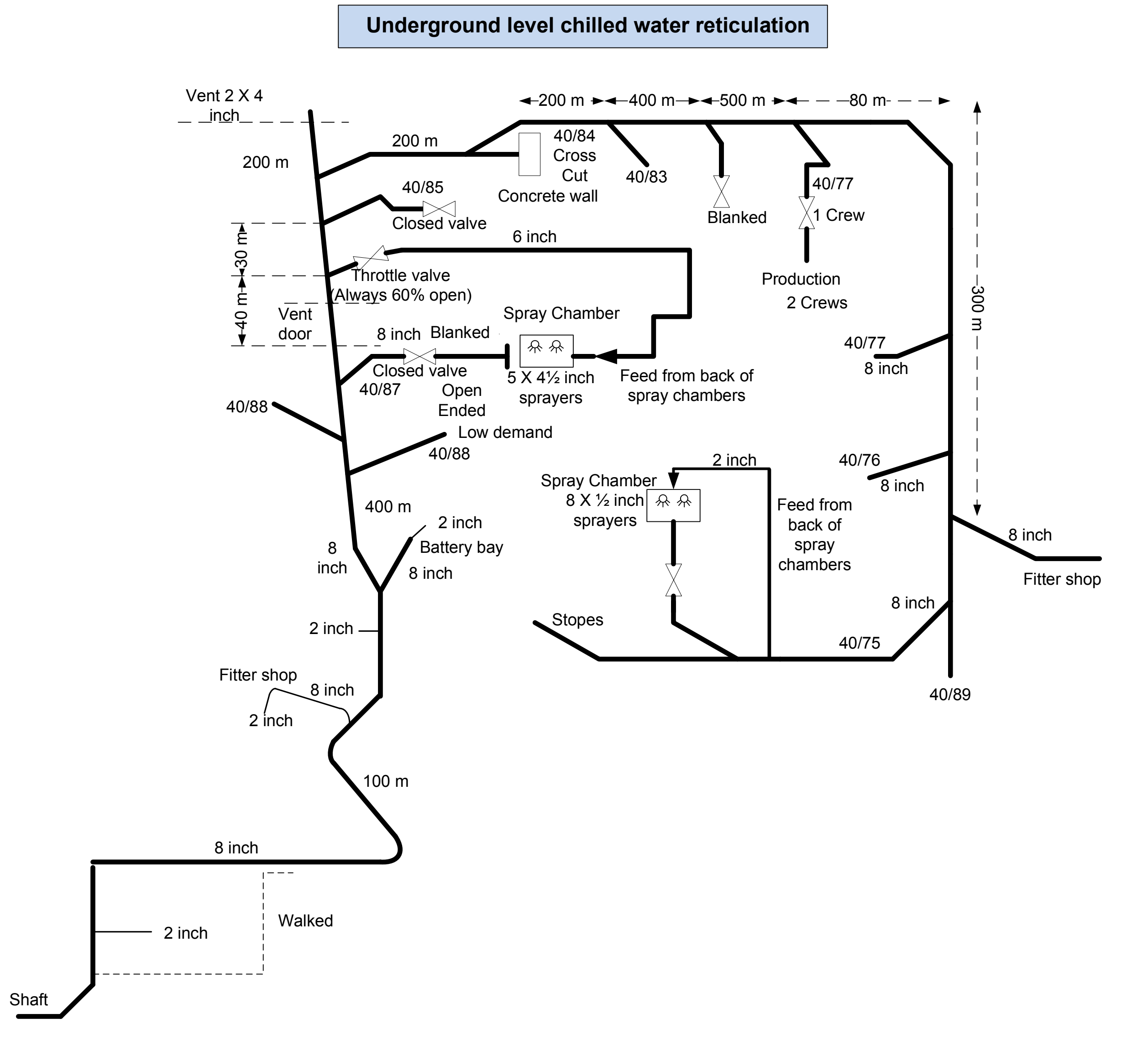


Figure 6: Water reticulation of a deep gold mine production level [34]

It can be seen from *Figure 6* that in this instance, this typical reticulation showing only one level is complex with numerous users and various demands. This increases the potential of finding chilled water leaks or even closed off areas where water is wasted or misused. With a reduction in the supply of chilled water, secondary effects must also be considered such as a reduction in turbine generation output capacity. A discussion on these aspects will follow later in this study.

1.4 Previous research

Research was completed by Botha on the optimisation of a mine water reticulation system to enable cost savings [6]. He concluded that water demand reduction strategies can result in substantial electrical energy savings due to reduced pumping.

At Kopanang, the first of two case studies, Botha determined that by reducing the pressure feeding into each mining level fitted with a control valve, the flow was also reduced. This resulted in an average daily electrical energy reduction of 9.6 MWh due to less hot water that had to be pumped by the dewatering system.

In the second case study, Botha used calculations to determine the impact of the reduction in chilled water on the electrical energy consumption of the dewatering system [6]. Numerous globe control valves and “stope” valves were installed for control and isolation during the non-entry period.

A leak detection and management system was also implemented and tested. In his conclusion, Botha suggested the following areas be investigated for further research opportunities.

- Equipment specific requirements of each individual demand node.
- A possible over performance of the savings and the reason for this.
- The effect of the reduction in water on the refrigeration system.

Vosloo found a reduction in the amount of chilled water to affect the load on the refrigeration plant [32]. He also developed a simulation model to predict optimal operation of deep mine water reticulation system to produce cost savings. He included dissipaters, surface refrigeration plant, dewatering systems and the 3CPFS.

Vosloo however, suggested that the ventilation and cooling be included in a complete simulation model [32], as the effect of the reduction in chilled water on the underground refrigeration, ventilation cooling and energy regeneration systems was not included in his research. The following was left for further study.

- A complete water integration system with the effects on refrigeration plants, ventilation and cooling.
- Ventilation and cooling should be included in the complete water reticulation system.

Murray developed models to simulate and determine the cost of operating a deep mine water reticulation system [35]. These models included a 3CPFS, dewatering system, turbine and dewatering system. However, other critically important systems such as refrigeration, cooling and ventilation were not included as part of his study.

This research aims to continue on work completed by Murray [35], Botha [6] and Vosloo [32] and extend this to other users throughout the mine that is functionally dependant on chilled water.

The areas of research not covered by these three studies will include chilled water cars (CWC), BAC spray chambers, refrigeration and ventilation. Specific attention will be placed on a DSM intervention reducing the chilled water used underground. The WSO project will have secondary system effects researched as part of this study.

1.5 Relation between chilled water and mine heat load

Deep mine cooling is achieved by a combination of ventilation air and refrigeration. The heat load to be removed will determine the amount of ventilation air needed from the fans. This includes the amount of electrical energy required by the compressor motor in order to cool the chilled water [36]. Chilled water is used extensively in cooling systems to reduce the temperature in underground working areas. The cooling system in conjunction with ventilation is used to address the underground heat load.

With large amounts of cooling required to ensure acceptable underground working conditions, there are financial implications. Controlling the underground mining environment conditions in a deep mine can typically account for up to 15% of the total mining costs [37]. If mining depth is increased to 5000m this can increase to as much as 20% [37].

In mining, a number of strategies such as refilling of worked out areas, recirculation of the ventilation air and insulation of walls on the intake haulages are used to reduce the mine heat load [38]. The heat present in a deep mine operation is caused by a number of elements. The main elements are:

- Mining machinery.
- Lighting.
- Fissure water inflow.
- Explosive blasting operations.
- Exposed rock.
- Auto compression (Joule-Thompson effect).

Exposed rock is the biggest heat source in deep mining. In the South African Witwatersrand region, the temperature of rock increases by ambient temperature plus approximately 1 ℃ for every 100m of vertical mining [39]. Exposed rock contributes to approximately 70 % of the total heat load. Heat load contributors are shown in Figure 7.

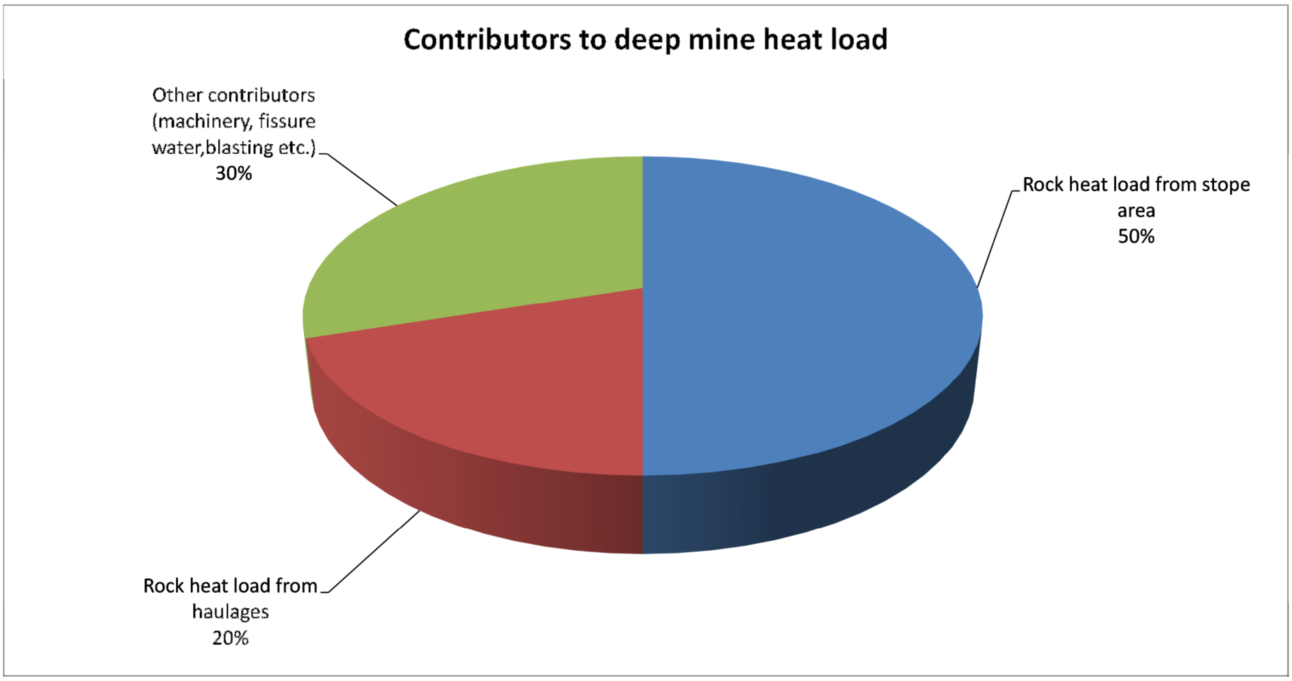


Figure 7: Contributors to deep mine heat load [37]

At extreme depths the mine heat load is removed with a combination of surface and underground cooling with secondary or tertiary cooling, if required. This is combined with cooling of water and distribution to the point of use [40]. If the one element such as cooled water is decreased the other element namely ventilation air temperature or quantity needs to increase. This is to ensure the same amount of cooling is achieved [19].

Underground miners will usually ply their trade in the mine stope area. Focus is placed here to ensure the work area is cooled to remain within the allowable constraints. The cooling contribution for each element in a typical narrow reef mining method stope area is given in *Figure 8*.

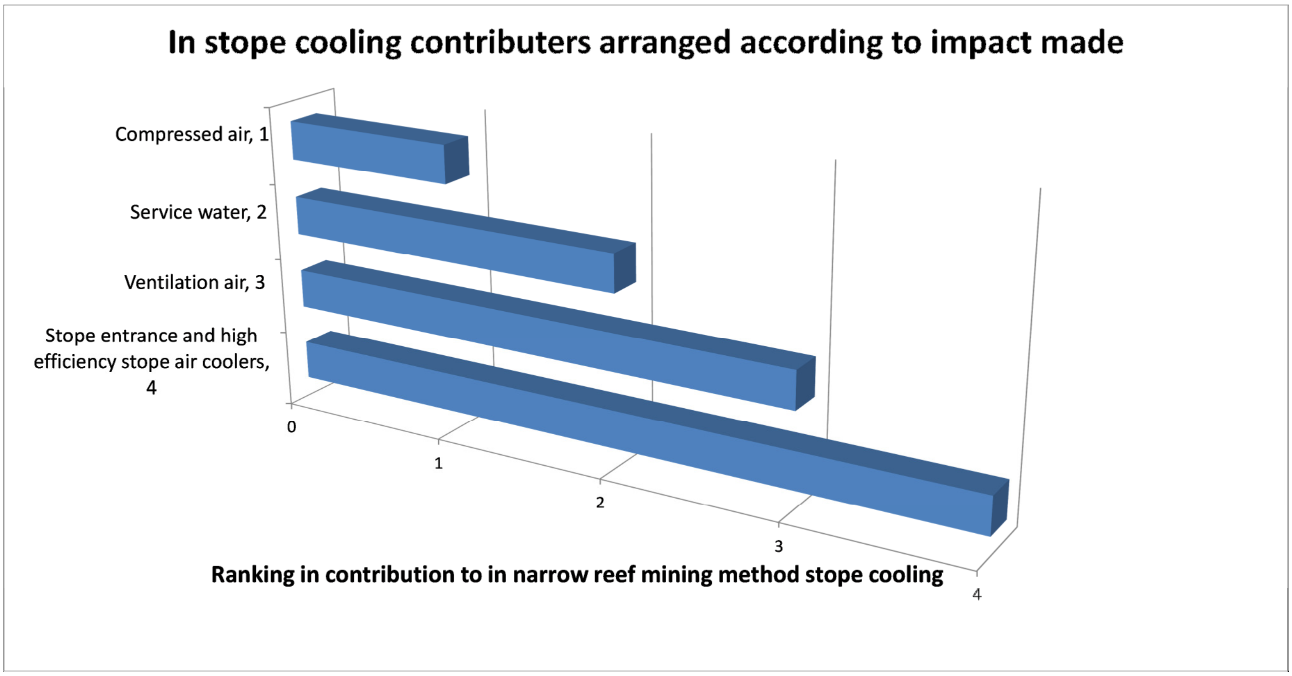


Figure 8: Cooling contributors in typical deep mine narrow reef stope [41]

From *Figure 8* it is evident that water plays a huge role in cooling typical underground stope areas either directly using service water or indirectly via cooled ventilation air sent to the workings or local cooling units.

The effectiveness of the refrigeration and cooling system to remove mine heat load is highly dependent on the amount of chilled water and temperature. If the temperature of the chilled water or the amount of chilled water sent underground is changed, it may influence underground environmental conditions.

1.6 Objectives of this dissertation

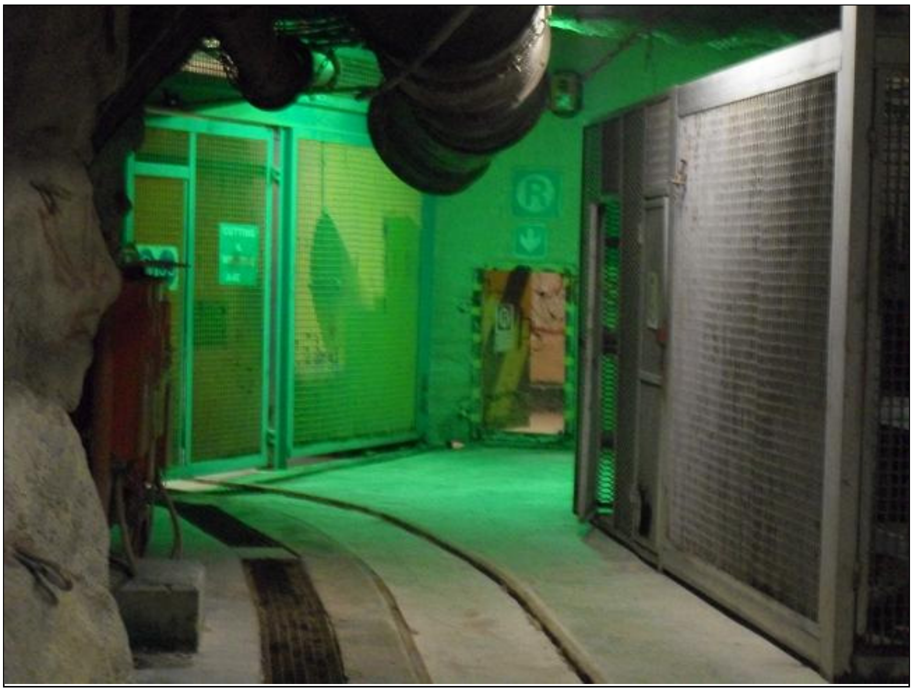
The objective of this study is to determine the integrated effect of a DSM water supply optimisation initiative on all systems within the mine that use chilled water to function. A typical WSO project reduces the amount of chilled water sent underground and results in positive financial implications on the dewatering system. However, the implications of this reduction in chilled water on the thermal and operational environment must be quantified.

This will be achieved by simulating the dependence of the different components on chilled water when it is reduced. Focus will be placed on how the reduction in the amount of water to the underground workings will affect different mining processes such as refrigeration, cooling and ventilation. All systems are analysed from an operational, electrical energy, cost and savings perspective.

The integrated effect on systems such as energy recovery devices, refrigeration and chilled water cooling systems are quantified in order for these effects to be compared. This will be achieved by a detailed investigation into the function of each component and forms part of Chapter 2.

In Chapter 3, the models for each of the components are developed and verified using testing simplified procedures. These models are applied to two case studies that form part of Chapter 4. In Chapter 5 the results from the case studies are discussed and recommendations for further study are made.

CHAPTER 2: RELEVANT CHILLED WATER COMPONENTS



Typical underground refuge bay on a deep level mine [photo by Iritron (Pty) Ltd]

Each component dependant on chilled water to function is discussed as well as a typical water supply optimisation DSM intervention. A model of each system is developed to determine the effect of chilled water reduction.

2.1 Introduction

In Chapter 1 the usage of chilled water and energy efficiency initiatives directly affecting the chilled water were discussed. Completed studies focused on the chilled water system optimisation and the effects on the dewatering pumps, turbines and 3CPFS.

Recommended areas for further study proposed the inclusion of the refrigeration and cooling components, the effects of chilled water reduction on the operation, and effectiveness with the incorporation of the energy recovery and dewatering system.

In this chapter, in-depth research will be conducted on the function of each component and its dependence on the supply of chilled water. Each component is discussed with operational and practical considerations, and mathematically modelled to be used as part of the simulation model.

2.2 Water dependant mining equipment

Deep mine's chilled water demand varies from day to day in accordance with mining and system demands. Chilled water is mostly reused to minimise cost due to the fact that if extra water is required potable water has to be purchased. The basic operation of the water cycle in a typical mine can be explained by referring to *Figure 9*.

In the mining water cycle, at indication A, hot water is pumped from underground to surface at a temperature of 30 to 35 °C. On surface, at indication B, hot water is sent to a pre-cooling tower where the water is cooled down close to ambient wet bulb temperature. This is commonly referred to as free cooling. If the water pumped from underground is warmer than surface ambient temperature, free cooling can be achieved in the pre-cooling tower.

From the pre-cooling tower water is fed to the refrigeration plant, at indication C, which cools the water to approximately 5 °C. At indication D, it is then sent to the surface BAC to cool the ventilation air or routed underground via the chilled water column. Typically, water used in the BAC is rerouted back to the refrigeration plant and sent to an intermediate dam to be cooled and reused.

Due to and depending on the depth of the mine, as the chilled water is sent down the shaft in a column, it increases in pressure to approximately 10 MPa with a head of approximately 1000m. This pressure can be harvested and converted to energy to be used in energy recovery systems at indication E. After the water served its purpose either for cooling or mining it is returned to the hot water circuit at indication F.

The first step in the hot water circuit is the settling process shown at indication G. In the settling circuit, the dirt laden drain water is cleaned by adding specific chemicals. The particles are then separated from the water using the settlers.

From here the water is sent to the hot water holding dams ready to be pumped by the dewatering system at indication H. This water ultimately reaches the surface holding dam where in most cases it is reused.

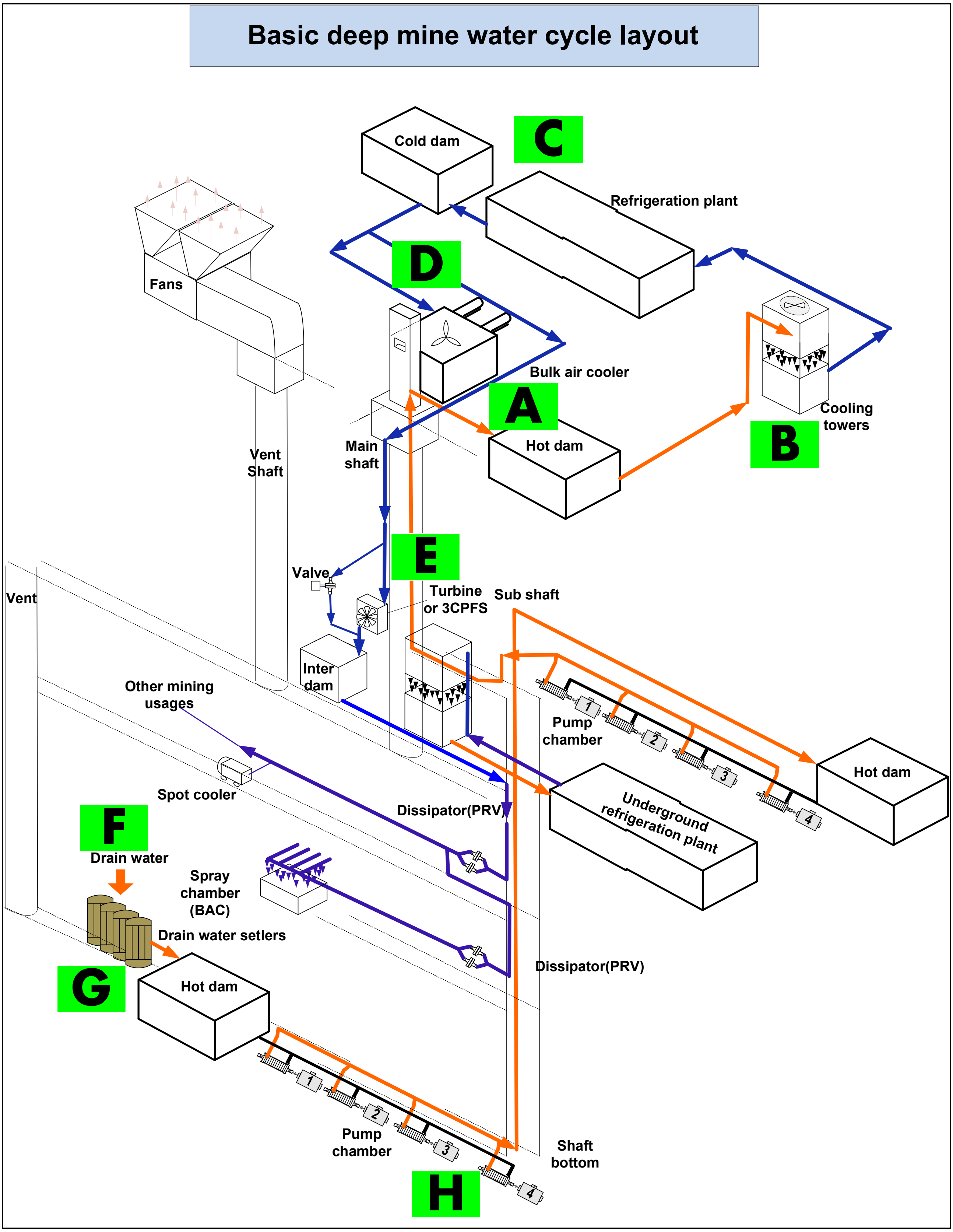


Figure 9: Basic deep mine underground water cycle layout

Numerous other systems also depend on chilled water to function. Some of these items are described in the following section and forms part of the complete mine water cycle. Each of the components discussed can be affected by the chilled service water with key focus placed on system responses.

2.3 Energy recovery

2.3.1 Three chamber pumping system

When cooled water is sent in piping down a mining shaft there is an increase in water pressure with the increase in depth. This pressure can be harvested and converted to energy and is commonly known as hydro power. Hydro power is the term used when water pressure of between 14 to 18 MPa is used to power equipment [42].

One system that uses the potential energy to pump water to surface is a 3CPFS. The 3CPFS works on a U-tube principle with cold water displacing the hot used water in columns back to the surface holdings dams. Though mixing of cold and hot water does take place, it is accepted as the 3CPFS can pump water with minimal usage of electrical energy [43].

A 3CPFS will usually have a dissipater bypass system installed to ensure water can still be sent down the shaft even if the 3CPFS is out of operation. With reference to *Figure 10*, the operation of the 3CPFS can be explained. Chilled water flows down the cold water columns and with the aid of sequential opening and closing of valves, cold water displaces the hot water in chamber C3 into the hot water column flowing to surface. The control system then opens or closes the specific valves to enable the replacement of the cold water in C3 with hot water and the operation is repeated. To account for losses, filling pumps are used to pump water to the respective dams to ensure correct operation of a 3CPFS.

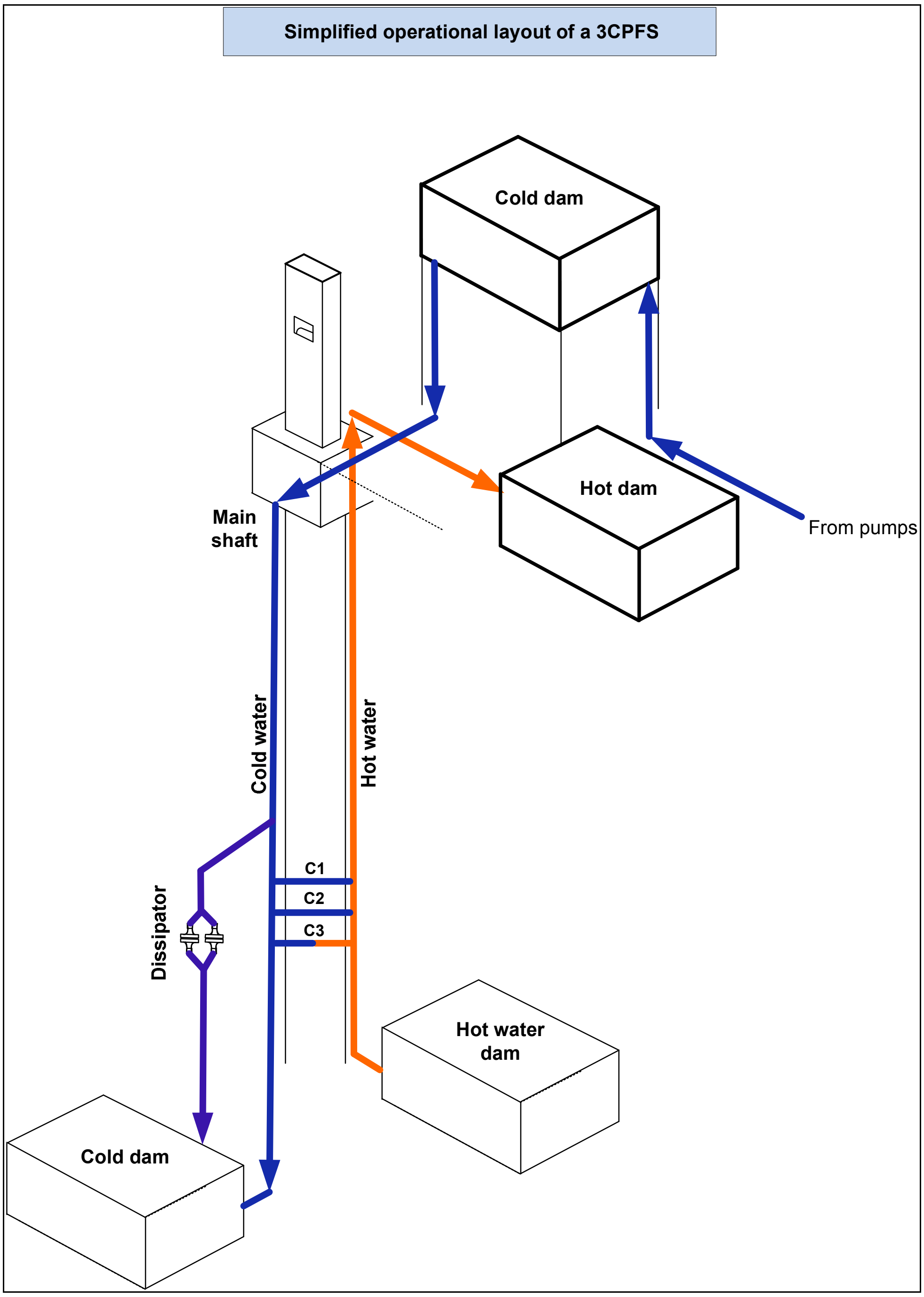


Figure 10: Typical 3CPFS operational layout

Frictional dissipation takes place when chilled water is sent down a water column. If an energy recovery device such as the turbine or 3CPFS is utilised rather than the pressure reduction station, there is less dissipation and a lesser increase in the chilled water temperature.

The 3CPFS has a typical efficiency that is much higher when compared to the typical underground Pelton turbine system of between 40 and 60 %. However, more importantly, the availability and operation of the 3CPFS with regards to chilled water is mostly dependant on the amount of water and levels of the applicable holding dams from which water is pumped and extracted.

Usually, if the 3CPFS is functioning correctly and one of the dam level constraints that forms part of the control is breached, the system will perform a controlled shut down. A typical 3CPFS with the dam level minimum and maximum indications is shown in Figure 11.

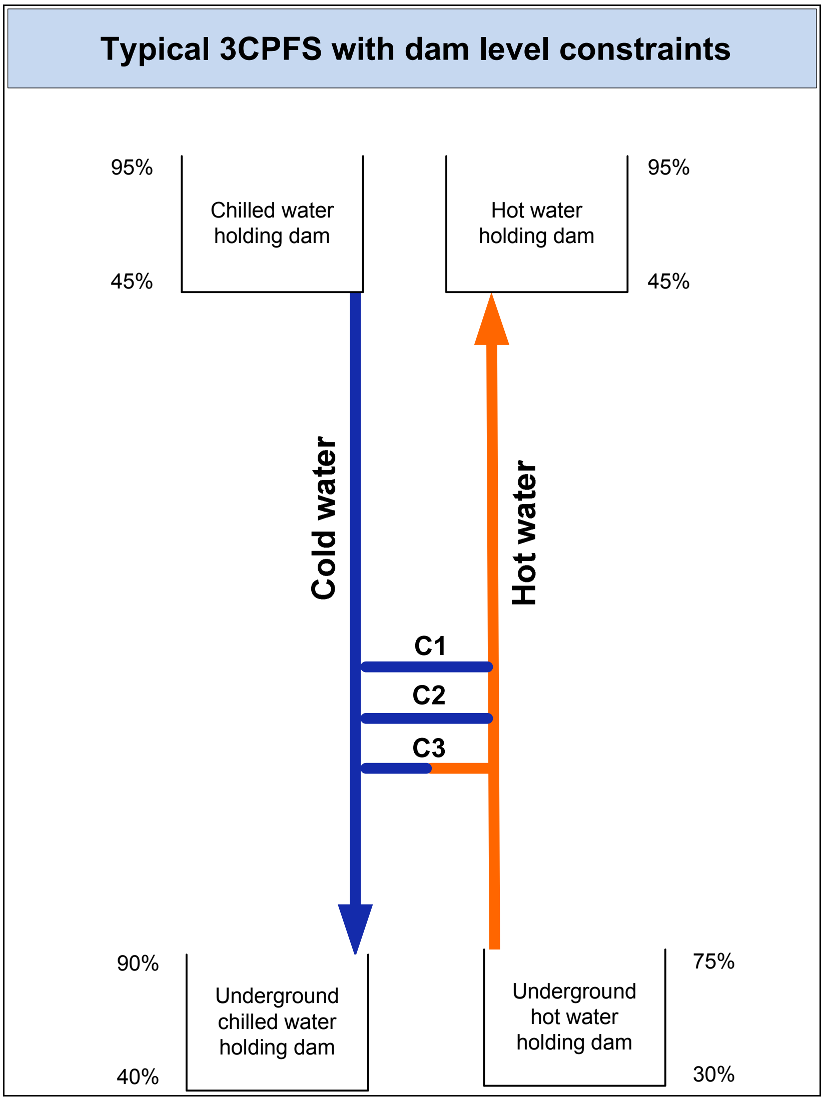


Figure 11: Typical 3CPFS configuration with dam level constraints

If the chilled water and subsequently the water in the system are reduced, it can affect the availability and subsequently the utilisation of the 3CPFS when the dam levels are not maintained within the 3CPFS dam constraints. This operational constraint can influence the utilisations of the 3CPFS. If the chilled water in the mine water cycle is reduced, the influence on the 3CPFS will be minimal as long as the dams are maintained within the control system constraints. With mainly an operational influence the 3CPFS is not modelled as part of this study.

2.3.1 Hydro Turbine

Another energy recovery system commonly found in the mining industry is the hydro turbine. Turbines are specified and used according to the head of the water and the typical available flow. The most commonly found turbines are the Pelton wheel, Francis and Kaplan turbine. These turbines can be used in almost all applications covering most types of heads and flows. [44]. An application breakdown of the three common turbines types are given in *Table 1*.

Table 1: Three main types of turbines and their application

Description	Francis Turbine	Kaplan	Pelton Wheel
Head (m)	20 - 900 m	10 - 70 m	200 - 1500 m
Capacity (MW)	Up to 800 MW	Up to 250 MW	Up to 300MW

The Pelton wheel turbine is a favourite found on underground mines. Another commonly found turbine is a reverse running centrifugal pump more commonly known as a Pump as Turbine (PAT). The reverse running pump has a lower efficiency when compared to a Pelton turbine, but the advantage is that mine personnel are familiar with the pump and its operation [45].

The Pelton turbine makes use of water jets discharging high pressure chilled water to atmospheric pressure onto the centre of a spoon shaped bucket. This bucket is placed on the outer circumference of a disk wheel thereby turning the wheel [46]. The bucket splits the inlet water stream and it flows around the two cups and leaves at the bucket sides.

The speed of the water leaving the bucket sides should ideally be zero ensuring all the available energy is completely absorbed by the bucket [47]. If losses are neglected, the optimum Pelton turbine efficiency will be achieved when the water jet hitting the bucket is approximately twice the speed of the bucket [47]. A typical Pelton turbine bucket is shown in *Figure 12*.

Figure 12: Pelton wheel bucket [47]

The turbine is usually connected directly to a generator that generates electrical energy when the disk wheel is turned. To operate at maximum efficiency and constant speed due to direct coupling of the generator, the speed of the turbine must remain constant even under load changes [48]. A typical Pelton turbine found underground is shown in *Figure 13.*

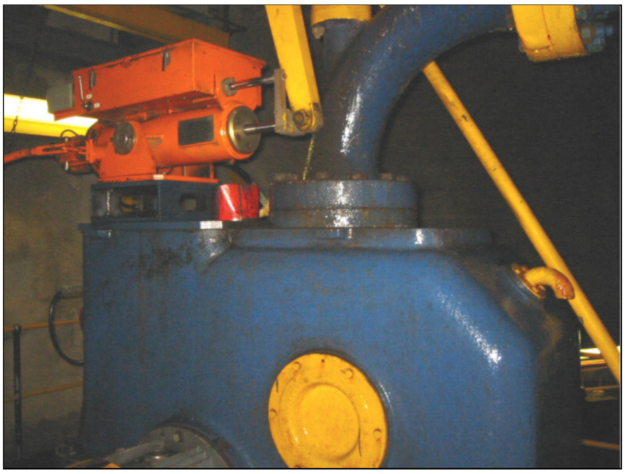


Figure 13: Typical Pelton turbine found underground [photo by D. du Plessis]

Usually a constant head from reservoirs supplies water to the turbine. The input water power to the Pelton wheel is adjusted by changing the flow through the water jet hitting the bucket. This is accomplished using a spear or needle valve. The spear valve moves forward and retracts inside the water jet altering the cross sectional area, thereby increasing or decreasing the flow to the bucket according to the measured load changes. However, the water used to operate the turbine has to be pumped from the mine at a later stage.

Chilled piping installations of a typical turbine usually consist of in-line and bypass valves [45]. Bypass valves are either opened or closed according to the required flow demand of the underground holding dams while at the same time ensuring high turbine system efficiency is maintained. A typical turbine configuration is shown in *Figure 14*.

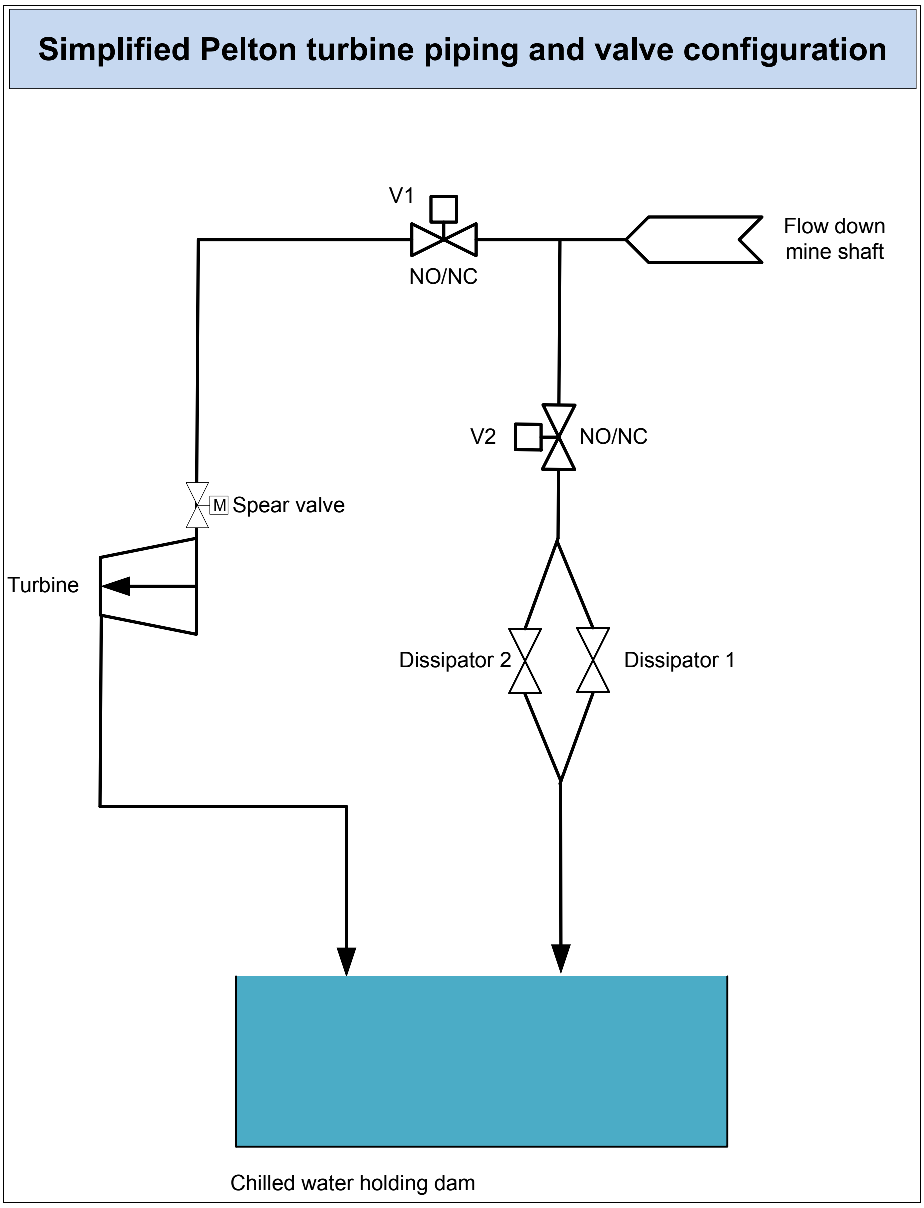


Figure 14: Typical Pelton turbine piping and valve configuration

Referring to *Figure 14*, if the turbine is not operational, V1 will be closed and the chilled water will flow through V2 and the dissipaters ensuring mining processes relying on chilled water can continue [49]. If the turbine is operational it will act as a pressure regulator and V1 will be open. The optimum amount of flow will go to the turbine and is regulated with the spear valve while the excess water will flow through V2.

As mentioned before, the turbine is merely used to reduce the electrical energy cost of a system due to the recuperation of the potential energy. Chilled water needed for mining purposes usually enjoys priority over the turbine utilisation.

Studies have been conducted on the feasibility and practicality of installing Pelton turbines on secondary cooling systems, for instance to operate return feed pumps on a BAC. However, with this study the focus is only placed on Pelton turbines installed underground utilising the pressure in chilled water piping installed in the main shaft cavity and not secondary turbines installed as mining level dissipater or secondary cooling system.

If the actual electrical energy output of the Pelton turbine system is known, it can then be used to determine the turbine's capacity factor. The capacity factor is the ratio of the actual electrical energy output to the maximum possible electrical energy that could have been produced over a certain time [50].

The typical overall turbine system efficiency that incorporates the generator and turbine losses will range from approximately 40 to 60% [51]. To model the turbine it is assumed that the turbine is functioning when there is water flowing through the turbine to the underground holding dams or workings.

It must be kept in mind that the turbine will exhibit a high efficiency during a wide range of flows. If the flow of water to the turbine and the static head is known, the output can be determined. This is accomplished by using the following formula:

$$E_p = \rho \times g \times h \times Q \qquad \text{Equation 2.1}$$

E_p	= Theoretical output of turbine while operational	[kW]
ρ	= Density of water taken as 1000 kg/m³	[kg/m³]
g	= Gravitational acceleration taken as 9.8 m/s²	[m/s²]
h	= Static head	[m]
Q	= Flow rate	[l/sec]

By using this formula, with the aid of a simulation, it will indicate an increase or decrease in the Pelton wheel average power with a change in flow. If the turbine is used as a pressure dissipater there will be a reduced increase in temperature of the chilled water when the pressure energy is recovered. The reduced chilled water sent down the mine can influence the average power of the turbine and is therefore included in the simulation.

2.4 Dewatering system and chilled water dissipater

2.4.1 Dewatering system

Deep mines are dewatered using large multistage clear water pumps. These pumps are driven by a constant speed electric motor. A typical pump and motor configuration is shown in *Figure 15*.

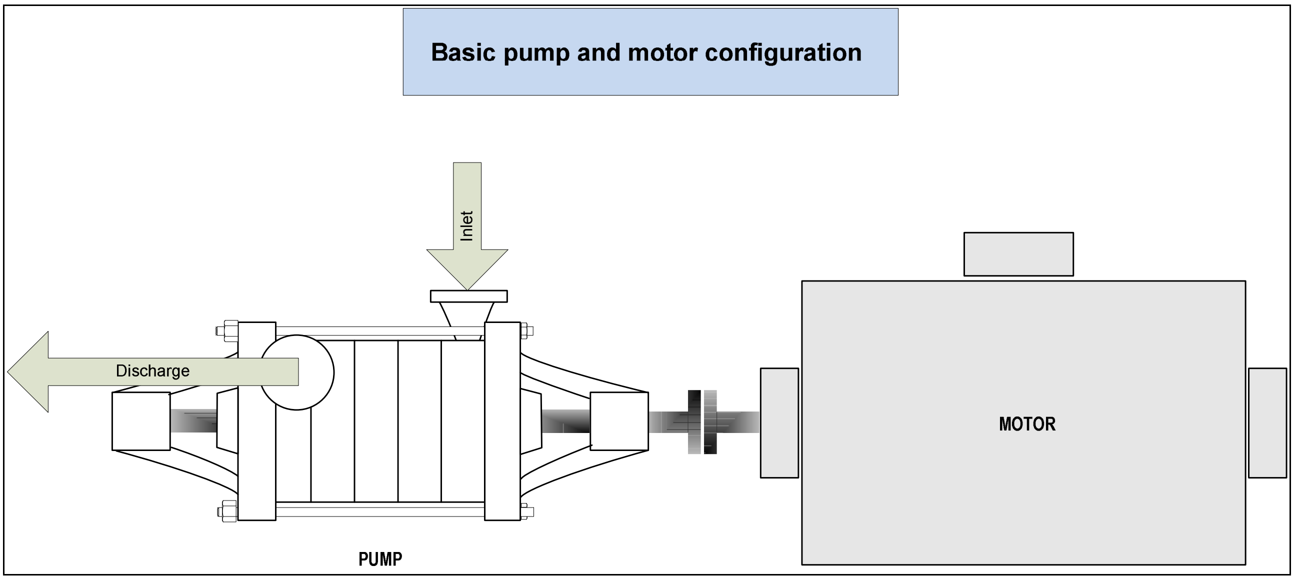


Figure 15: Electric motor and multistage pump configuration

Due to extreme depth and high static head, multistage centrifugal pumps are mostly used. A centrifugal pump consists mainly of an impeller and diffuser. The operation of a typical multistage pump is explained by referring to the water path in the pump. From the inlet, water enters the centre of the impeller, the motor turns the impeller and the resultant centrifugal force forces the water to the diffuser passages while gaining velocity and pressure [52]. In the case of a pump with multi stages, the flow directed from the diffuser is fed into the impeller of the next stage. This summation of pressure provided by each stage is the static head the pump can deliver [53].

Due to a varying inflow and discharge flow demand of the holding dams, pumps found on an underground pump station are configured to operate in parallel ensuring outflow can be varied by stopping or starting a pump. This also ensures flexibility and redundancy with the ability of pumps to pump independently into different discharge columns if necessary. A pump with column and static head is shown in *Figure 16*.

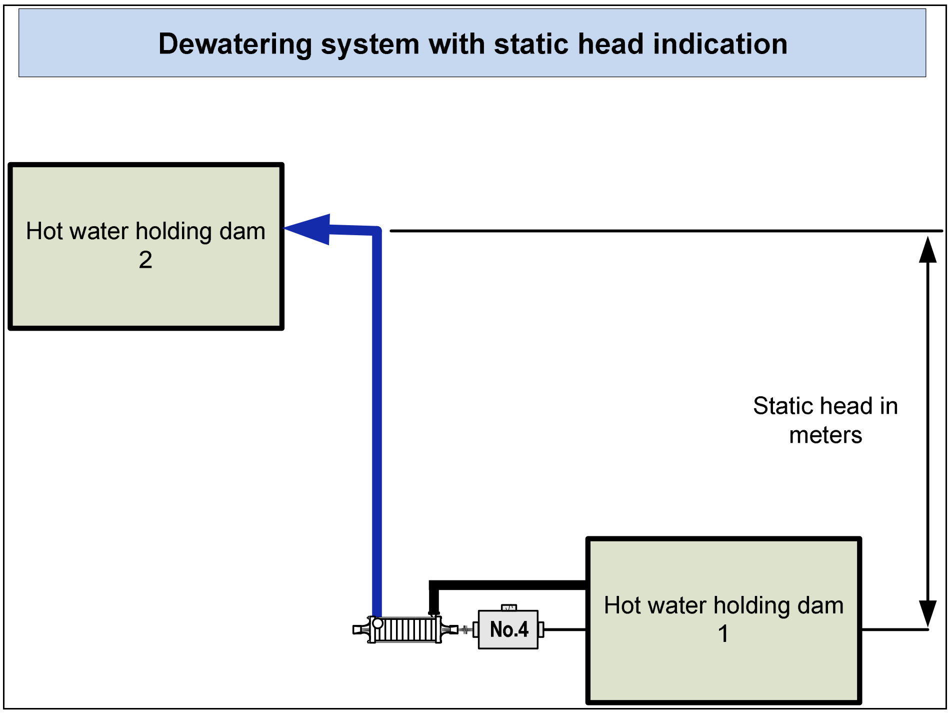


Figure 16: Underground hot water dams with simplified static head indication

In a typical pump station when no pumps operate an approximation of the static head is measuring the pressure developed at the pump discharge when no flow occurs. This is achieved by using the formula applicable to hydrostatic pressure calculations represented by the following equation:

$$P = \rho \times g \times H \qquad \text{Equation 2.2}$$

H	= Static head	[m]
g	= Acceleration of gravity	[m/s²]
ρ	= Liquid density	[kg/m³]
P	= Pressure at pump discharge	[Pa]

Neglecting the difference in the pump suction with regards to the pump discharge distance, the pump discharge pressure developed can give an approximation of the dynamic head when subtracted from the static head. This can be determined when one pump is operated in a single column.

The dynamic head of each pump chamber will also affect the amount of electrical energy required to pump from one preceding level to the next. If the dynamic head of each pump chamber can be calculated from the pump discharge pressure and compared to the static head, theoretical approximations of the losses can then be quantified.

To determine the typical dynamic head on a pump chamber a total of 16 different pump chambers with multiple pumps was analysed. The average dynamic head was calculated by comparing the static head to the developed dynamic head from the pump discharge pressure readings when only one pump is running. The results are shown in *Figure 17*.

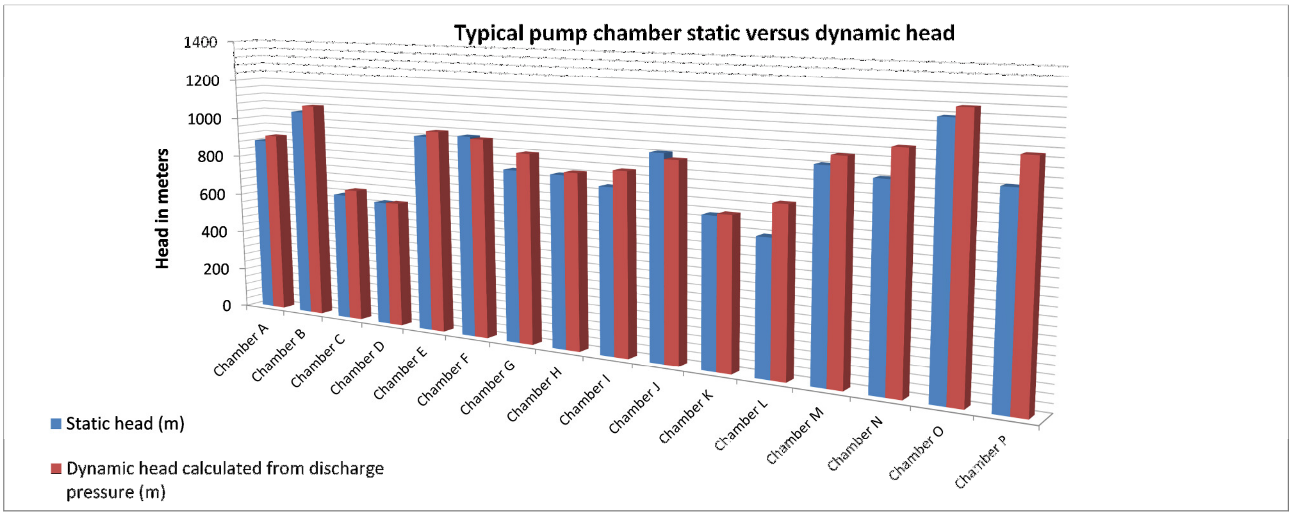


Figure 17: Pump chambers measured, static versus calculated dynamic head

By measuring 16 different pump chambers varying from three to ten pumps per chamber it was found that a typical pump chamber can have a dynamic head of approximately 5.4% more than that of the static head [54]. It can also be seen that this varies from pump chamber to pump chamber. With more than one identical pump operating in parallel and pumping into a common discharge column, each added pump will operate at a lower flow rate. This can ultimately reduce system efficiency.

To determine an approximation of the amount of required energy, gravitational potential energy calculations can be used. Referring to a water mass that has to be pumped from one pump chamber on a mine to the next, a simple yet effective method is to determine how much energy is required to transport this water from one level to the next. The formula for gravitational potential energy in conjunction with the average frictional factor calculated is used to determine the amount of energy required to transport water from one pump chamber to the next. This can be represented by the following formula:

$$\mathrm{P_e} = \mathrm{M_1} \times \mathrm{g} \times \mathrm{H} \qquad \text{Equation 2.3}$$

H	= Corrected head (head increased by an average of 5.2%)	[%]
g	= Acceleration of gravity	[m/s²]
$\mathrm{M_1}$	= Liquid mass (water)	[kg/m³]
$\mathrm{P_e}$	= Potential energy needed to transport water from pump chamber	[kJ]

The efficiency of dewatering pump/motor combinations found in underground mining operation usually ranges from 60 to 80%. An efficiency factor of 70% for the pump and motor must be included in the calculations to ensure a more accurate model. This can be used to determine the electrical energy required to pump hot water to surface. If the chilled water is reduced, there will be a reduction in the electrical energy usage of the dewatering system. Hence, the dewatering system is included in the simulation.

2.4.2 Pressure reduction valves

Chilled water is transported to the underground workings using pipes, valves, pressure reducing valves, holdings dams and other elements. These mining level chilled water supply systems can have characteristics of high pressures and intermittently high flows. In some cases the supply pressure and flow fluctuations can be as high as 3500 kPa and 70 l/sec respectively.

Usually there are two types of configurations used to transport water safely to underground. One configuration makes use of holding dams situated in a cascade manner throughout the mine to enable safe transfer of water from one level to the next lower level. The dams are used as a pressure regulator to reduce head pressure. The other configuration uses a complex piping system consisting of pressure reducing or pressure sustaining valves.

Referring to *Figure 18*, the pressure in the system is changed using pressure reduction or sustaining valves to achieve a lower pressure [55]. This ensures that the water pressure does not increase to such an extent that it can damage equipment or injure personnel. Apart from a PRV, a restricting orifice is also installed as a safety device. One of the important functions of a restricting orifice is to limit the water flow during a pipe failure downstream of the orifice [56].

In terms of control, if a control valve is installed, with the correct specifications, in the position of the PRV, if may be used to control the downstream pressure. When this valve is not available, a bypass control systems is installed downstream of the pressure reduction station to enable control. The bypass system consists of a linear control and an isolation valve that enables two possible scenarios when they are operated. Scenario one is approximately zero line friction when the isolation valve is open and optimised control on the bypass valve when the isolation valve is closed.

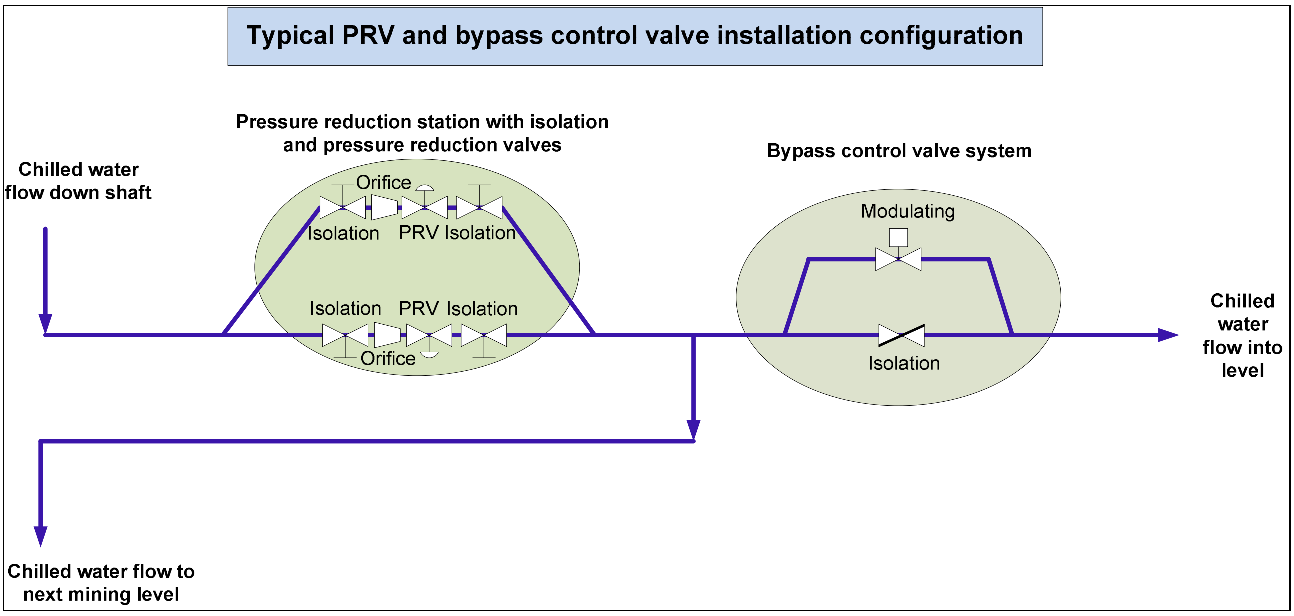


Figure 18: Simplified PRV and bypass control system installation configuration

At the pressure reduction station, two PRV's are usually installed in parallel to ensure redundancy in case of failure of one of the valves. This in conjunction with the isolation valves also ensures that a PRV can be replaced without influencing the chilled water supply to the mining levels. A typical pressure reducing station with pressure reduction and isolation valves are shown in *Figure 19*.

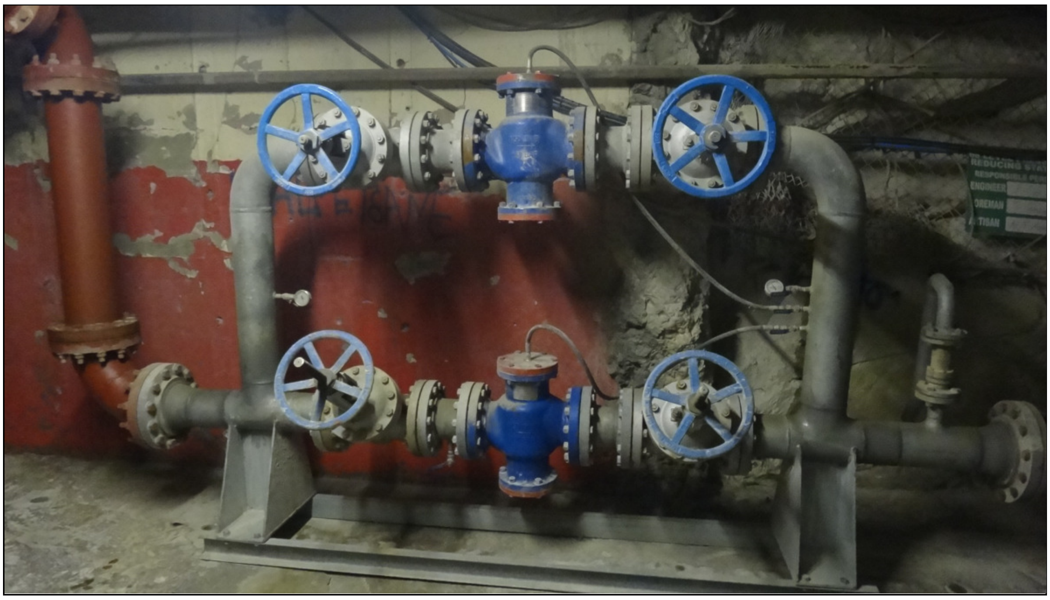


Figure 19: Typical underground pressure reduction station [Photo by Mr. C. Kriel]

With no energy recovery device operated in conjunction with a PRV system an increase in chilled water temperature is inevitable. More importantly, there are other operational aspects of the PRV system that can be severely affected by a reduction in chilled water flow.

One such concern is commonly known as valve "chatter". This is essentially when the flow through the valve is reduced below its allowable minimum causing rapid successive opening and closing as the pilot valve tries to maintain the desired set point. This can cause large pressure and flow fluctuations in the piping system.

Another aspect is when flow through the system is reduced, the system pressure increases up to the maximum point where there is no flow. This increase in pressure can increase the possibility of component wear and fouling and it must be ensured that the equipment has the correct pressure ratings as high pressures may occur with such a reduction in flow.

The dissipaters is a crucial component in the mine water cycle, but the impact of reducing the chilled water on the dissipater is confined to a operational influence rather than thermal of efficacy. It is assumed, as part of this study that the dissipaters are functioning correctly and therefore not included in the simulation.

2.5 Refrigeration and cooling

2.5.1 Chilled water cars (CWC)

With an increase in mining depth there is an increase in the Virgin Rock Temperature (VRT). These temperatures have been measured as high as 60℃ at depths of 3300m below surface [57]. As mentioned previously, initially primary surface bulk air cooling ensures acceptable working conditions underground even when the rock temperatures exceed 60℃ up to a certain depth.

Underground cooling is achieved by a combination of ventilation air and chilled water. However, there are certain work areas found underground with a high air temperature that is difficult to cool with conventional bulk air cooling and local units are used to cool these strategic areas, commonly known as localised cooling [38].

One typical localised cooling unit is a chilled water car (CWC) installed in the specified area where cooling is necessary. A CWC consists of a silencer, fan, cooling unit and chilled and hot water piping. Chilled water is piped to the workings in a thermally insulated pipe. Cooling ventilation air with a CWC is based on the principle of heat transfer between the cold water flowing through the heat exchanger in the car and the warm air flowing over the heat exchanger fins of the car.

Hot ventilation air is vented through the CWC using a fan. The CWC is placed in orientation to direct the cooled air towards the section where colder air is needed. After the hot water leaves the CWC it is either dumped or more commonly routed back in hot water returns to holding dams. A typical CWC is shown in *Figure 20*.

Figure 20: Typical underground CWC [photo taken in February 2013]

When a valve is installed in the chilled water column feeding into a specific level and the water pressure is reduced, there will be a reduction in the water flowing into that level defined by the downstream network characteristics [32]. Most of the CWC's are installed some distance downstream of a typical PRV and bypass control station. If the water pressure is reduced the amount of chilled water supplied to the CWC is reduced.

In order to determine the exact effect of the reduction in pressure and thereby the reduction in flow, will have on the cooling ability of the car, is complex. To simplify, the temperature of the water entering the CWC as well as the flow of chilled water is required and can be used to make an approximation of the cooling output.

A simplified method can be used, if no change of state occurs, calculating the heat gains or heat losses in the heat exchanger. In this instance, heat losses to the CWC body are neglected and it is assumed that the heat transferred from the hot air entering and the cold air exiting the CWC is absorbed by the water flowing through the chilled water car.

$$Q = \dot{m} \times Cp \times [T_{in} - T_{out}] \qquad \text{Equation 2.4}$$

Q	= Heat transfer rate	[kJ/s = kW]
Cp	= Specific heat of water [4.1855 kJ/kg ℃] (15℃ 101.325 kPa)	
$\dot{m}$	= Mass flow rate of chilled water	[kg/s]
T_{in}	= Inlet fluid temperature	[℃]
T_{out}	= Outlet fluid temperature	[℃]

The supplier specified output cooling capacity of the chilled water car must be determined for an approximation of the efficiency to be calculated. This is usually indicated on an information plate located on the car itself and then compared with the determined kW cooling output. This can be used as an approximation to determine the CWC effectiveness if the flow of chilled water through the CWC is changed. The equation is given as:

$$\eta = {}^{Q}/_{\text{Rated kW}} \qquad \text{Equation 2.5}$$

Q	= Heat transfer rate	[kJ/s = kW]
η	= Efficiency	[%]
Rated kW	= Rated kW cooling output of CWC	[kW]

Another effect of reducing the temperature of the air flowing through the CWC is a reduction in the absolute humidity due to condensation. This can be seen by the condensate left behind on the CWC heat exchanger. The CWC can be severely affected by a reduction in chilled water pressure and subsequently flow. Thus, the thermal implications of the CWC form part of the simulation.

2.5.2 Bulk Air Coolers (BAC)

One of the methods to reduce the temperature underground in a deep mine is by cooled ventilation air using bulk air coolers (BAC). BAC's can be found on surface and underground. The surface BAC's cools the ventilation air sent down the downcast shaft. If the surface BAC's are not able to reduce the temperature of the air in the underground tunnels connecting the workings to the shaft, secondary bulk air cooling is introduced [31]. If cooling air is introduced underground the effects of auto compression on the temperature increase of the surface BAC air can be reduced.

With regards to underground cooling, BAC's can be classified into groups namely closed and open circuit systems. As the name states, in closed circuit systems, water is usually circulated from the refrigeration plant to the heat exchanger or BAC where water is heated and returned to the refrigeration plant where the water is cooled and the cycle is repeated. In an open circuit chilled water is supplied to a BAC that is usually a spray chamber situated some distance from the shaft. After this water is used it is ultimately returned to the hot water circuit.

In an open circuit spray chamber where feed is taken from the pressure reduction piping system, the chilled water comes into direct contact with the hot air that needs to be cooled, thus the name a direct contact heat exchanger. When comparing the non-contact BAC with a spray chamber BAC, the non-contact BAC is more efficient as less pumping is required but less thermally efficient when compared to the open circuit system spray chamber BAC [22].

The open circuit systems on the other hand may be more susceptible to a reduction in chilled water flow. With a typical WSO project, if the water pressure and flow of water sent to a level with an open circuit bulk air cooler is reduced, there can be a reduction in the required pumping and electrical energy usage. But careful consideration must be taken to ensure the cooling ability is not affected. In this study focus is placed mainly on the open circuit systems as they are more likely to be influenced by a typical WSO project.

The operation of a typical BAC spray chamber can be explained by referring to *Figure 21*. Chilled water is sprayed vertically into the air using the pressure of the water in the chilled water pipe. The fitted nozzles produce a water spray. With a multi staging arrangement a smaller amount of water is used to achieve the same cooling than would have been attained in a single stage due to the reuse of water in the secondary stage.

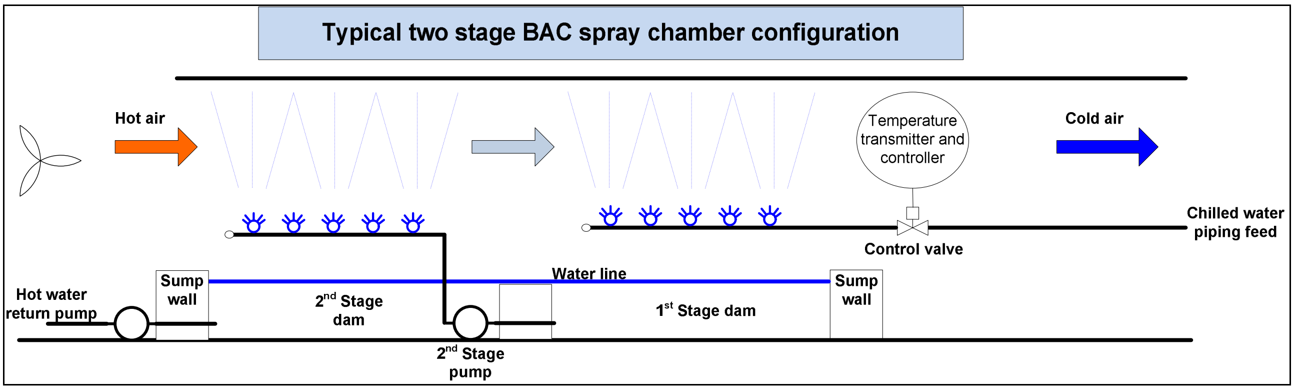


Figure 21: Adapted simplified underground BAC spray chamber [58].

Hot air flows from the entrance of the chamber and comes into direct contact with the cooled water spray and flows to the chamber exit. The hot air must have a wet bulb temperature higher than the chilled water temperature for heat to be transferred from the water to the air by a combination of conduction and convection [59].

Usually a control valve maintains the temperature of the air by decreasing or increasing the amount of flow to the 1st stage spray nozzles. This control configuration is still susceptible to feed flow and pressure fluctuations. More importantly, in the event that the control valve is not fitted to the chilled water pipe supply line, the temperature of the hot air leaving the chamber may vary due to change in the feed pressure that affects the spray pattern [58].

To model the performance of a typical spray chamber the concept of sigma heat is used in conjunction with a sigma heat chart. Sigma, used mostly in the mining industry can be explained as the energy within a unit mass of humid air and usually expressed in kJ/kg.

With the direct contact of water with the incoming hot air, the dry bulb temperature will decrease and the humidity will increase while the sigma heat remains constant. There exists a balance between the rate of the heat gained by exiting chilled water and the cooling of the air exiting the spray chamber [59]. This can be modelled by the following:

$$\dot{m}_{air} \times (\mathrm{S_{out}} - \mathrm{S_{in}}) = \dot{m}_{water} \times C_{water} \times (\mathrm{T_{water\ in}} - \mathrm{T_{water\ out}}) \quad \text{Equation 2.6}$$

$\dot{m}_{air}$	= Mass flow of air	[kg/s]
$\dot{m}_{water}$	= Mass flow of water	[kg/s]
C_{water}	= Specific heat of water	[4.187 kJ/kg ℃]
$\mathrm{S_{out}}$	= Sigma heat of air at specific temperature leaving spray chamber	[kJ/kg]
$\mathrm{S_{in}}$	= Sigma heat of air at specific temperature entering spray chamber	[kJ/kg]
$\mathrm{T_{water\ in}}$	= Temperature of water entering spray chamber	[℃]
$\mathrm{T_{water\ out}}$	= Temperature if water existing spray chamber	[℃]

With the aid of a psychometric chart and assuming a barometric pressure of 110 kPa the sigma heat can be determined for the change in temperature. The BAC spray chamber can be influenced by a reduced chilled water pressure and flow. A decrease in cooling output can be induced due to chilled water feed changes, consequently the BAC spray chamber will be included in the simulation.

2.5.3 Ventilation

Ventilation can be seen as the control of the flow of fresh air to underground to maintain a safe and workable environment [60]. The main reasons for deep mine ventilation of underground workings is the “transport of cooling” to remove heat from underground as well as ventilate dust particles and naturally occurring gases.

Ventilation fans are installed in the surface BAC and used to send cooled air from surface to underground. Extraction fans are installed on the ventilation shaft to extract the hot ventilated air from underground and ventilate this to atmosphere. A typical layout of a ventilation system on a mining shaft is shown in *Figure 22*.

Basic underground ventilation air path

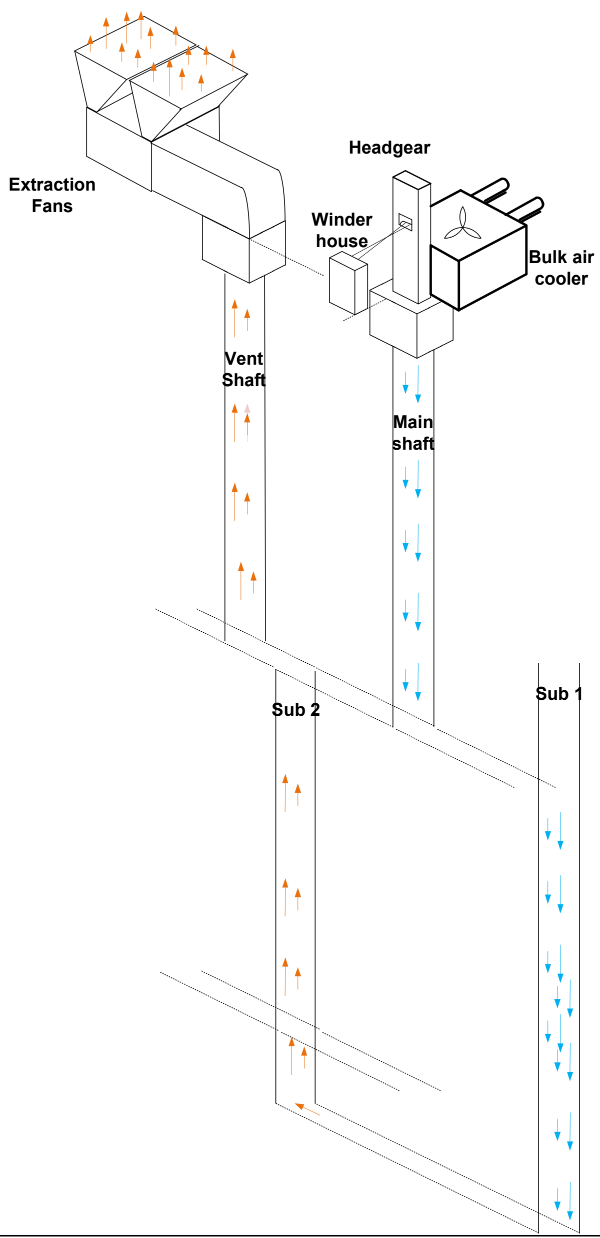


Figure 22: Simplified ventilation air path in a typical underground mine

With regards to the underground haulages, Return Airways are used to transport the contaminated air underground from the workings to the ventilation shaft. This is mostly done without mixing the fresh cool ventilation and hot contaminated air. To minimise pressure losses the velocity of the ventilation air is usually kept below 7 m/s and for the return air usually not more than 10 m/s [61]. The RAW are also used to convey heat rejected by the underground refrigeration plants to surface.

The environmental conditions underground are controlled and affected by the ventilation force draft and extraction fans. It is also affected by the refrigeration plants and subsequently chilled water supplied to the bulk air and air cooling units.

The effectiveness of ventilation air has numerous influences. One major factor is a phenomenon commonly referred to as auto compression. This occurs when ventilation air is sent vertically down a mining shaft and the air is compressed by its own weight resulting in an increase in pressure and subsequently a rise in air temperature [62].

If the cooling ability of the ventilation air must be assessed with regards to the temperature, the Air Cooling Power (ACP) can be used as an indication of the relation of air speed to wet bulb temperature. ACP is used in the mining industry for the design and planning of cooling systems [63]. ACP is a calculation of the heat transfer that takes place between a human body and the surrounding environment in which that person is working [64].

When designing the ventilation requirements of a deep mine, an air cooling power of 300 W/m² and a wet bulb temperature of 27.5 °C are commonly used to determine if underground working conditions are satisfactory with regards to heat.

To maintain an ACP of 300 W/m² in an underground environment and a wet bulb temperature of 27.5 °C, the air velocity must be approximately 0,5 m/s. If the wet bulb temperature is 25 °C the air velocity necessary to maintain 300 W/ m² is halved to 0.25 m/s.

The ACP is reduced when the ventilation air is kept constant, and the wet bulb temperature is increased. If the BAC system is not effectively cooling the ventilated air, a higher air velocity that is usually kept constant, is required to produce the same cooling effect experienced underground.

Thus, the temperature of the chilled water and subsequently the cooled air determines the effectiveness of ventilation air sent to the underground workings. But the impact of a reduced amount of chilled water as a result of optimised control on the ventilation system is minimal. Hence, the ventilation air system does not form part of the simulation.

2.5.4 Refrigeration

Refrigeration machines on deep mines can be found in numerous configurations namely series, parallel or in an arrangement that will optimally satisfy the system requirements [65]. The two refrigeration cycles primarily used is mechanical vapour compression and absorption. The compression refrigeration cycle is shown in *Figure 23*.

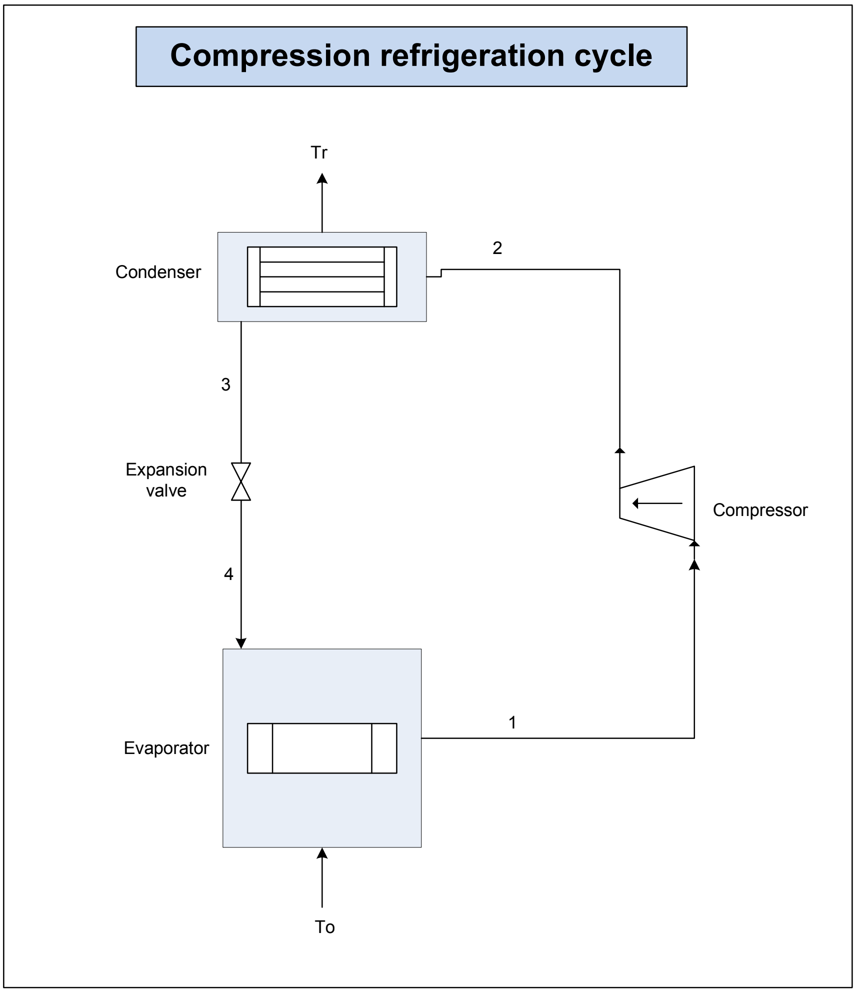


Figure 23: Simplified compression refrigeration cycle

In the compression refrigeration cycle, at indication 1, the heat was absorbed by the refrigerant from the process fluid (hot water) entering the evaporator. At indication 2 the refrigerant was compressed by the compressor in such a way that no heat is exchanged with the environment thus increasing the refrigerant pressure and temperature.

At indication 3, heat rejection occurred in the condenser while the pressure was maintained. At indication 4, the isentropic expander, typically an expansion valve reduced the pressure of the refrigerant resulting in a temperature decrease and ultimately ensuing in a low pressure and low temperature refrigerant entering the evaporator [66].

The compression refrigeration cycle is more commonly found in the mining industry. A generic mine surface compression refrigeration plant is shown in *Figure 24*. Hot water is pumped from underground at a temperature of between 30 to 35℃ using the dewatering system and stored in a hot water dam.

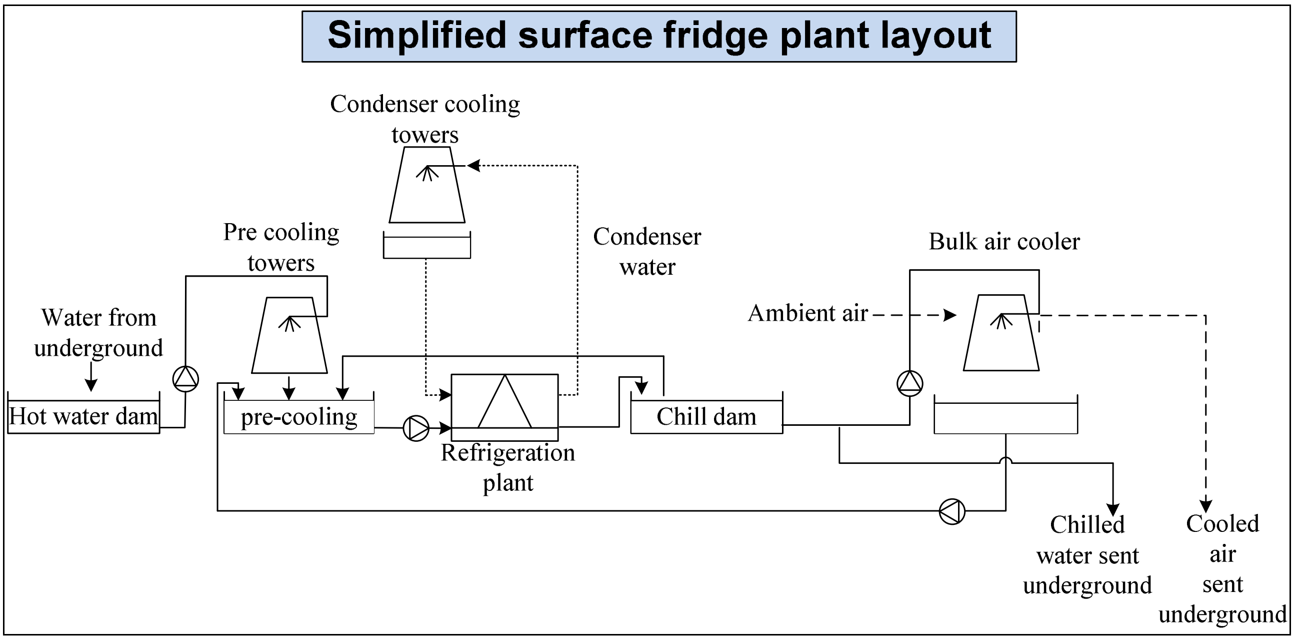


Figure 24: Simplified surface refrigeration plant layout

The pre-cooling tower cools the water to very nearly ambient wet bulb temperature. This water is then sent to the evaporator of the refrigeration plant and cooled even more, to typically 3℃. Thereafter, the water is sent to the BAC to cool the ventilation air and sent underground using chilled water columns. Water collected in the BAC sump is pumped back to the pre-cooling dam as the water is at a lower temperature than the water cooled in the pre-cooling tower.

A typical closed loop underground refrigeration plant operates similarly to the surface plant. These plants can range in size, but the cooling output delivered depends mostly on the amount of thermal energy that can be rejected to the RAW. Usually in a closed loop configuration chilled water is sent to the underground BAC thereby reducing the wet bulb temperature of the ventilation air. The hot used water is then returned from the BAC sump to the refrigeration plant to be reused, which reduces the required amount of supplementary water.

Thus, if the water used underground is reduced, the impact on the underground closed loop refrigeration plant will be negligible. The effect will be evident on the surface fridge plant due to a decrease in the amount of water sent through the plant affecting the load [32]. However, it must be kept in mind that the refrigeration requirements must be adhered to at all times. When this water is reduced, the reduction in average kW can be determined using the following approach:

$$\mathrm{Q} = \dot{m} \times C_p \times (\mathrm{T_{in}} - \mathrm{T_{out}}) \qquad \text{Equation 2.7}$$

Q	= Heat transfer rate (kW cooling)	[kJ/s=kW]
$\dot{m}$	= Mass flow rate of water	[kg/s]
Cp	= Specific heat of water	[4,187 J/kg ℃]
T_{in}	= Inlet fluid temperature	[℃]
T_{out}	= Outlet fluid temperature	[℃]

The heat flow can be determined using the water temperature entering and exiting the evaporator as well as the flow. To determine the effectiveness of the fridge plant the coefficient of performance is introduced. This is given as the ratio between the electrical power input and the cooling output defined by the following:

$$\mathrm{COP} = \frac{kW_{electrical}}{Q} \qquad \text{Equation 2.8}$$

COP	= Coefficient of performance	
Q	= Heat transfer rate	[kJ/s=kW]

$kW_{electrical}$ = Electrical power input [kW]

It must be appreciated that the water cycle is complex with each mine exhibiting unique site characteristics and constraints. In some cases the effect in the reduction of water flow may only be evident on some dewatering and refrigeration systems after as much as 24 hours, as the water cycle takes time to be completed[1].Determining the time when the dewatering system electrical energy usage decreased due to a reduction or closure of the chilled water feed to underground, will show the cycle time.

The reduced chilled water in the mine water cycle will directly affect the electrical energy consumption of the surface refrigeration plant. This necessitates the inclusion of the surface refrigeration plant in the simulation.

2.6 Other hydro dependent demands

A number of processes exist that can be affected when the chilled water is reduced. These concerns can be addressed by investigating the possible usages. These effects are not included in the modelling process but it must be taken into account during the WSO project design phase. Examples are:

- Generic equipment exists and operates downstream of the control system, which in turn can be affected.
- Water reduction could hamper firefighting strategies during an emergency, if no procedures are in place to ensure ample water supply.
- Chilled water used underground to cool motors or other equipment [mostly site specific].

Chilled water leaks are also affected during the optimised control of a typical WSO project. If the pressure in the chilled water pipe is reduced, the chilled water pipe leakage flow is also reduced. There are numerous factors that influence the number of chilled water leaks found underground on a deep mine. Some of these factors include the size of the piping

[1] Personal communication, Mr. G. Putter, Superintendent Electrical, Goldfields Mining Group

network, system pressure, aged infrastructure and maintenance. Combined leakages of up to 65 litres per second have been reported on deep mine water reticulation systems.

In mining compressed air systems, found alongside chilled water systems, compressed air leaks can account for up to 20% of the supply [67]. These pipelines are mostly found in close proximity to each other and used to deliver chilled water and compressed air to the mining operations. It is assumed that, in deep mines, the amount of leakage in the compressed air networks will resemble that of the chilled water reticulation system. However, chilled water leaks will be less than compressed air as water leakage is easily detected by visual inspection.

With the availability of data at case study B, chilled water leakage data was retrieved from the mine. A firm specialising in leak detection was contracted by the mine to inspect the complete underground system and establish the amount of leaks, position and approximate their respective sizes.

The total leakage in litres per second found in October 2011 was compared to the amount of chilled water supplied to the system. The average demand was found to be between 160 and 200 litres per second and the leakage flow was approximately 18 litres per second. Thus, the leakage flow proportional to the total flow was found to be approximately 10 %.

2.7 Conclusion

In this chapter, the operation of each system affected by the reduction in chilled water was determined. Emphasis was placed on the effect of chilled water on the functionality of other systems when it is reduced. A model of each applicable system was developed to quantify and represent this impact in a simple comprehendible manner.

There are numerous effects on various systems that can be brought upon as a result of a reduction in chilled water flow or pressure. However, the motivation for water reduction is financial savings, if the systems affected can be operated optimally and effectively. The processes that can be affected by the reduction of the chilled water sent underground is summarised and tabulated in *Table 2*.

Table 2: Summarised table indicating affected systems with cause

Description	Type	Influence	Possible influence type
Surface refrigeration plant	Open loop	Yes	COP
Underground refrigeration plant	Closed loop	Negligible	Negligible
3CPFS	-	Negligible	Utilisation (maintaining dam levels)
Dissipator	Pressure reduction valve	Yes	Flow cut-off (operational influence)
Turbine	Closed loop	Yes	Energy output
Surface BAC	Closed loop	Negligible	Negligible
Underground BAC spray chamber	Open loop	Yes	Spray chamber cooling output
Chilled water car	Open loop	Yes	CWC cooling output
Ventilation	-	Negligible	Negligible
Dewatering	-	Yes	Energy consumption
Chilled water leakages	-	Yes	Reducing wastage / increase efficiency
Water treatment	Dosing	Yes	Less chemicals required

In *Table 2* each of the influences on components such as the dewatering systems, surface refrigeration system, BAC, turbine and CWC are given. These components form part of the mine water cycle affected by a typical WSO and are therefore included in the simulation. This simulation will ultimately quantify the effect on the entire underground network of components using water flow as the common denominator. The modelling, simulation construction and verification form part of Chapter 3.

CHAPTER 3: INTEGRATED SIMULATION MODELLING

Surface BAC to cool ventilation air sent down a shaft [Photo taken in February 2013]

The approach to the modelling is explained. Simulation models are constructed to represent all systems with the effects of reducing the amount of chilled water on operation. These models are verified through extensive testing procedures making use of actual process data.

3.1 Introduction

To determine the cost implications of a typical WSO DSM intervention on a mine's water reticulation and cooling system, each affected component is modelled. In the previous chapter the effects of reducing chilled water were broadly discussed. In this chapter, components that will be impacted by a WSO intervention are modelled.

Numerous operational impacts are also considered but not all systems are modelled. The effects of a typical WSO project on certain components are negligible, which can be determined without modelling. The dissipater, 3CPFS and ventilation system are excluded from the simulation.

After the model is verified it is used to determine the financial implications of the optimised method of operation. In Chapter 4, simulations are applied on case studies to assess implications of the reduction in chilled water on typical mining operation.

3.2 Integrated simulation layout

Simulations can be described as mathematical representations of systems to predict certain outcomes with changes in system variables. Models will always exhibit certain errors as factors of the world are included and others not [68]. To construct a simplified model for each of the chilled water components, a step by step approach was followed. This included developing a model, perform simulation, analyse the output data and draw a conclusion. The following adapted steps will form part of the simulation modelling process [69].

1.) Collect relevant information and data.
2.) Develop a model.
3.) Validation.
4.) Select experimental data.
5.) Determine conditions for experiment.
6.) Perform simulation.
7.) Verification.
8.) Interpret results and form conclusion.

The simulation model consists of different components forming part of the mines water cycle. The simulation model was constructed with the aid of Microsoft Excel ®. Assumptions were made to simplify the model with minimal effect on the simulation accuracy. The components forming part of the integrated simulation is shown in *Figure 25*.

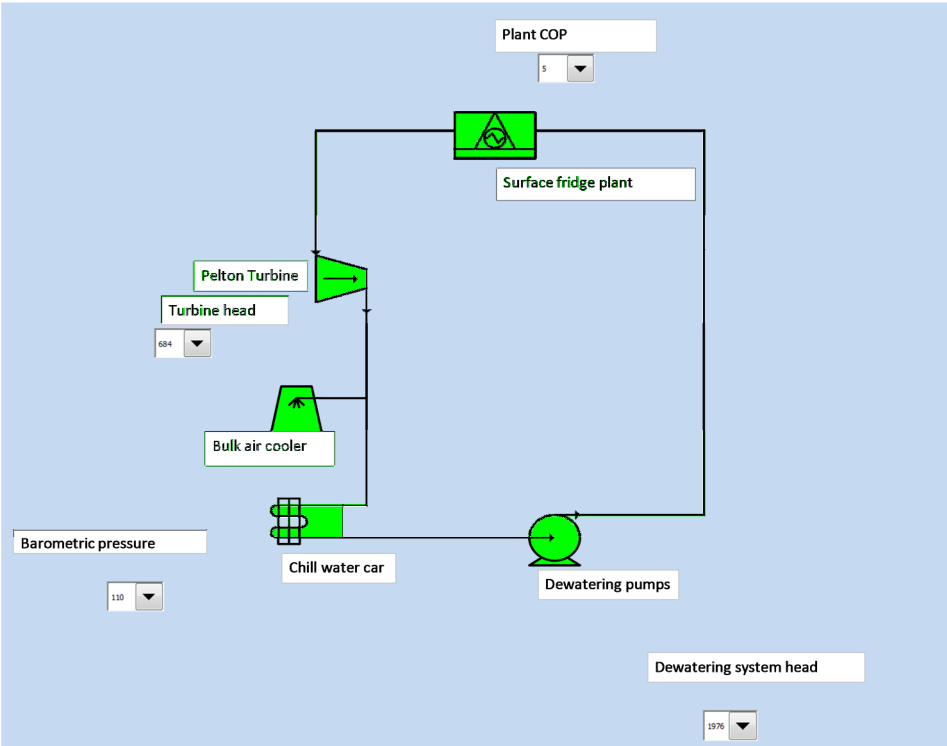


Figure 25: Integrated simulation layout of mine water reticulation and cooling system

The model uses discrete events with specific time intervals changing from one input parameter to the next. These process input parameters such as flow, temperature and head are used to simulate the output parameters. This data and information was retrieved from the SCADA system as well as collected from mining personnel and used in the simulation. A basic example of the simulation with input parameters, function and output parameters is shown in *Figure 26*.

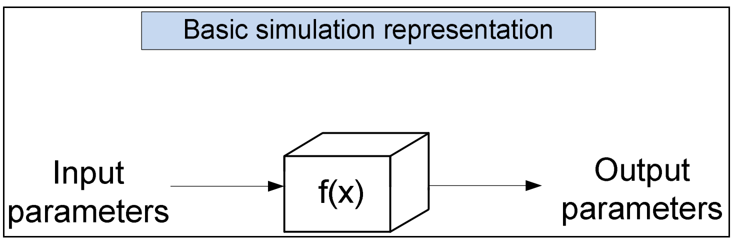


Figure 26: Simplified simulation representation

The output simulated data is compared to the retrieved actual mine data to verify the model and also determines the error margin. The actual mine data consists of data retrieved from different mining sites throughout the industry. An example of the simulation process is shown in *Figure 27*.

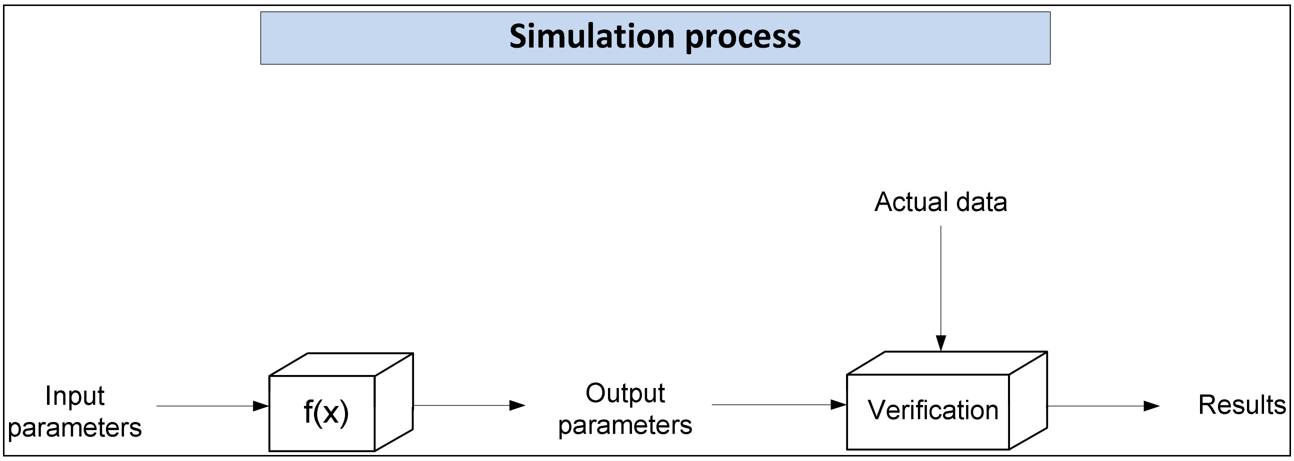


Figure 27: Simulation process

To simplify this process, it is assumed that the simulated component constraints are adhered to while the systems are operated. During the verification process the results are interpreted and using statistical correlation they are compared to determine the accuracy.

3.2.1 Dewatering system simulation result

To validate the simulation for a typical dewatering system the simulated average power was compared to the average power data retrieved from the mine. A pump chamber with parallel pumps of a deep mine was analysed and actual flow, head and power data was collected. Using the simulations, the average power required to pump the measured amount of flow for the static head, was simulated and compared to the retrieved average power of this pump chamber. The pump model used in the simulation is shown in *Figure 28*.

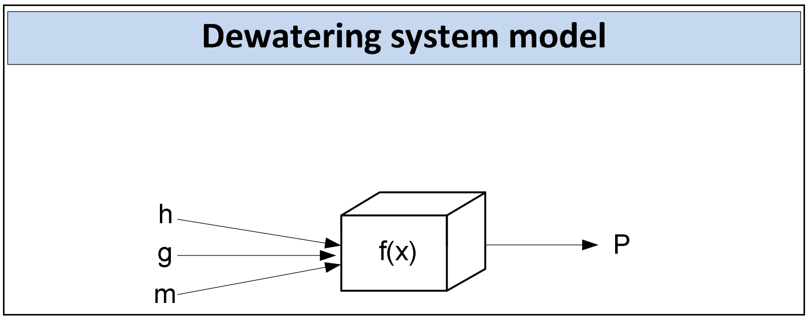


Figure 28: Dewatering system model

The weekday simulated and measured average power demand with one month's data was compared. The simulation was found suitable to indicate the required theoretical average power needed to transfer the water from one pump chamber to the next. An efficiency of 70% was assumed and found suitable for this simulation. The average simulated and measured power usage is shown in *Figure 29*.

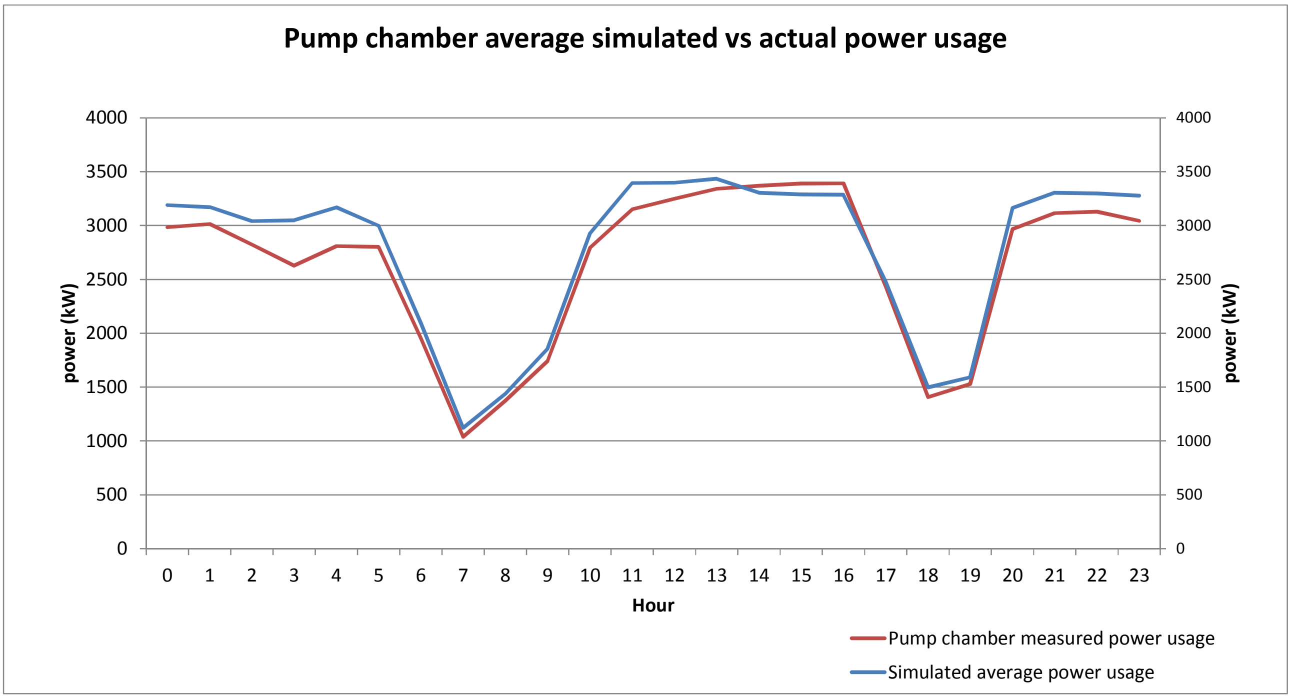


Figure 29: Average simulated versus actual power usage of a dewatering system

Using Microsoft Excel® the correlation coefficient between the measure pump chamber power and the simulated average power was determined to be 0.98 for the simulated and measured data.

3.2.2 Pelton Wheel turbine simulation result

To validate the simulation of the Pelton wheel turbine, actual data had to be retrieved. This data consisted of the head of the turbine, measuring the inlet chilled water flow and average power output when the measured flow is passed through the turbine. The turbine model used in the simulation is shown in *Figure 30*.

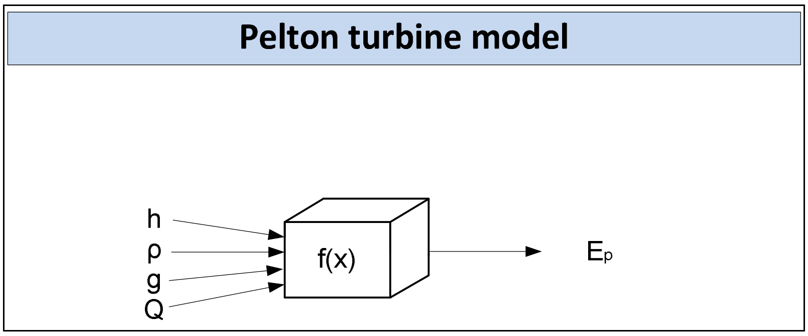


Figure 30: Pelton turbine model

Using the measured chilled water flow passing through the turbine and the turbine head, the average power output of the turbine was simulated. The efficiency of the turbine was assumed as 0.76%. This was compared to the retrieved average power output as shown in *Figure 31*.

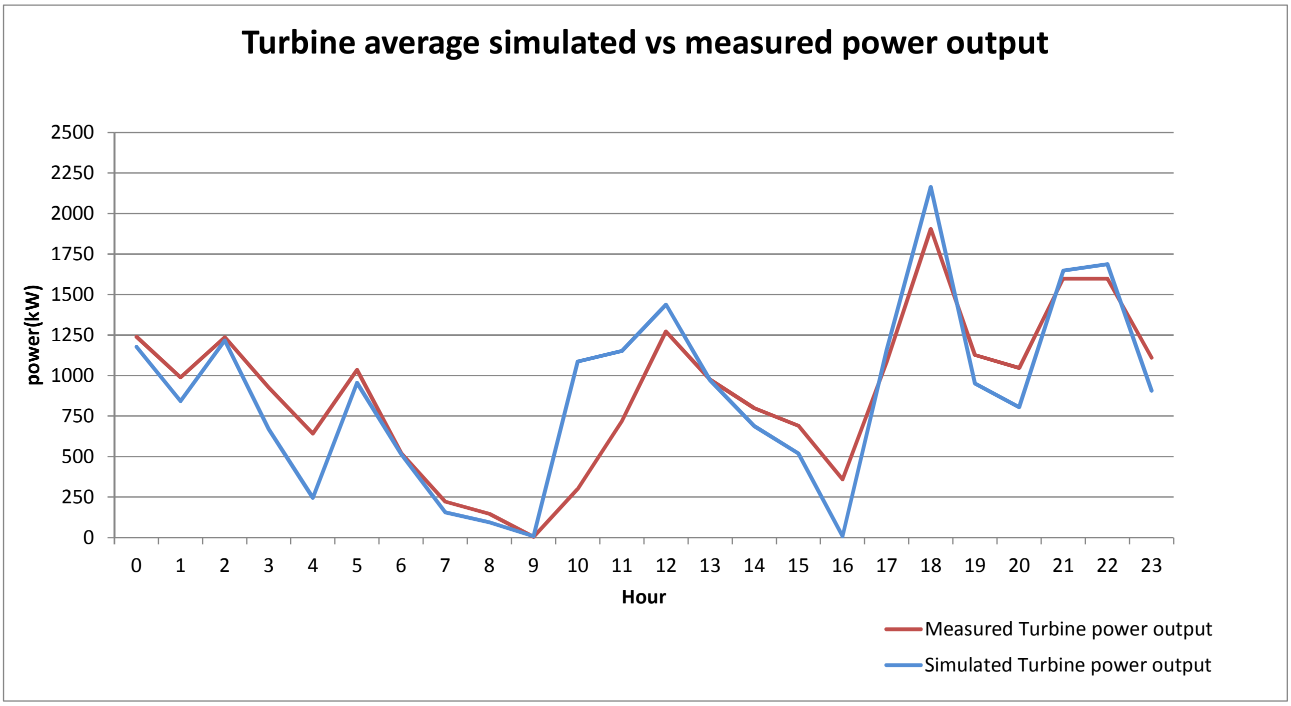


Figure 31: Average simulated versus actual power output of a Pelton turbine

It was determined using Microsoft excel® that the correlation coefficient is 0.88 for the simulated and measured data. Thus, the simulation model is accurate with an acceptable margin of error for this application.

3.2.3 Chilled water car simulation result

Verifications of the model for the CWC are complex. In practice a number of different techniques are used to determine the cooling output effectiveness of a typical CWC when in operation. Chilled water cars numbers can range from one to more than 40 per client site. This makes it impractical to measure real time parameters of each CWC when they are situated on various levels throughout the shaft.

To verify the simulated value, data was retrieved from the mine for numerous CWC units. The simulated kW cooling output was compared to the kW cooling output determined by mine officials. This was used to conclude if the simulation model is accurate with acceptable errors, even with no real time data available. The CWC model used in the simulation is shown in *Figure 32*.

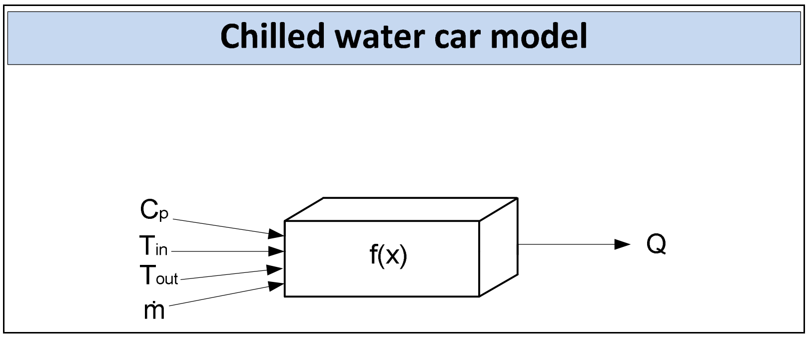


Figure 32: Chilled water car model

A total of 27 CWC cars with different sizes and in different locations throughout a typical mine was used in the analysis. The temperature of the inlet and outlet chilled water of the CWC and the water flow rate of each unit is usually determined by mine personnel once every six months. Using this CWC data collected, the kW cooling was simulated using the inlet and outlet water temperature and flow. This was then compared to the data retrieved from mine personnel.

It was found that the kW output correlated well with that determined by the mine personnel. This confirms that the model can be used as an approximation to determine what effect the chilled water flow will have on the kW cooling output of the chilled water car and approximate efficiency. The simulated and retrieved kW cooling output of each unit is shown in *Figure 33*.

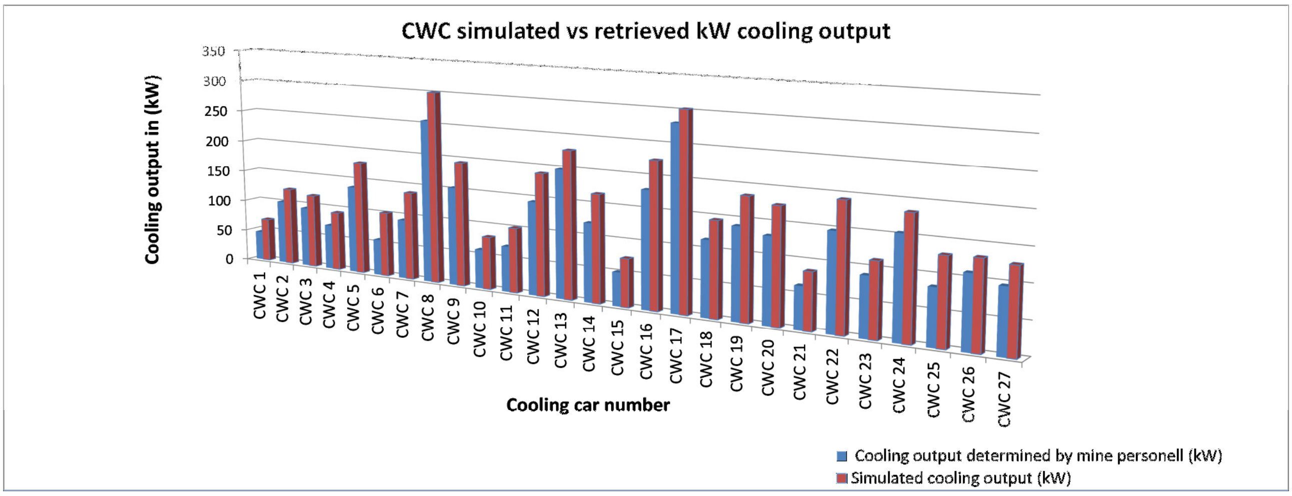


Figure 33: Average simulated versus retrieved kW cooling output of chilled water cars

With the aid of Microsoft Excel® the correlation coefficient was determined to be 0.98 for the simulated and actual data. The simulated values are constantly higher than the retrieved data, and may be attributed to neglecting losses. This simulation will give an accurate representation of the effect of the reduction in chilled water on the chilled water car kW cooling output. The average kW cooling output can also be determined from this simulation.

3.2.4 Bulk air cooler simulation result

In an underground BAC a balance exists between the rate of the heat gained by the exiting chilled water and the cooling of the air exiting the cooler. To verify the simulation model, data was collected from the mine. This consisted of the data of six BAC's that include the wet bulb temperature of the air entering and exiting the BAC as well as the temperature of the chilled water entering and leaving the BAC. This was tabulated to be used in the simulation model. This data retrieved is shown in *Table 3*.

Table 3: Summarised data table for actual BAC's installed underground

Unit	WB temp air in (°C)	DB temp of air in (°C)	Temp of water in (°C)	WB temp of air out (°C)	DB temp of air out (°C)	Temp of water out (°C)	Flow rate of air in (kg/s)	Flowrate of water in (l/s)	Rated Duty (kW)
Level 1 BAC	21.5	25	7.8	19.6	20.1	11.6	30	14	500
Level 2 BAC	23.5	27	10	19.4	20.2	19	57.8	25.5	2500
Level 3 BAC	26.8	30	9.5	14.9	14.9	19	60.2	57.77	2500
Level 4 BAC	25.3	29.8	9.5	12.2	12.2	23	60.5	41.7	2500
Level 5 BAC	27.2	30.1	20.5	26.5	26.7	26.5	58.7	8.75	1500
Level 6 BAC	28	31	19	24	24.5	22	38.6	70.69	1455

The relation between the heat gained by the water and heat loss from the air to the water was used in the model. Equation 2.8 was used in the analysis and the sigma heat of the wet bulb temperature of air entering and leaving the BAC was determined using a sigma heat chart converted to a usable graph using Microsoft Excel®.

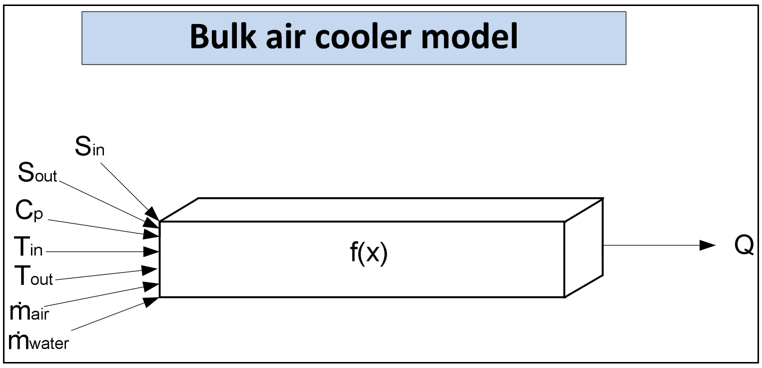


Figure 34: Bulk air cooler model

The kW cooling output of the BAC, determined by mine officials was retrieved and compared to the simulated kW cooling output as given by the simulation model. Using chilled water flow with the aid of a sigma heat chart the simulated and retrieved kW cooling output was compared. This is shown in Figure 35.

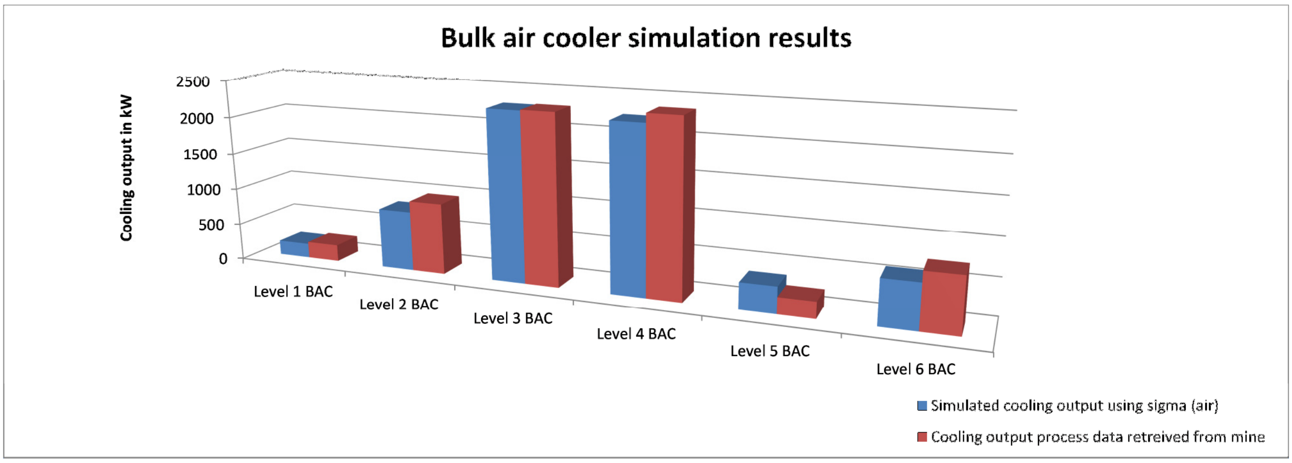


Figure 35: Simulated and retrieved kW cooling output of six underground BAC's

The correlation coefficient was determined using Microsoft Excel® and found to be 0.98. Thus if the water flow rate, air mass flow rate, barometric pressure, temperature of air and water in and out of the BAC of the system can be determined, an approximated cooling output can be calculated using the model. If the chilled water flow to the BAC is changed the theoretical kW cooling output of the system can be simulated with the change in flow.

3.2.5 Refrigeration simulation result

The surface refrigeration system usually consists of various units including a number of refrigeration machines and cooling towers. To verify the simulation model, data was again retrieved from the mine. This consisted of the temperature of the water entering and exiting the refrigeration cycle as well as the total flow and average power measured at the electrical incomer feeding the total refrigeration circuit. The refrigeration model used in the simulation is shown in *Figure 36*.

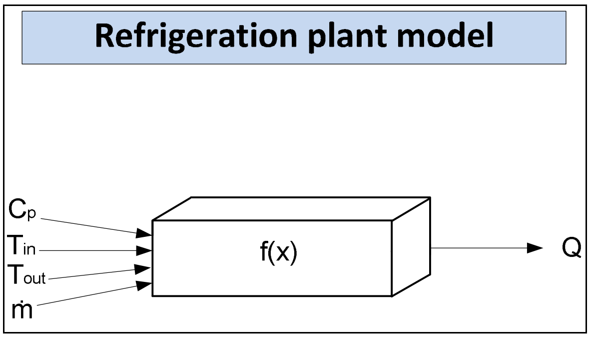


Figure 36: Refrigeration plant model

The flow and temperature of water entering the plant was measured and the heat transfer was simulated using the change in temperature of the water exiting the fridge plant. In the simulation, a COP of 4.5 was assumed and the simulated average power was compared to the average power data retrieved. The measured average power included smaller auxiliary equipment, which can explain the small difference in the measured versus simulated power readings. The actual versus simulated average power is shown in *Figure 37*.

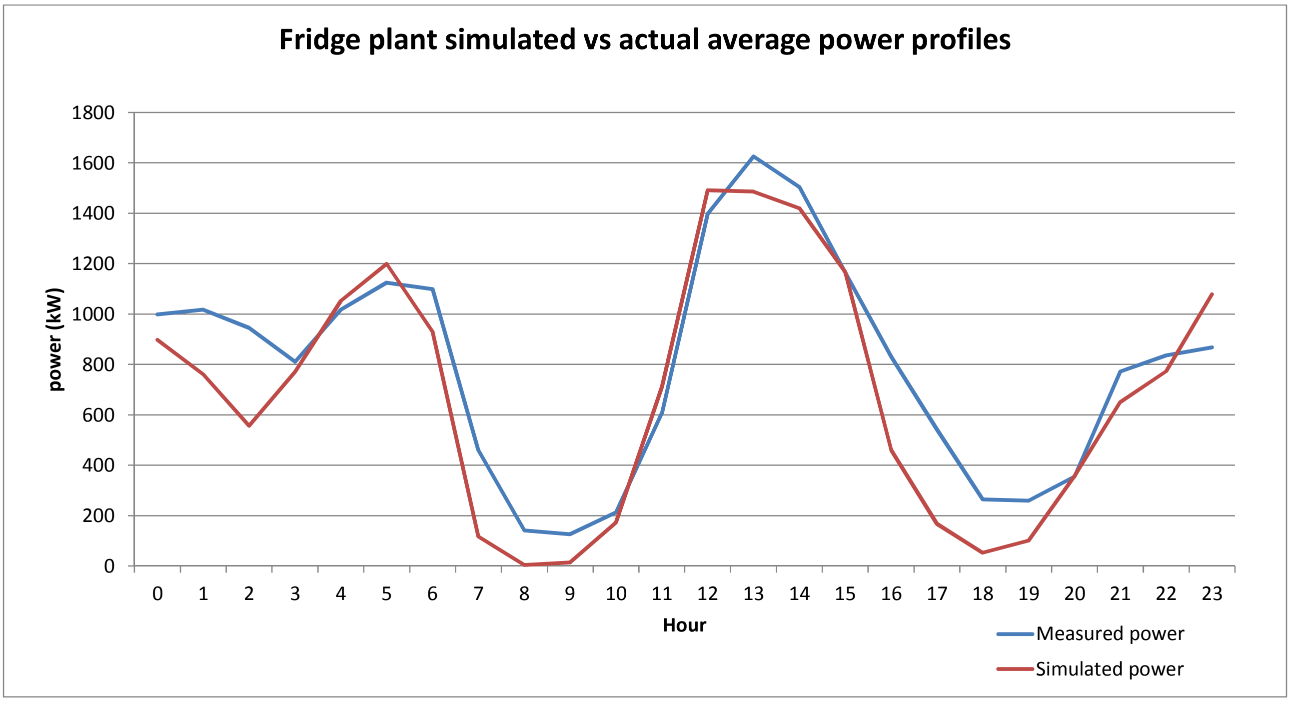


Figure 37: Actual versus simulated average power of refrigeration plant

With an assumed COP of 4.5, and using Microsoft Excel® the correlation between the retrieved and simulated average power was determined to be 0.94. It was found suitable for an approximation of the reduced average power with the reduced flow sent through the refrigeration circuit.

3.3 Incorporated control strategy

Before an incorporated control strategy of the reduction in chilled water can be implemented it must be determined which system apart from DSM interventions will be affected and in what manner. The magnitude of these effects must be considered as this will determine the cost implications. This is achieved by arranging the noticed effect into three categories namely operational, thermal and electrical. Due to the various components and their functions the integrated system must consider all aspects to determine the optimal operation. The flow chart in *Figure 38* is used to determine the most effective scenario of operation on a trial and error basis.

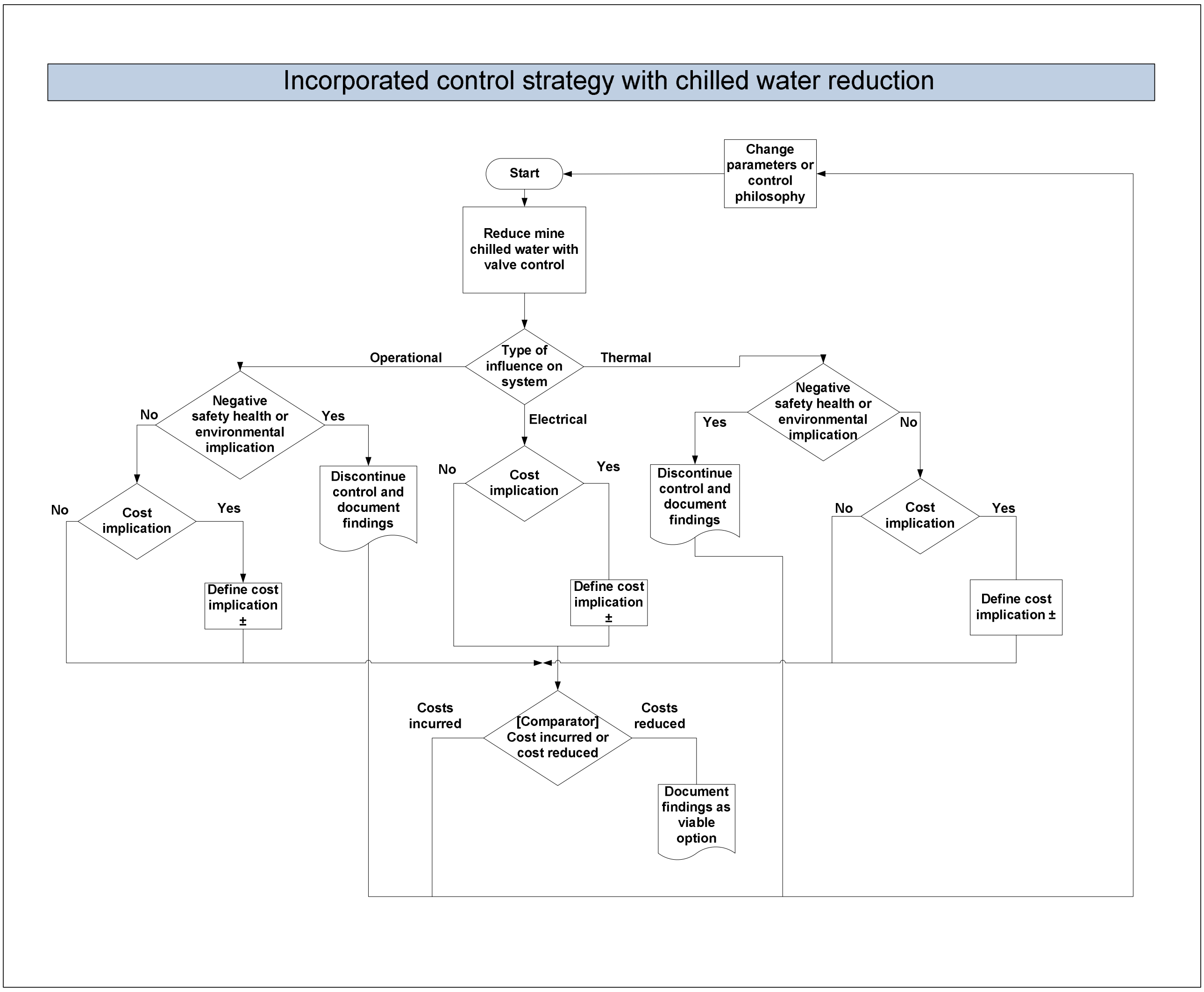


Figure 38: Flow chart to determine optimal control

Using the flow chart the optimal control can be determined. It is important to ensure that each effect is documented with the relevant implications. The cost implication must also be considered in this respect.

3.4 Determining most cost effective control

To ensure that the most cost effective control strategy is implemented, a cost comparison between each system affected by the reduction in chilled water is necessary. This is achieved with the aid of the simulation model. Apart from the operational and safety perspective, if the constraints are satisfied, the simulation model can be used to determine the cost implications of the intervention on the complete mining water cycle.

In an underground water reticulation system determining the cost of chilled water in relation to temperature can become intricate due to the many influencing factors. To define the cost with regards to electrical energy used, the tariff structure must be analysed.

Large energy consumers such as mines use the Megaflex tariff structure found in Appendix G. This tariff can be arranged into three periods of a typical week namely Weekdays, Saturdays and Sunday. The peak, standard and off peak period changes in cost per kWh and vary from winter to summer. The average weekday summer kWh unit cost for the Megaflex tariff structure is approximately R0.43 and R0.80 during the more expensive winter periods. This results in an average cost of R0.60 per kWh per annum.

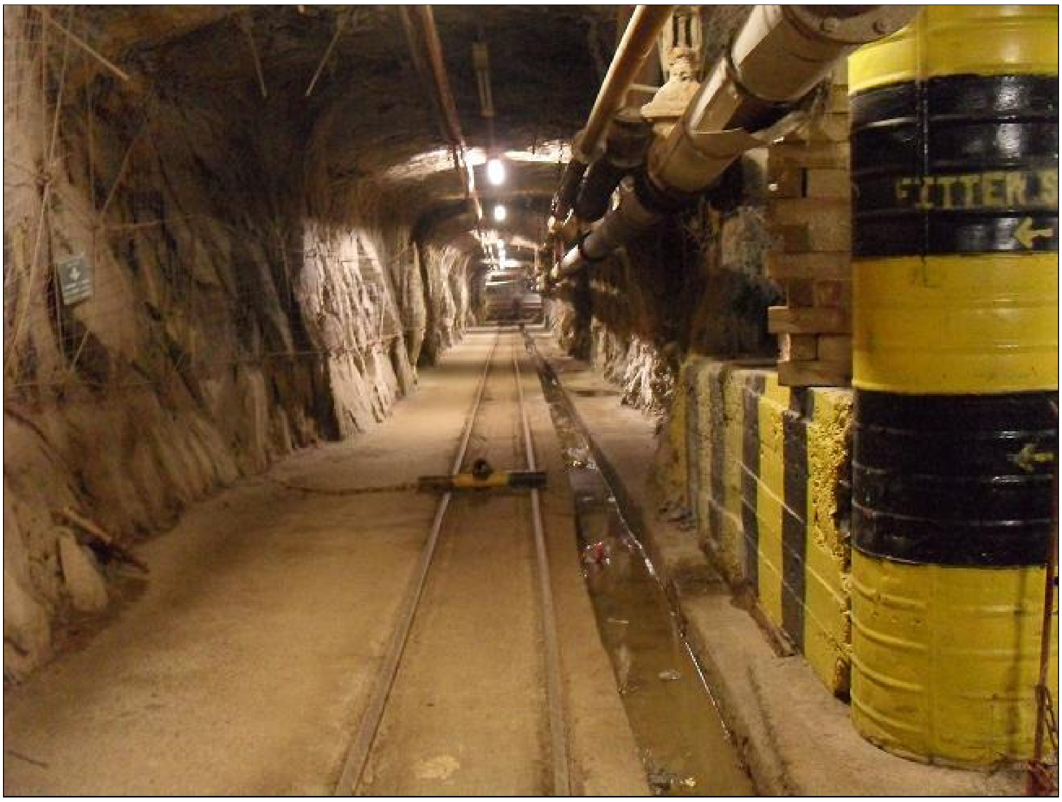
The results will be based on the cost of electricity using the Megaflex TOU tariff structure to determine the implications in the cooling, energy recovery and dewatering systems. This will ensure these different aspects can be compared to each other when the impacts are related to electrical energy costs.

3.5 Conclusion

In Chapter 3, each of the models representing a system affected by the reduction in chilled water flow was constructed. Each component was validated using actual data retrieved from the mine and correlations were determined for each data set. Correlation coefficient values ranged from 0.88 to 0.98.

A simplified strategy was developed to determine the most cost effective operation of the system by a succession of trial and error operations. The best possible operation can then be determined. In Chapter 4, these models will be applied to a case study to determine the effect of the reduction in chilled water on each system and then determine the cost impact of the operation.

CHAPTER 4: CASE STUDIES



Mine haulage with overhanging mining services piping [Photo by Iritron (Pty) Ltd]

Simulations are applied to case studies to determine actual functional influence as well as financial cost and operation implications. Recommendations are made to ensure optimal operation.

4.1 Introduction

There are numerous mining operations throughout South Africa that have one or more of the system components described and modelled as part of chapter 2 and chapter 3 in operation. However, it is not common to find a mine with all the system components operational in one shaft.

In this chapter, Mine A and Mine B were used as case studies to demonstrate the effects and determine the operational influence and cost implications of the reduction in chilled water flow on components throughout the mine.

4.2 Case study - Mine A

4.2.1 Background

Mine A is situated close to Carletonville near the N12 road. The mine consists of two main or vertical shafts and two sub shafts reaching depths of approximately 3500 meters below surface. There are a number of Pelton turbines, BAC's, fridge plants and dewatering pumps installed throughout the mine. The chilled water piping network is complex with numerous users and different demands. The basic operation with regards to the chilled and hot water used throughout the mine can be explained by referring to the layout shown in *Figure 39* and *Figure 40* respectively.

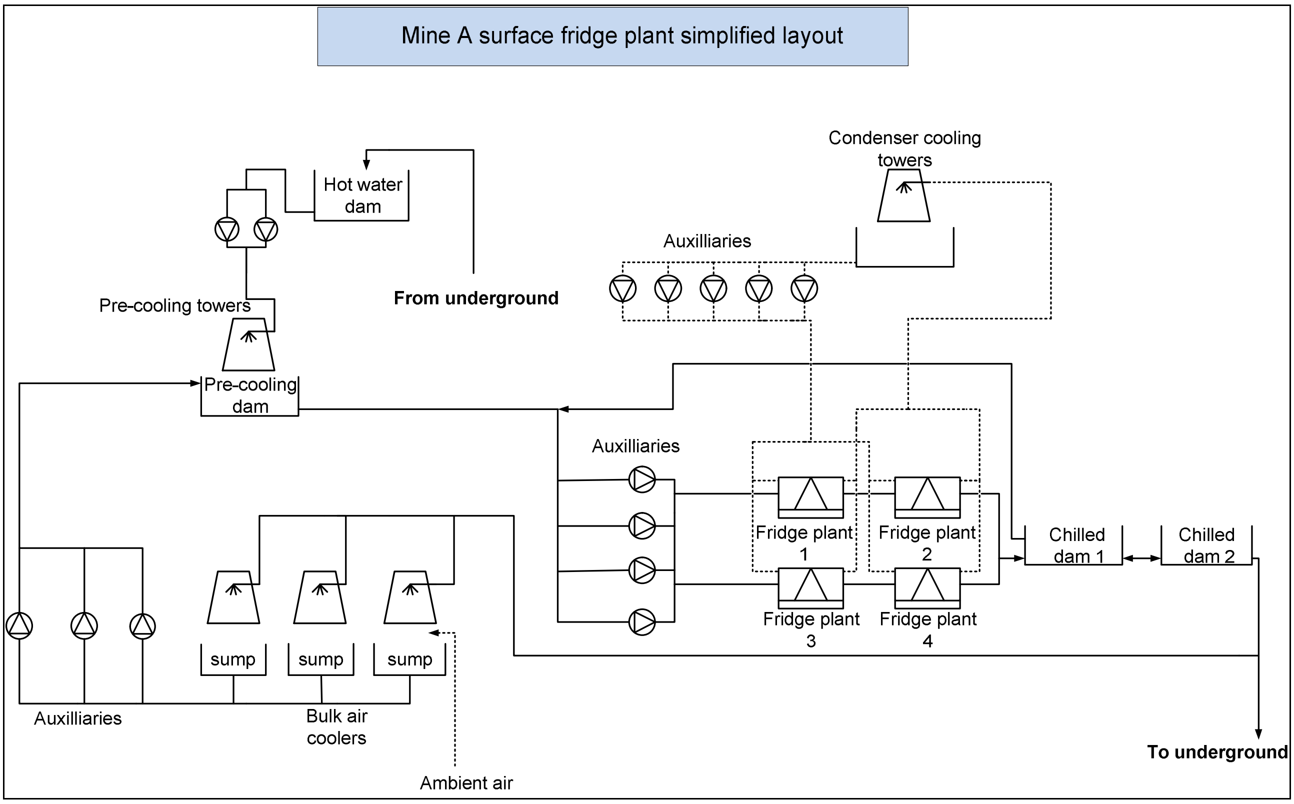


Figure 39: Simplified surface fridge plant layout of Mine A

In the surface refrigeration plant, hot water is pumped by the multistage pumps at 29 L to the surface holding dam at approximately 29 ℃. On surface, this hot water is pumped through the pre-cooling towers that reduce the temperature to nearly 19 ℃. The cooled water is pumped from the pre-cooling sump to the first two of four fridge plants that cools the water to 5 ℃ and is ultimately stored in the chilled water dams.

The total COP of the fridge plant is 5.25 [2] with an installed cooling capacity of 42 MW. From the chilled water dams, approximately 185 litres per second is sent to the surface BAC, to cool the ventilation air, and the residual water is sent underground.

[2] Dr. D. Arnt, Consulting Engineer, Enoveer, *Research and Development,Contracted to Temm International,* 17 Jan. 2010.

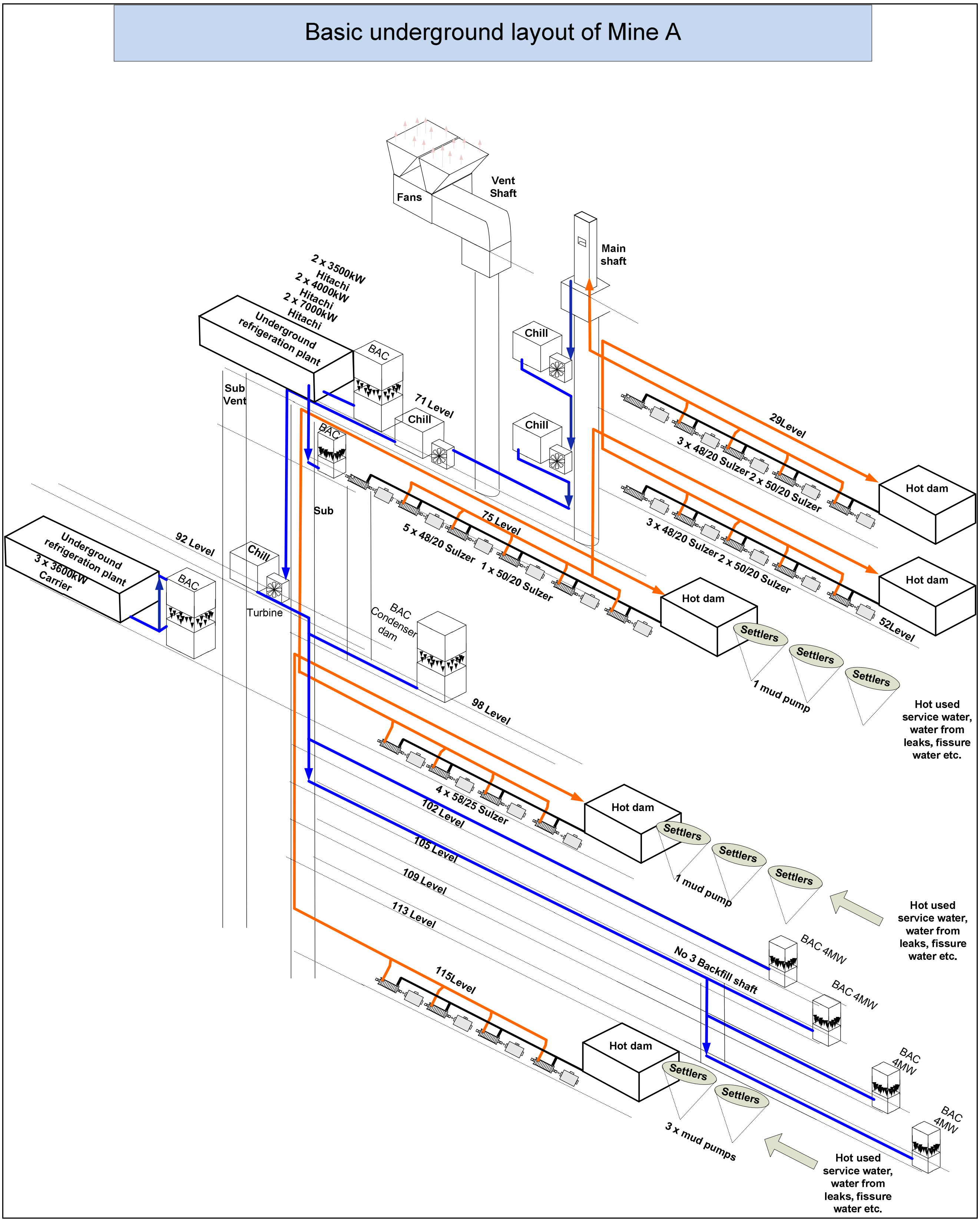


Figure 40: Basic underground layout of Mine A

In terms of the underground water cycle, chilled water sent underground flows to the 29L turbine. The Pelton turbine on 29L is installed in parallel with a dissipater valve. The flow is controlled by the needle valve installed on the Pelton turbine. A repetition of the Pelton turbine installation on 29L is found on 52L, 71L and 92L, but with different installed capacities.

The production levels are situated from level 78L downwards with each level consisting of a main haulage and a RAW transporting ventilation air towards and from the workings. Various types of BAC's are installed on levels 71L, 75L, 98L, 100L, 102L, 105L, 109L and 113L with various cooling capacities.

In the water circuit, after the water was used either for mining or in the cooling circuit it is processed through the settlers on all pumping levels except 52L and 29L. The clear hot water is then held in the hot water storage dams ready to be pumped to surface. The dewatering system consists of multiple multistage dewatering pumps pumping water in a cascade manner from each level to the next and ultimately to surface. The pumping levels include 115L, 100L, 75L, 52L and 29L.

A WSO project was implemented on site. With the collection of historical data and the simulations, the effect of the WSO project can be determined throughout the mine. An independent measurement and verification (M&V) team determined the performance assessment of the project for the months of March, April and May in 2011.The M&V team determined an average impact of 3.152 MW for Mine A's WSO project as shown in *Figure 41*.

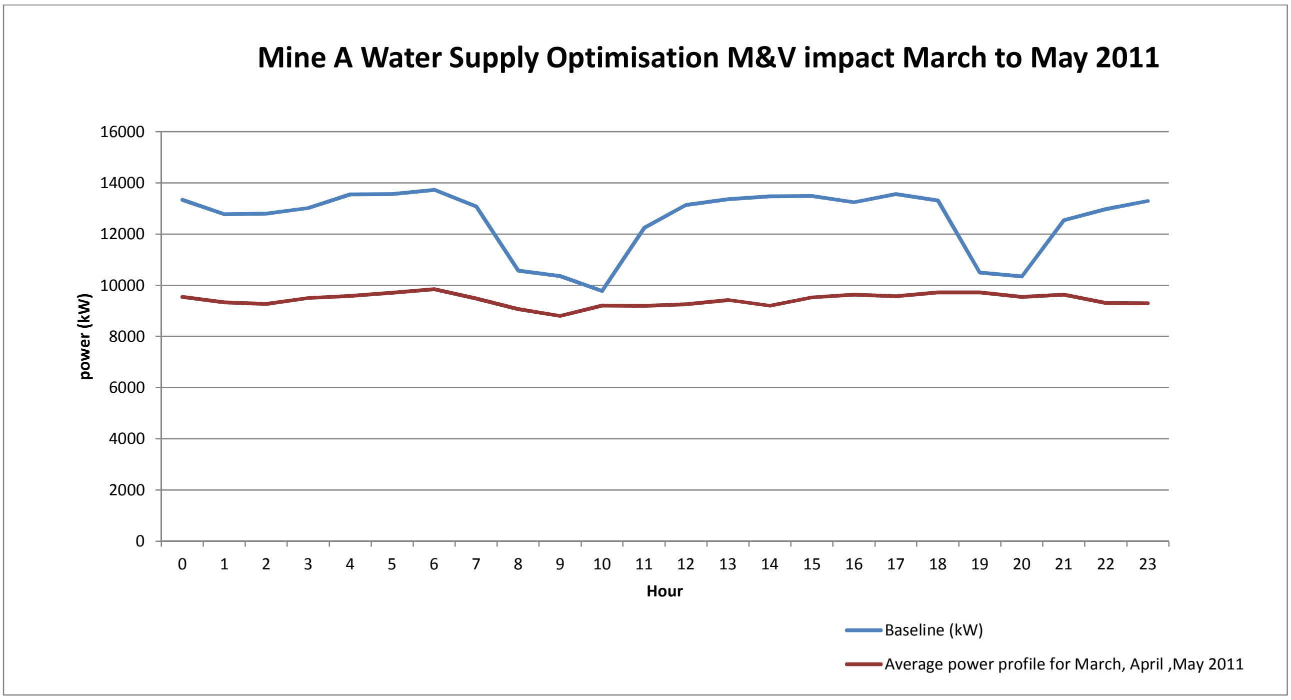


Figure 41: Mine A performance assessment impact for March, April May 2011

Using the available historical chilled water flow data for the baseline and performance assessment period, the reduction in chilled water was determined. The baseline period ranged from September to November 2009. Using these dates, historical data was gathered on the chilled water flow sent to 88L, 92L, 95L and 98L. The simplified chilled water system configuration used in calculations is shown *Figure 42*.

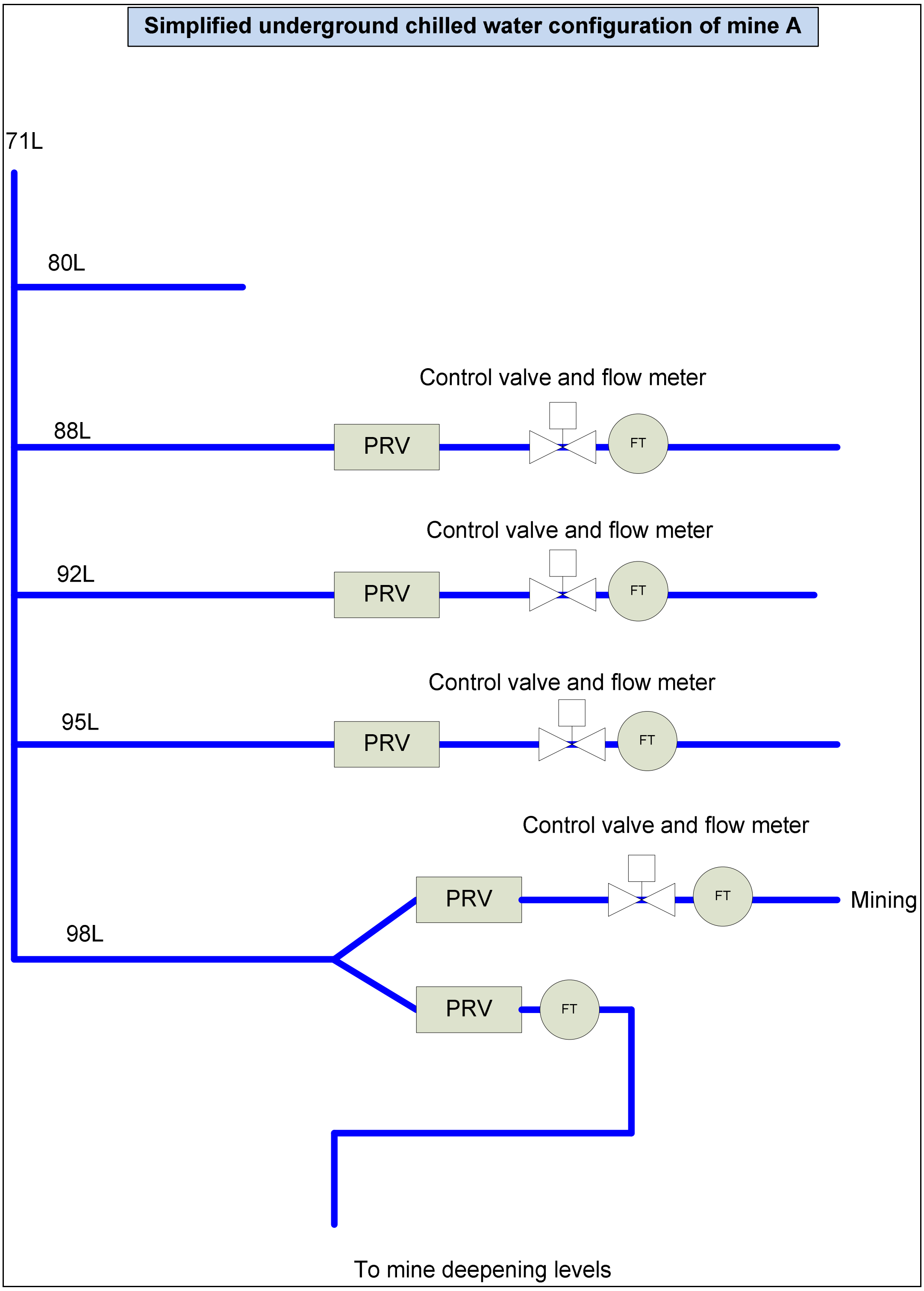


Figure 42: Mine A simplified underground chilled water piping configuration

Using one month of historical data, the average weekday flow for the month of September 2009 was compared to the average weekday flow for the month of April 2011 for the same mining levels. The average weekday chilled water flow difference of one month between the baseline and performance assessment period discussed is shown in *Figure 43*.

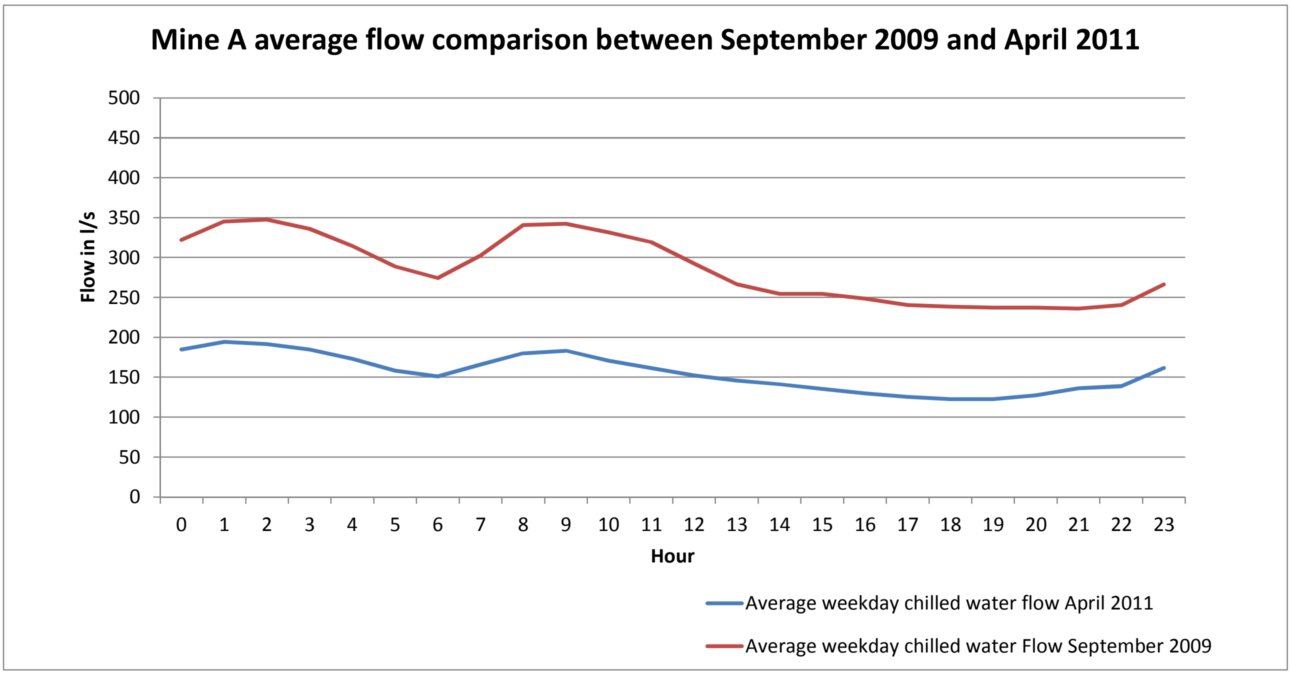


Figure 43: Mine A chilled water flow of baseline vs. performance assessment period

4.2.2 Turbines

It was assumed that 80% of this water is finally collected in the bottom pump chamber holding dams as production takes place from 78L downwards. The average reduction was found to be approximately 100 litres per second during a 24 hour weekday. This flow reduction was used to simulate the effect on the Pelton turbine as well as the surface refrigeration plant. The average weekday flow reduction used in the simulation system is shown in *Table 4*.

Table 4: Calculated reduced chilled water flow

Hour	Chilled water flow reduction in l/s
0	110
1	121
2	125
3	121
4	113
5	104
6	98
7	109
8	129
9	127
10	129
11	126
12	112
13	97
14	90
15	95
16	95
17	92
18	93
19	91
20	88
21	80
22	81
23	84

From the reduced chilled water flow to underground, the approximate output of the Pelton turbines was determined using the simulation. All Pelton turbines installed throughout the shaft were used in the simulations resulting in a cumulative impact, but due to technical problems, it must be noted, that at the time of this study most of the turbines were out of operation.

Using the simulation, the approximated average power reduction of the turbines situated on the four levels was determined. The cumulative average power reduction of all four turbines over a typical week day is shown in *Figure 44*.

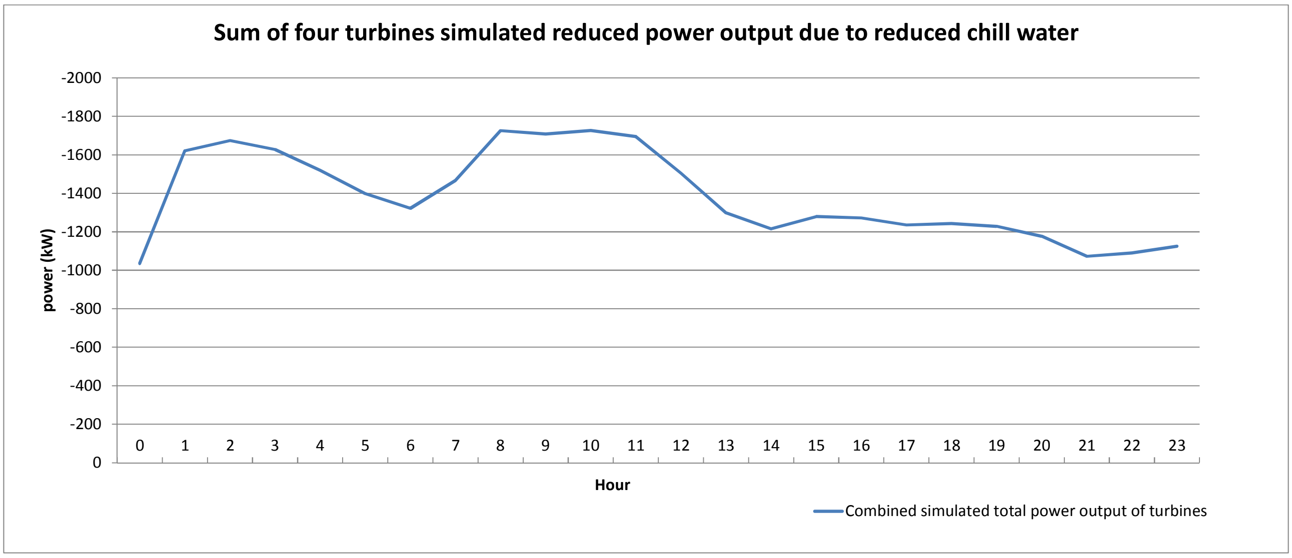


Figure 44: Mine A cumulative turbine simulated reduced average power output

For simplification and as a worst case scenario, the turbines utilisation in the simulation period was assumed to be 100%. It can be seen from *Figure 44* that there is a reduction in the average power output of the four turbines if they were operated continuously and simultaneously.

4.2.3 Fridge plant

Another component affected as a result of the reduction in chilled water is the surface refrigeration plant. As a result of the reduced flow to underground there will be a reduced flow to the surface plant. Subsequently there will be a reduction in the amount of electrical energy required to cool the chilled water, due to less water sent through the cooling process.

To simulate the average power reduction, the COP is required. The COP was found to be 5.25 and the temperature of the chilled water entering the surface refrigeration system was measured to be 30℃ during an average weekday.

The average temperature of the chilled water stored in the chilled dams was measured to be approximately 6 ℃ during weekdays. These values were used to simulate the average power required to cool the water to the desired set point temperature. The simulated average power required is shown in *Figure 45*.

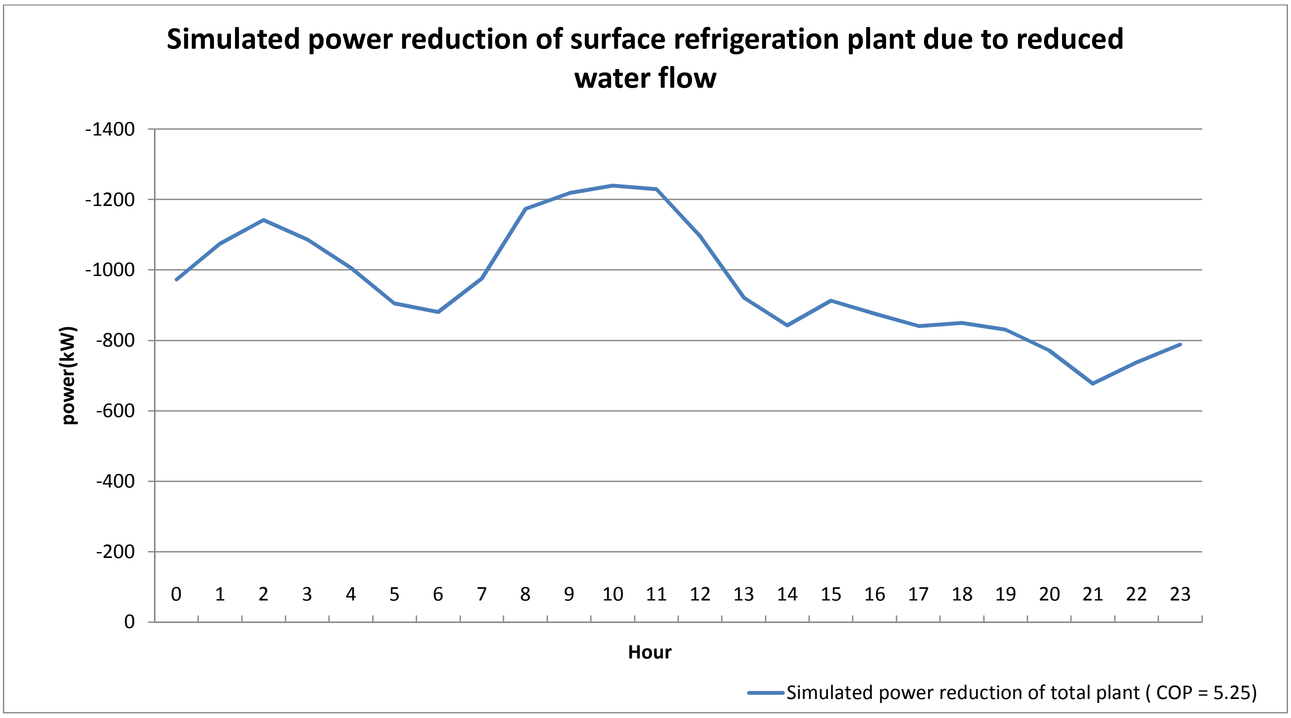


Figure 45: Mine A refrigeration plant simulated power reduction due to reduced flow

4.2.4 Bulk air cooler

The underground cooling system consists of refrigeration plants, BAC's and cooling units. At Mine A, the BAC situated on 98L comprises of two stages and is installed approximately 1.5 km from the shaft station. This BAC was selected in the analysis as it can be affected by the WSO control valve on 98L. In the case of this BAC, it was found that the chilled water is not supplied directly to spray nozzles but rather to a reservoir that supplies the second stage of the BAC. A simplified layout of the BAC on 98L is shown in *Figure 46*.

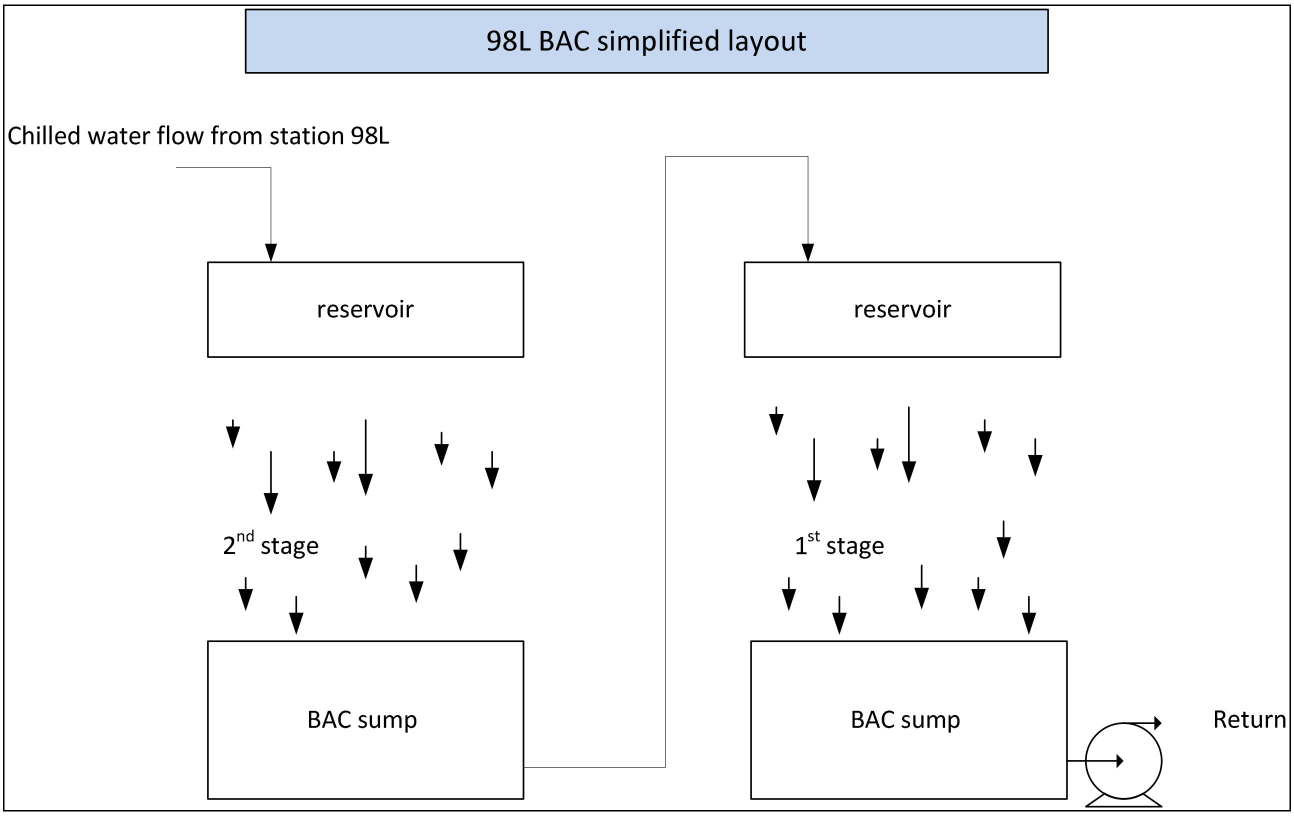


Figure 46: Simplified layout of mine B 98L BAC

With this type of configuration, the change in pressure as a result of the WSO project control will not affect the effectiveness of the BAC but rather the water level of the reservoir supplying the BAC. The mine is planning to install a flow regulator on this chilled water supply line to the BAC. It was noted that the reduced flow to the BAC as a result of a reduced pressure in the chilled water line, can result in drainage of the reservoir, thereby stopping the operation of the BAC. However, the BAC cooling output will not be directly affected by the pressure and therefore not simulated.

4.2.5 Chilled water car

Another facet applicable to the cooling system and influenced by the reduction in chilled water is the CWC. It was noted by mining personnel that there are numerous CWC's installed throughout the shaft with installed capacities ranging from 200 kW to 300 kW. No real time data of the CWC is available. Usually, no digital or analogue communications is available to their location for logging real time data. Only mining weekly or monthly "check sheets" are available that makes it difficult to determine the real time effect when the water is reduced.

The CWC installed on 88L was used in the simulation. Using historical data for the performance assessment month of April 2011, the effect of the valve control on the downstream pressure was determined. Two typical days was selected and average pressure reduction was compared to the average pressure in the non-entry period when no control took place. This is shown in *Figure 47*.

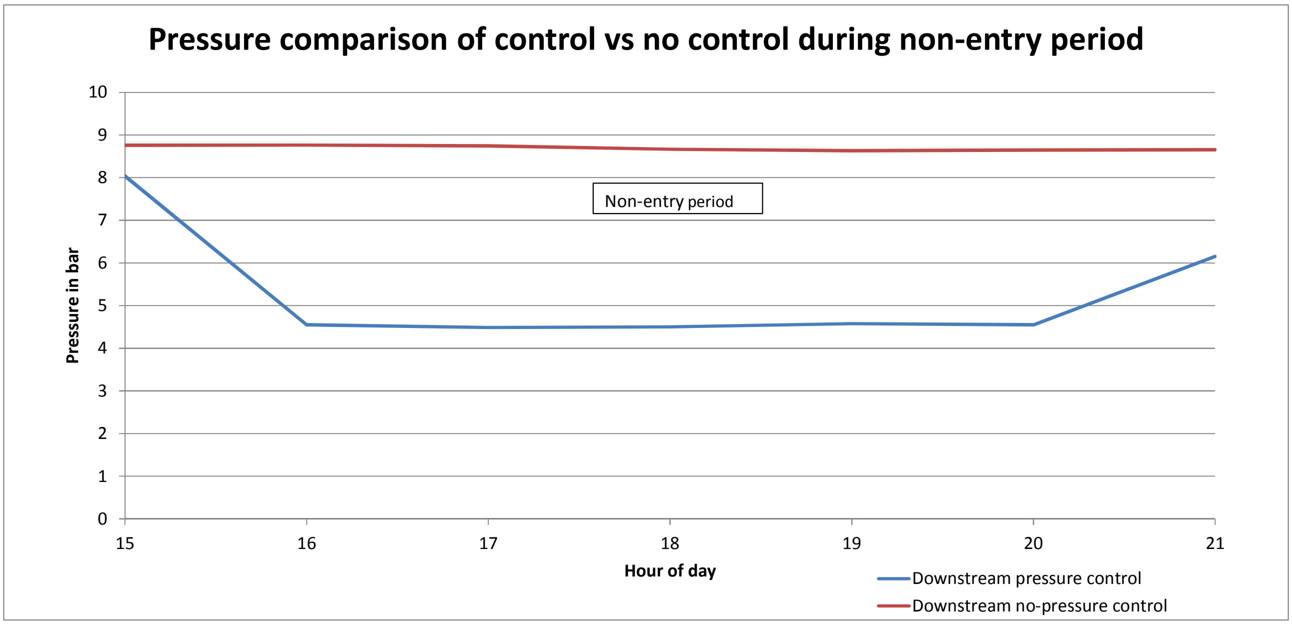


Figure 47: 88L pressure with no control and control enabled during the non-entry period

It can be seen from *Figure 47* that there is a substantial reduction in pressure, however as on most of the levels that are controlled, the pressure is only reduced to a minimum of approximately 4,2 bar during the non-entry period. Using the conducted test on a typical CWC described in Appendix F, as a basis, the pressure versus flow relation was determined. This is given in *Figure 48*.

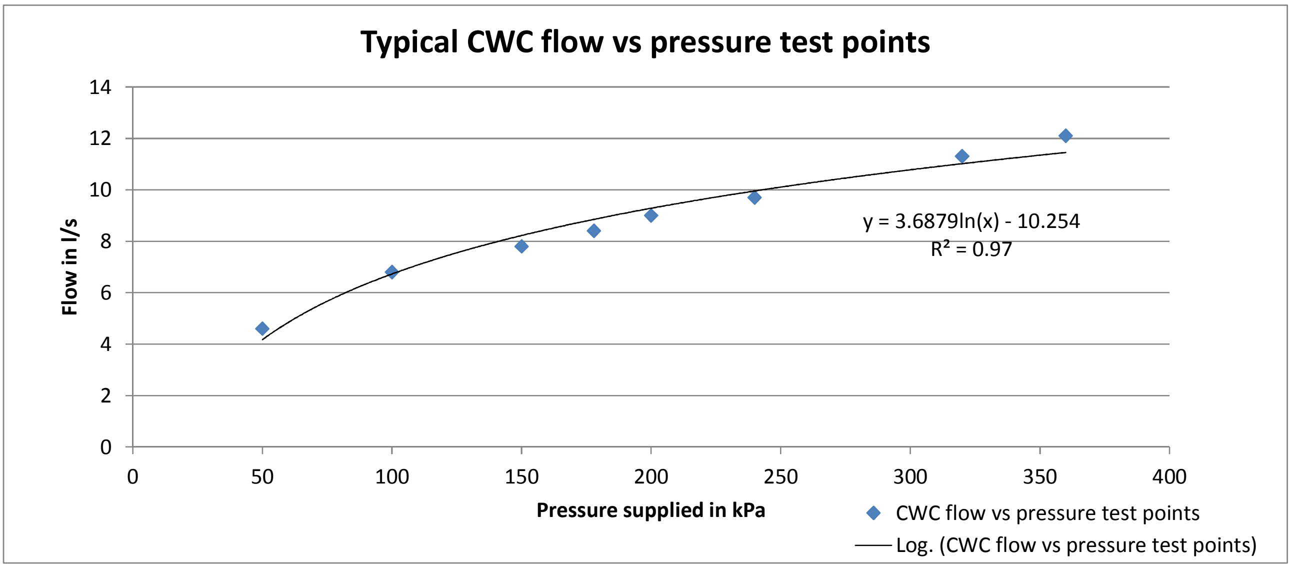


Figure 48: CWC test pressure versus flow relation

It can be seen that the flow through the CWC increases with an increase in supply pressure. This relation was used in approximating the effects of the reduced pressure and subsequently the reduced flow on the CWC effectiveness. However, assumptions had to be made, which are given below.

- Neglecting line losses, booster pumps etc., thus the pressure supplied is the pressure at the inlet of the CWC.
- Used water is dumped to the drain.

It was found that reducing the pressure from approximately 800 kPa to 420 kPa only has a minimal effect on flow through the CWC when no constant flow valve is installed. In the test it was determined that at 350 kPa, the flow through the CWC is approximately 12 litres per second. In this case study, reducing the pressure from 800 kPa to 420 kPa results in an average flow reduction from approximately 14.7 to 12.7 litres per second. Using the information obtained from the mine for this CWC's inlet and outlet temperature of 18.3° and 26.7° respectively, a cooling reduction of approximately 68 kW was found.

4.2.6 WSO impact on total system

To determine the financial impact, a cost model was developed. The 2013/2014 Megaflex tariffs were used to determine the annual cost. The 24-hour average profiles determined with the aid of simulations was used in the model shown in *Figure 49*.

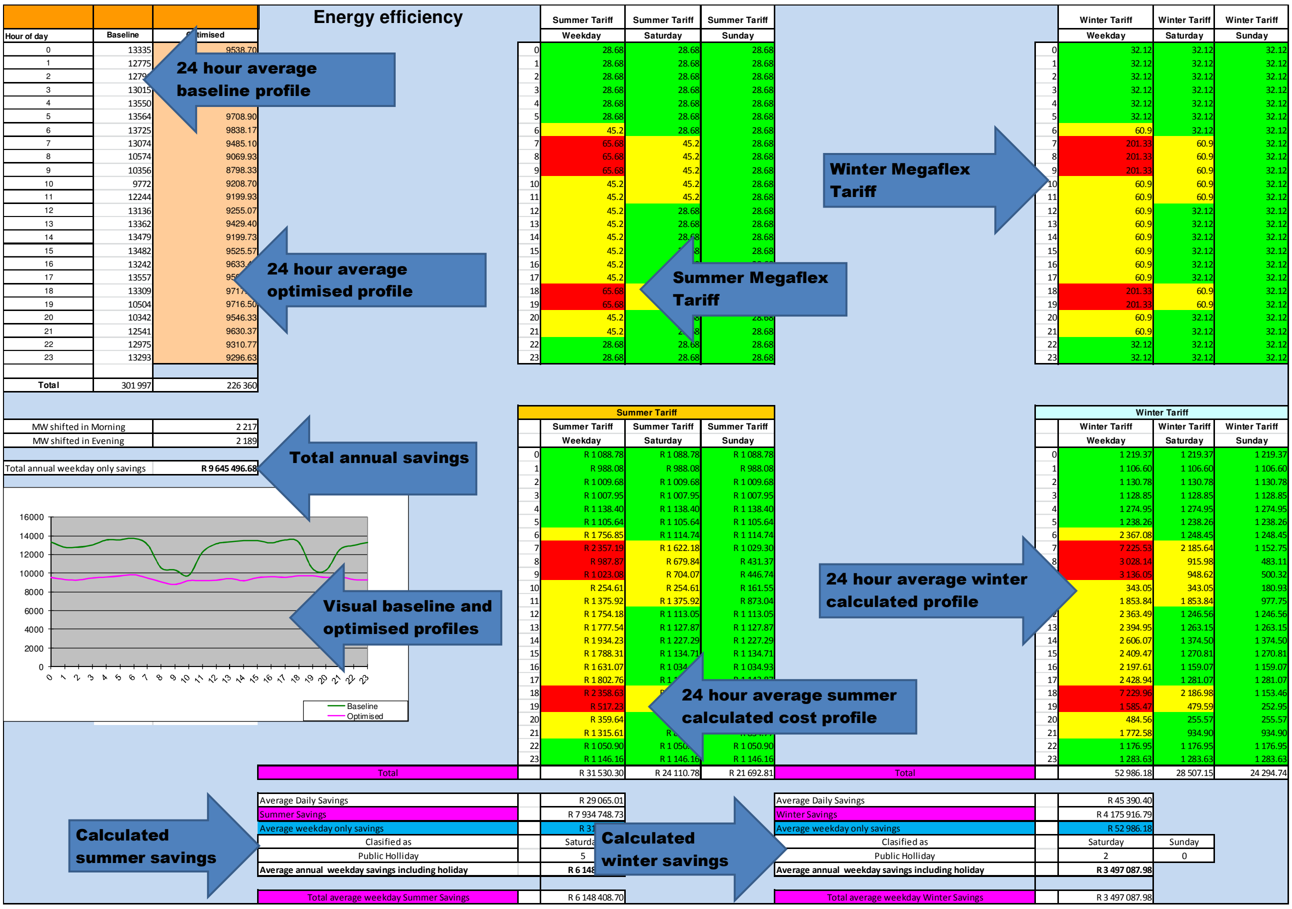


Figure 49: Model used for cost comparison

The cost implication on each system was compared. The annual cost comparison between the components simulated was captured and tabulated and is shown in *Table 5*.

Table 5: Cost comparison between each system

Description	Average impact (kW)	Cost (R/per annum)
Mine dewatering system	3150 kW	R 9 640 000.00
Turbines	- 1400 kW	-R 4 710 000.00
Surface refrigeration plant	960 kW	R 3 230 000.00
Total simulated annual saving		R 8 160 000.00

From *Table 5* it can be seen that there is a substantial cost saving even with the simulated worst case scenario negative effect of the Pelton turbines. The reduced chilled water flowing through the surface refrigeration plant already accounts for the potential savings on the CWC and BAC's due to the reduced flow.

To give an indication of the effect of the reduced cooling output of the simulated CWC and BAC on the mining operation, an assumption was made. The total CWC cars and BAC's installed on the applicable mine levels was determined using the current available figures. It was then assumed that the simulated reduced cooling will be experienced by each of the applicable CWC units. The combined average cooling reduction was then compared to the total cooling capacity of the surface refrigeration plant. The results are shown in *Table 6*.

Table 6: Cooling system comparison

Description	Number of possibly affected units	Simulated cooling output reduction	Combined cooling output reduction
CWC	13	68 kW	884 kW
BAC	n/a		
Total			**884 kW**
Average annual surface fridge plant cooling output in kW (COP of 5.25)			**28300 kW**
Difference in percentage			**3.10%**

From *Table 6* it is seen that the reduced cooling output as a result of the WSO project is relatively small when compared to the surface refrigeration plant cooling capacity. The reduced cooling output was found to be approximately 3.1 % using a basic extrapolation technique and the assumption that each CWC affected is of the same magnitude.

4.3 Case study - Mine B

4.3.1 Background

Mine B is situated on the outer region of the Gauteng province. The mine consists of a main shaft and a sub shaft reaching to depths of 3000m below surface. Numerous pump chambers, BAC's, CWC's and refrigeration plants are installed throughout the mine. The mine chilled water can be explained by referring to the representation of the underground water cycle and surface refrigeration plant given in *Figure 50* and *Figure 51*.

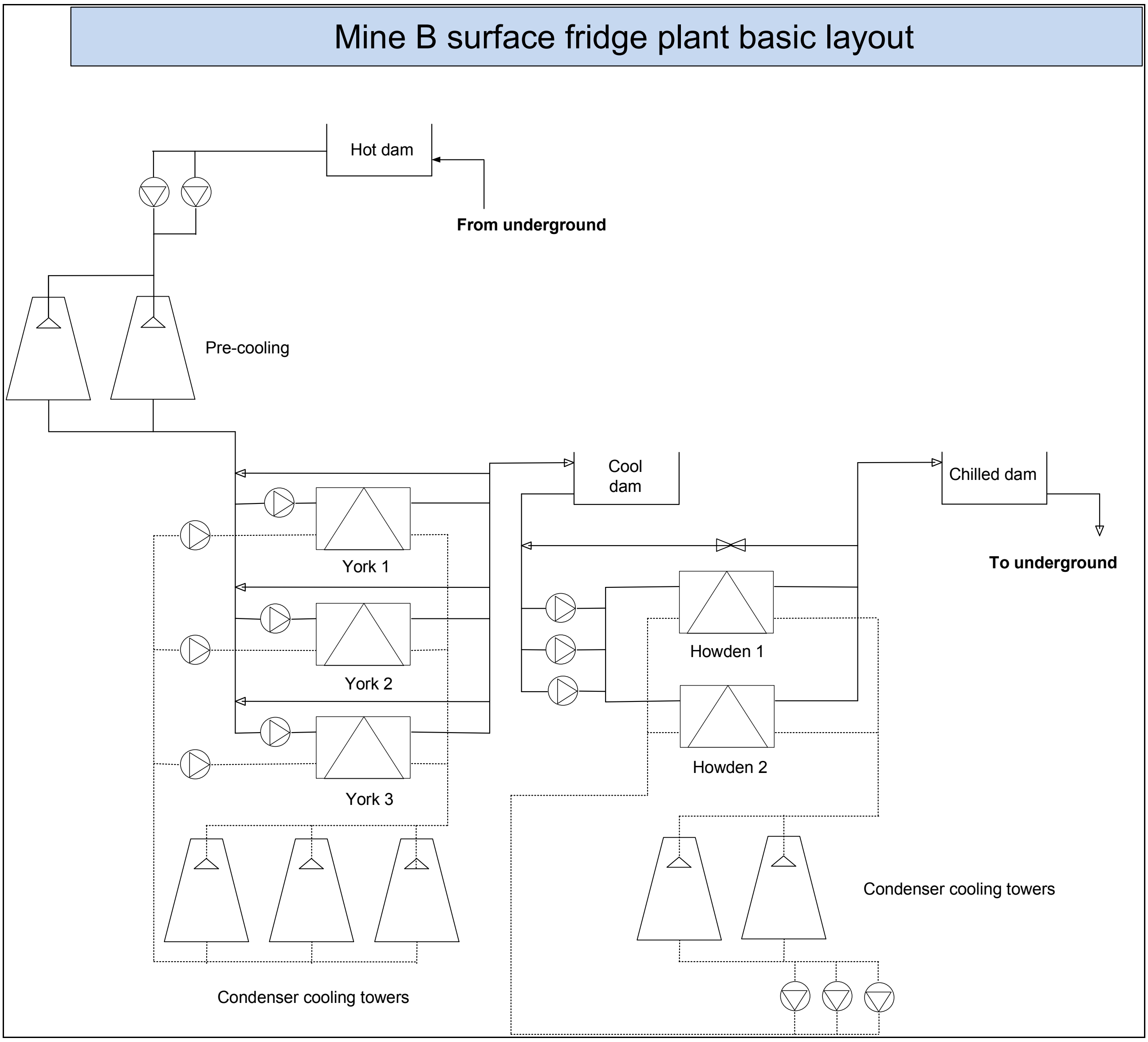


Figure 50: Simplified surface fridge plant layout of Mine B

Water is pumped into the surface hot water holding dam at approximately 30℃ from the dewatering pumps on the Intermediate Pump Chamber (IPC) level. The pre-cooling towers cool the water temperature to approximately 15 ℃ using ambient temperature. The pre-cooled water is then sent through the three parallel York chiller plants that cool the water to 6 ℃ that is stored in the cool dam. Finally, the water is sent through the Howden ammonia chillers that cool it to approximately 2℃, after which it is stored in the chilled dam ready to be sent underground.

The water sent underground is stored in chilled water holding dams on 20L and is then supplied to two main sections underground. The main production levels are 37L, 39L and 40L that have the highest demand for chilled water compared to the other levels.

Underground production levels consist of haulages with RAW to transport the hot contaminated air back to the shaft for extraction via the surface ventilation fans. There are BAC's installed on 39L and 40L with different installed capacities.

The dewatering system consists of settlers on 40L and four multistage pumps pumping to 31L. From here water is pumped to 20L, then IPC, and lastly to surface. Each of the four pump chambers consists of four multistage pumps. These pumps are installed in a parallel pumping configuration with two dewatering columns at each pump station. A simplified layout of Mine B is shown in *Figure 51*.

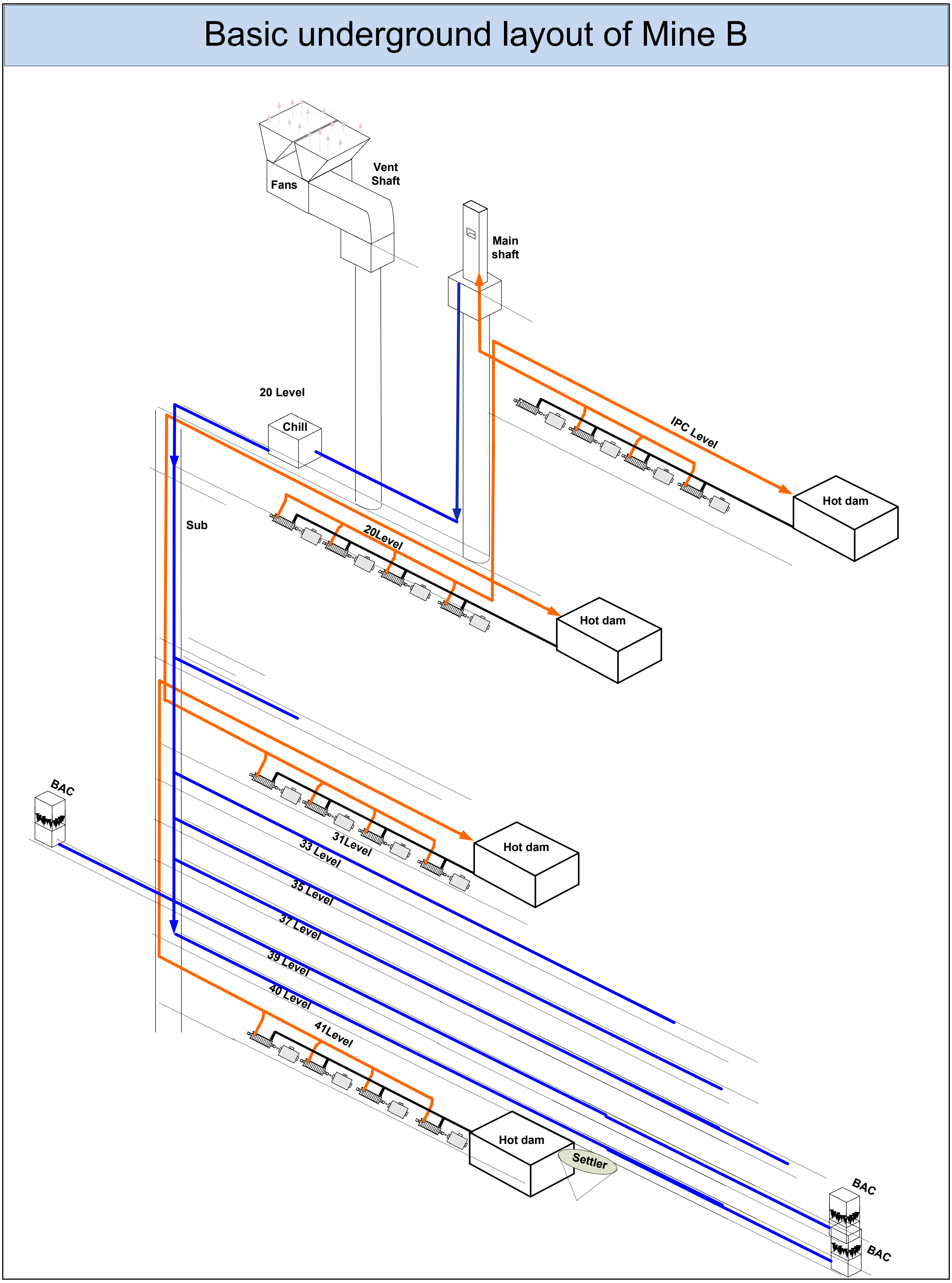


Figure 51: Simplified underground layout of Mine B

With the implementation of a WSO project on Mine B, an independent M&V team determined the impact of the intervention for the months of January, February and March 2012. The findings were reported in three official performance assessment reports. It must be noted that hot water can be exported from one of the sister shafts to Mine B, which resulted in an adjustment to the baseline during each performance assessment month.

The M&V team determined an average impact of 3.54 MW during the performance assessment period. The baseline and performance assessment period versus average optimised profile is shown in *Figure 52*.

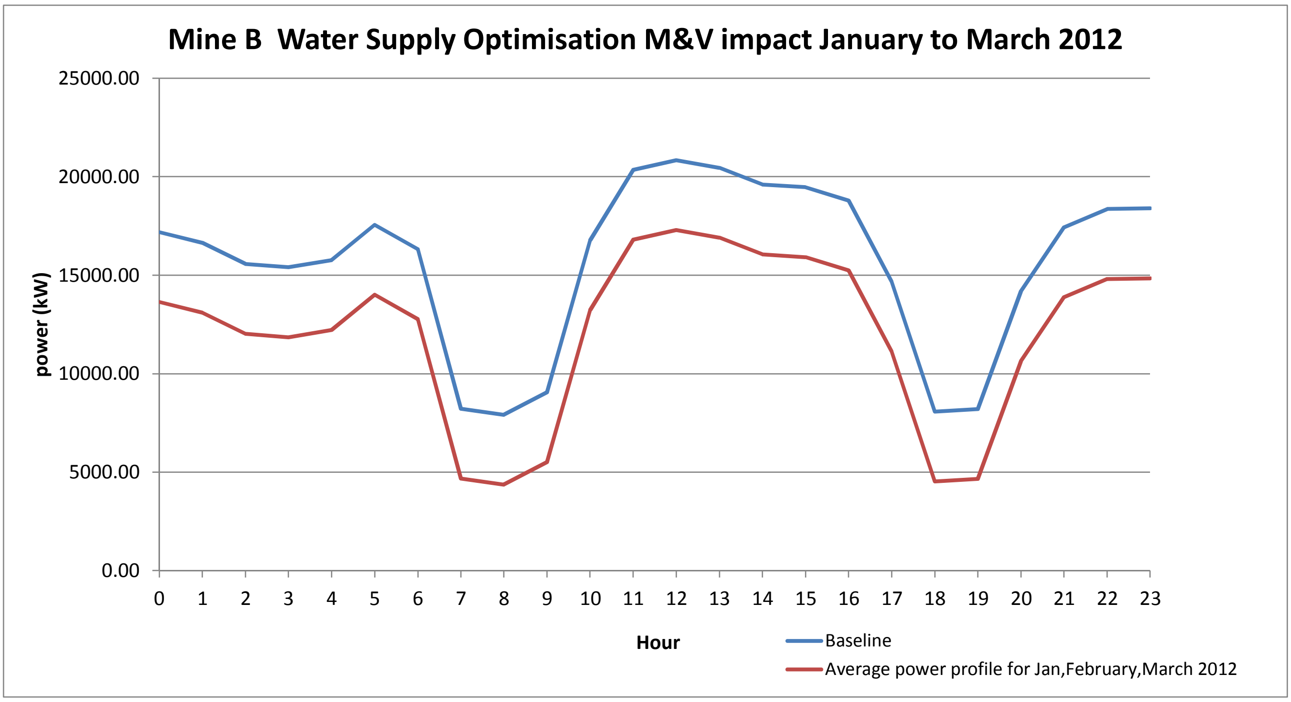


Figure 52: WSO performance assessment baseline and optimised profile of Mine B

Using the baseline and performance assessment periods historical data was gathered. The baseline period consisted of March, April and May of 2009 and the performance assessment period consisted of January, February and March of 2012.

The most productive mining levels use close to 80% of the total water consumption. These levels include 35, 37, 39A, 39B and 40L. The basic layout of the chilled water configuration system used in the analysis is shown in *Figure 53*.

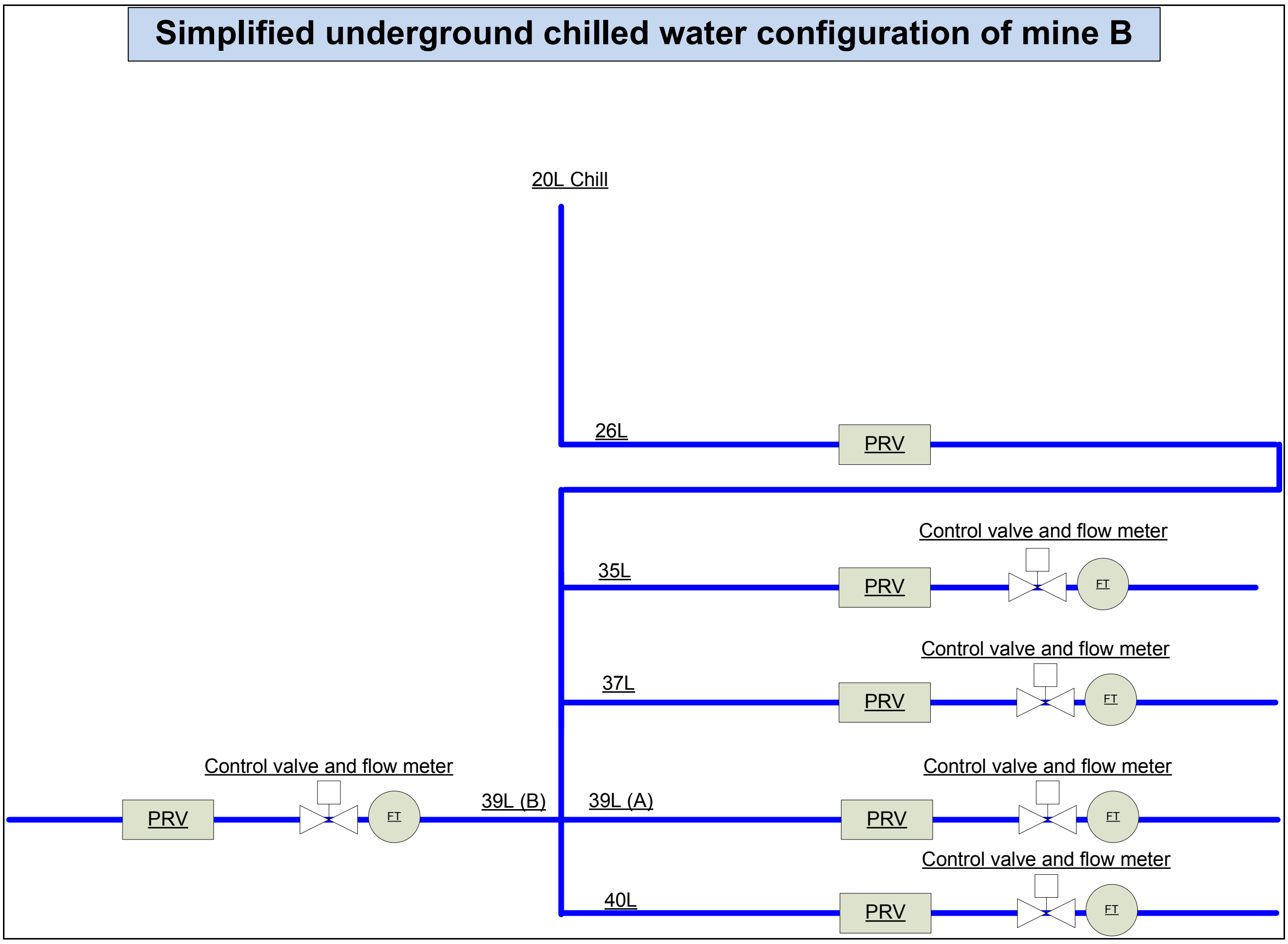


Figure 53: Simplified layout of Mine B chilled water supply system

No historical flow data was available for the baseline period. The average flow for one month after the baseline period (June 2009) was used in the analysis as this will closely resemble the chilled water flow in the baseline period.

The average weekday flow for June 2009 was compared to the average weekday flow for the performance assessment period month of February 2012. The levels showed in *Figure 53* were used in the analysis. The average reduction for these levels, when compared, is shown in *Figure 54*.

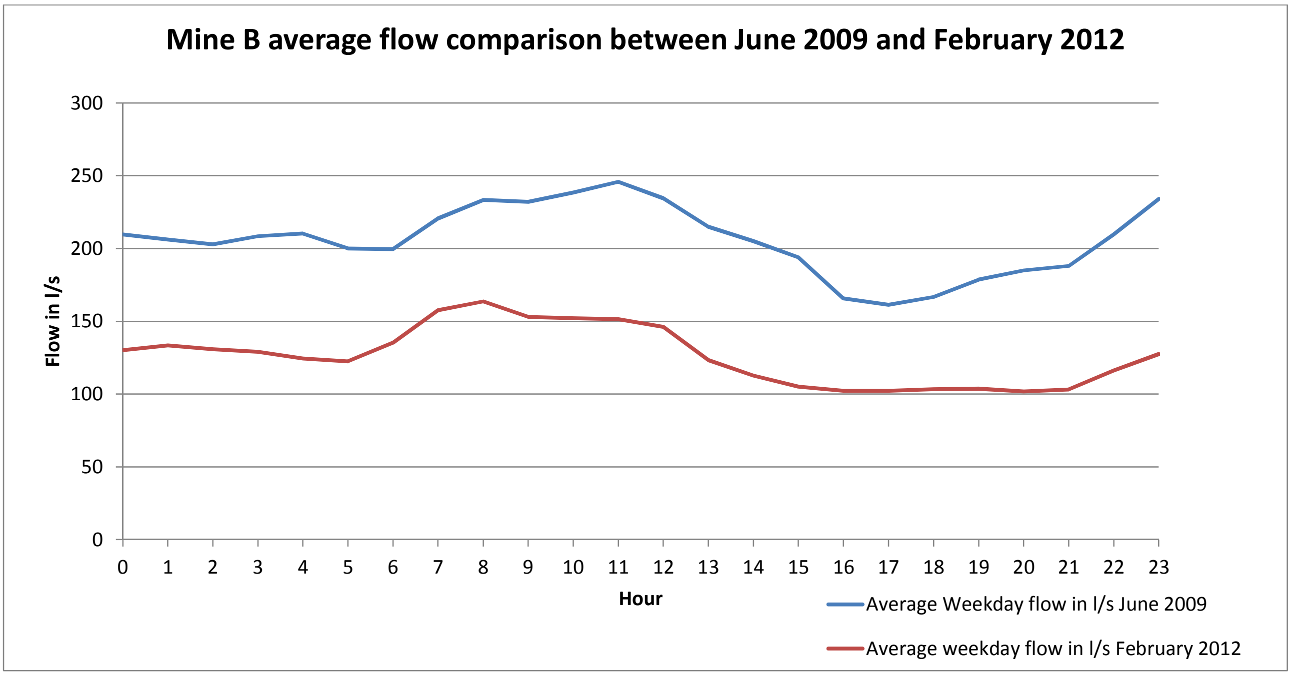


Figure 54: Average weekday flow comparison with flow saving

The reduced chilled water flow was determined to be approximately 79 litres per second for a typical weekday. Using this flow profile, the refrigeration plant and dewatering system were simulated. The average weekday flow reduction used for simulation is shown in *Table 7*.

Table 7: Calculated reduced chilled water flow

Hour	Chilled water flow reduction in l/s
0	79.6
1	72.7
2	72.0
3	79.4
4	85.8
5	77.7
6	64.3
7	63.1
8	69.7
9	79.1
10	86.2
11	94.4
12	88.3
13	91.6
14	92.5
15	88.7
16	63.6
17	59.0
18	63.4
19	75.1
20	83.1
21	84.8
22	93.5
23	106.6

4.3.2 Fridge plant

With the reduced chilled water, the first component simulated is the surface refrigeration plant. The reduced flow to underground will result in less water pumped to surface and ultimately less water sent through the cooling circuit. The surface fridge plant has a COP of approximately 6.3 [3].

Using this COP and the measured difference in temperature of 15℃ for the inlet and an average chilled outlet water temperature of 2℃, the average power reduction was simulated as shown in *Figure 55*.

[3] Dr. D. Arnt, Consulting Engineer, Enoveer, *Research and Development, Contracted to Temm International,* 17 Jan. 2010.

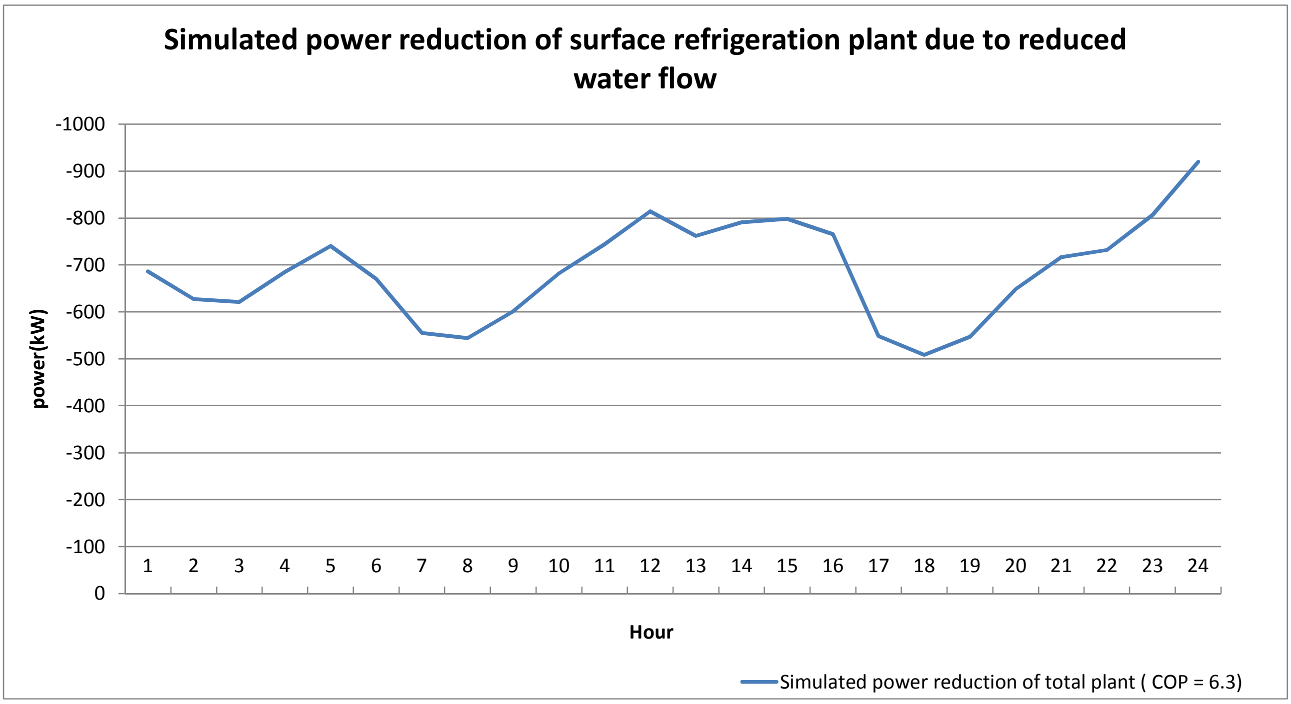


Figure 55: Simulated average power saving due to reduced chilled water through circuit

It can be seen from *Figure 55* that there is a reduction in the average power of the surface refrigeration plant with the reduced amount of flow sent through the cooling circuit as a result of the WSO project. The average daily reduction in electrical energy consumption was approximately 16500 kWh.

4.3.3 Bulk air cooler

The underground cooling units of Mine B consist of BAC's and CWC's installed throughout the mine. Water exits the 20L chilled dam at approximately 5 °C and is sent to the main mining levels. One of the BAC's used in the analysis is installed on 39L. This BAC spray chamber is installed on the 39L (B) line approximately 300m from the shaft. To determine the effect of the pressure fluctuations on the BAC the spray nozzles were used in the analysis. The nozzles were changed by a mine official from a ½ inch using 1 litre/sec to a ¼ inch using approximately 0.5 litres per second. These two types of nozzles are shown in *Figure 56*.

Figure 56: 39L BAC spray nozzles [Photo taken in October 2011]

By analysing the flow demand of a typical standard BAC spray nozzle with a change in chilled water pressure, the total consumption of the first stage of the BAC can be determined. However, assumptions had to be made as listed below:

- Assuming a total of 30 nozzles and 15 out of 30 are in the first stage (65° angle similar to specifications)
- A worst case scenario neglecting chilled water line pressure losses to the BAC.
- No flow control valve installed on the BAC supply line.
- Neglecting the effect of pressure change on spray pattern.

Two typical weekdays in the performance assessment period was selected for the analysis. The two days consisted of non-entry periods when no pressure control was visible and the second day when the pressure was reduced during the non-entry period. The difference in pressure was found to be approximately 2.8 bar on average during the non-entry period. This is shown in *Figure 57*.

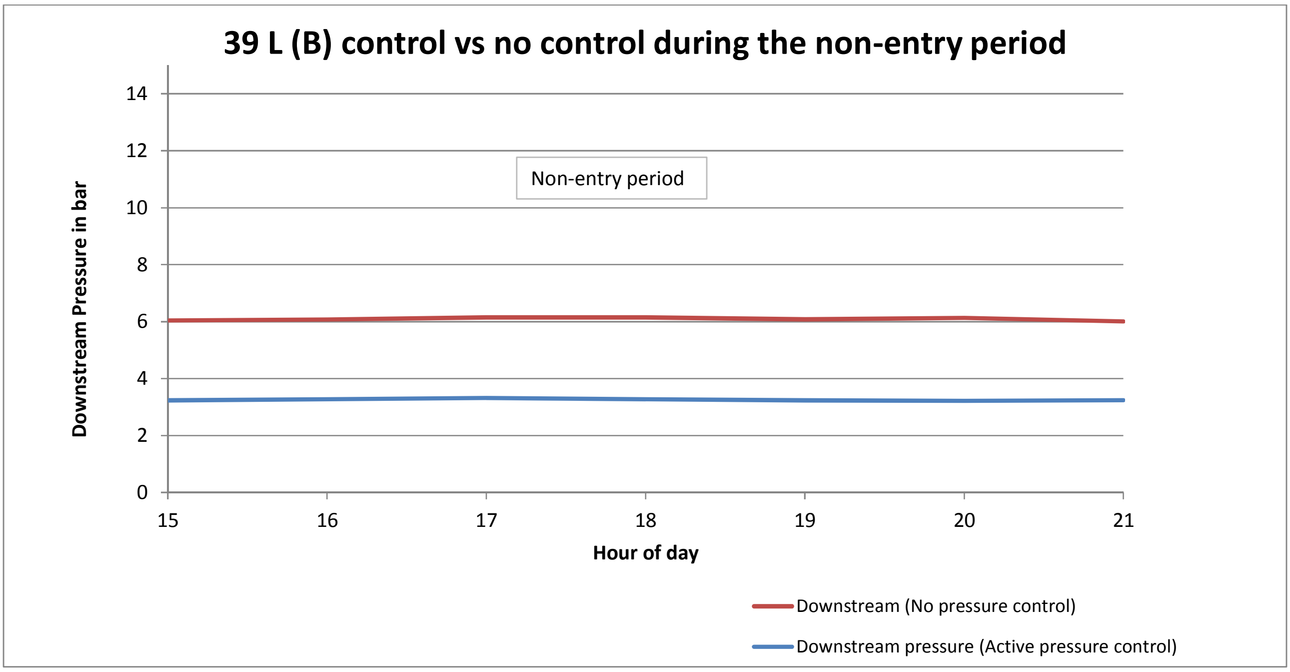


Figure 57: Difference in control pressure for 39 L (B) during non-entry period

Using the design specifications of the spray nozzles in Appendix E, the approximated reduced flow can be determined with the reduced supply pressure. Only the 15 first stage spray nozzles were used in the approximation and the average total flow reduction was determined to be 4.1 litres per second during the non-entry period.

With the aid of the simulation and the determined flow reduction as a result of the control during the non-entry period, the reduced cooling output was simulated. Mine officials stated the temperature of the water feeding the BAC is approximately 11℃ and the temperature of the outlet water is approximately 23℃. The simulated reduction in cooling output is shown in *Figure 58*.

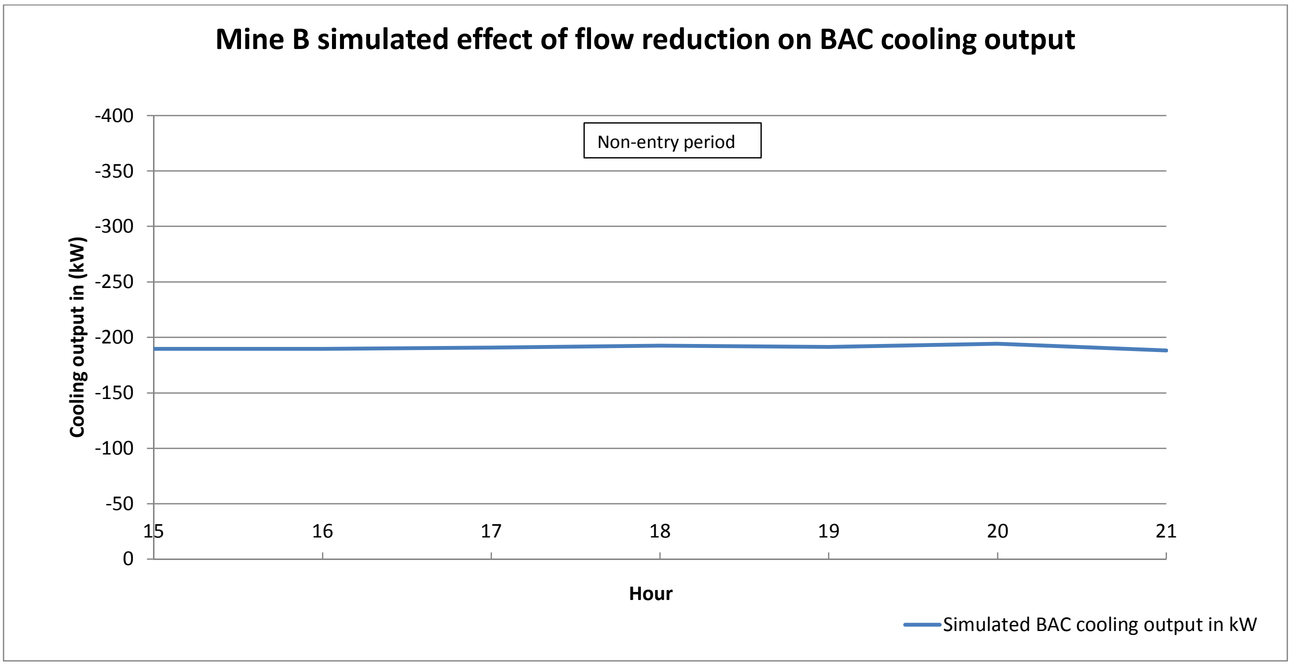


Figure 58: Simulated kW cooling output reduction of 39L (B) BAC

The reduction in chilled water resulted in reduced kW cooling output that can be seen in *Figure 58*. The reduced cooling output of the BAC as a result of WSO project control reducing the pressure during the non-entry period is approximately 190 kW.

4.3.4 Chilled water car

The feed line on 39L can feed to 39L (A) and 39L (B). The CWC installed on 39L (A) in the proximity of the locomotive battery bay was used in the analysis. In the performance assessment period no weekday data was available to represent a scenario where no control took place. A Saturday was selected to represent an inactive control scenario and used in the analysis. The pressure comparison is shown in *Figure 59*.

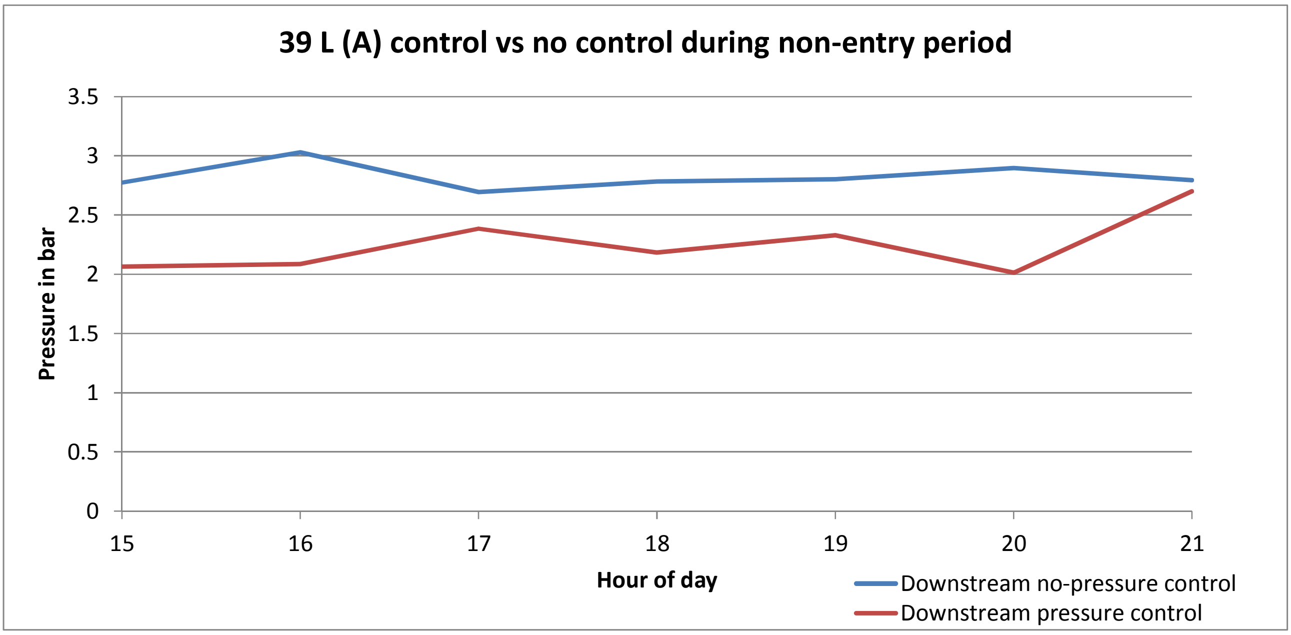


Figure 59: 39L (A) pressure comparison for a typical Saturday and weekday control

Using the difference in pressure from the scenario when no control was active to the same period when control was active, the reduction in flow was determined. Using the test conducted on a typical CWC on surface explained in Appendix F, as a basis, the flow reduction was determined. However, again certain assumptions had to be made, which are listed below.

- A worst case scenario neglecting line pressure losses to the CWC.
- The CWC dumps used water to drain.
- No booster pumps are installed.

It was determined from mining personnel that the inlet temperature of the water feeding into this CWC is approximately 15.5 ℃ and the outlet temperature was nearly 20 ℃. Using the change in temperature and the difference in flow, the cooling output reduction of the CWC was simulated and shown in *Figure 60*.

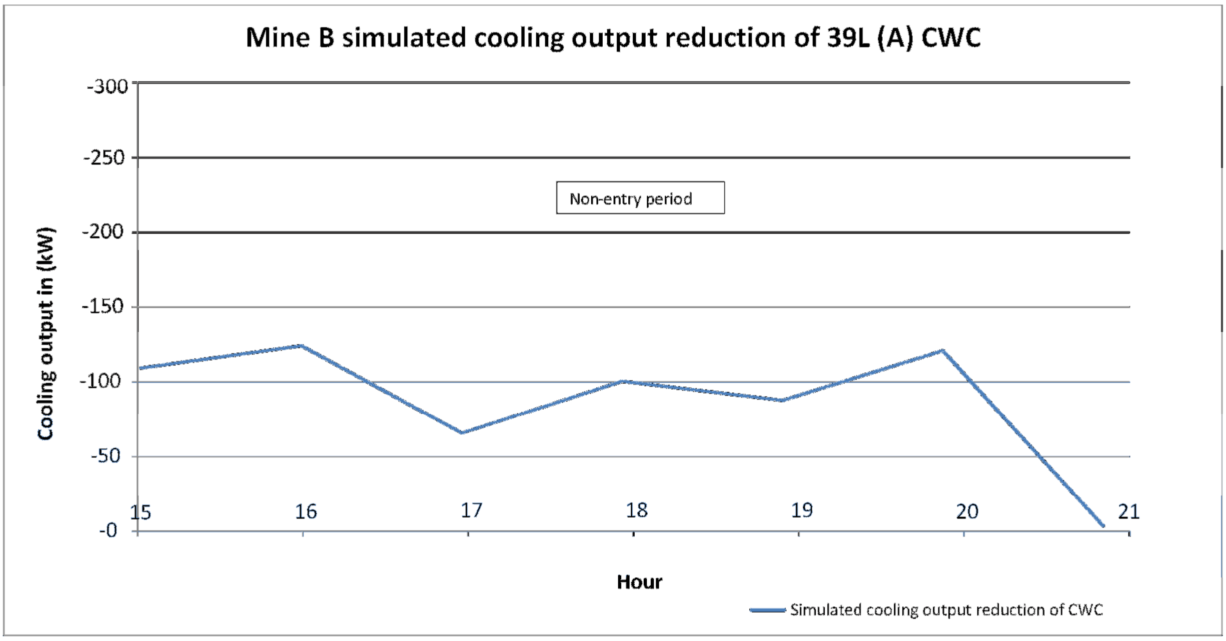


Figure 60: Simulated kW cooling output reduction of CWC

The reduced pressure as a result of the control resulted in an average reduction of 3.9 litres per second to the CWC car. Using the simulation, the reduced cooling output as a result of the flow reduction was found to be approximately 70 kW during the non-entry period.

4.3.5 WSO impact on total system

To determine the financial impact, the cost model shown in *Figure 49* was used. The savings as a result of less cooling output on the BAC and CWC cannot be added to the overall savings as the reduced water is already accounted for in the savings achieved on the surface refrigeration plant. The cost implication on each simulated component of Mine B was tabulated and is shown in *Table 8*.

Table 8: Tabulated cost comparison for each component of Mine B

Description	Average impact (kW)	Cost (R/per annum)
Mine dewatering system	3500 kW	R 11 800 000.00
Surface refrigeration plant	680 kW	R 2 200 000.00
Total simulated annual saving		R 14 000 000.00

From *Table 8* it can be seen that there are significant savings on the refrigeration and dewatering system, however there is also a negative effect on the cooling effectiveness of the BAC and CWC. In order to approximate the effect of this cooling reduction on all the mining components affected by the WSO control as a whole, a simplified extrapolation technique was used.

At the time of this intervention there were approximately seven coolers installed on levels 33 to 40L that could be affected by the reduction in pressure. Also two other BAC's are installed on 39L and 40 L. These components vary in size and installed capacity. The combined approximated reduction cooling delivered as a result of the WSO project is shown in *Table 9*.

Table 9: Tabulated approximation of cooling reduction for Mine B

Description	Number of possibly affected units	Simulated cooling output reduction (kW)	Combined cooling output reduction (kW)
CWC	7	70	490 kW
BAC	2	190	380 kW
Total			**870 kW**
Average annual surface fridge plant cooling output in kW (COP = 6.3)			**20200 kW**
Difference in percentage of installed vs reduced (%)			**4.30%**

4.4 Applying this research to other client sites

Using this study it can be determined to what extent the chilled water sent underground can be reduced without affecting the cooling circuit in such a way that it is unable to maintain acceptable working conditions underground. Secondary savings as a result of a typical WSO project will be brought upon the cooling circuit. This may now be determined and reported on by the appointed M&V team.

Two other sites where a WSO project was implemented showed the potential savings as well as the average simulated reduction in chilled water. Using the performance assessment reports captured by the M&V teams the reduced chilled water impact was simulated and given in *Table 10*.

Table 10: Research expanded to other mining sites

Mine site	Performance assessment average MW	Lowest pump chamber depth (m)	Approximated reduction (l/sec)
Mine C	3.8	3153	98 l/sec
Mine D	4.2	3680	93 l/sec

From the approximated values given in *Table 10* it can be seen that there is a large reduction in chilled water to underground with the implementation of a typical WSO project. The surface fridge plant was used in the analysis due to easily accessible data. Using the flow reduction with an assumed COP of six and a temperature difference between the input and output water of 10 ℃, the reduced average power was simulated as is shown in *Figure 61*.

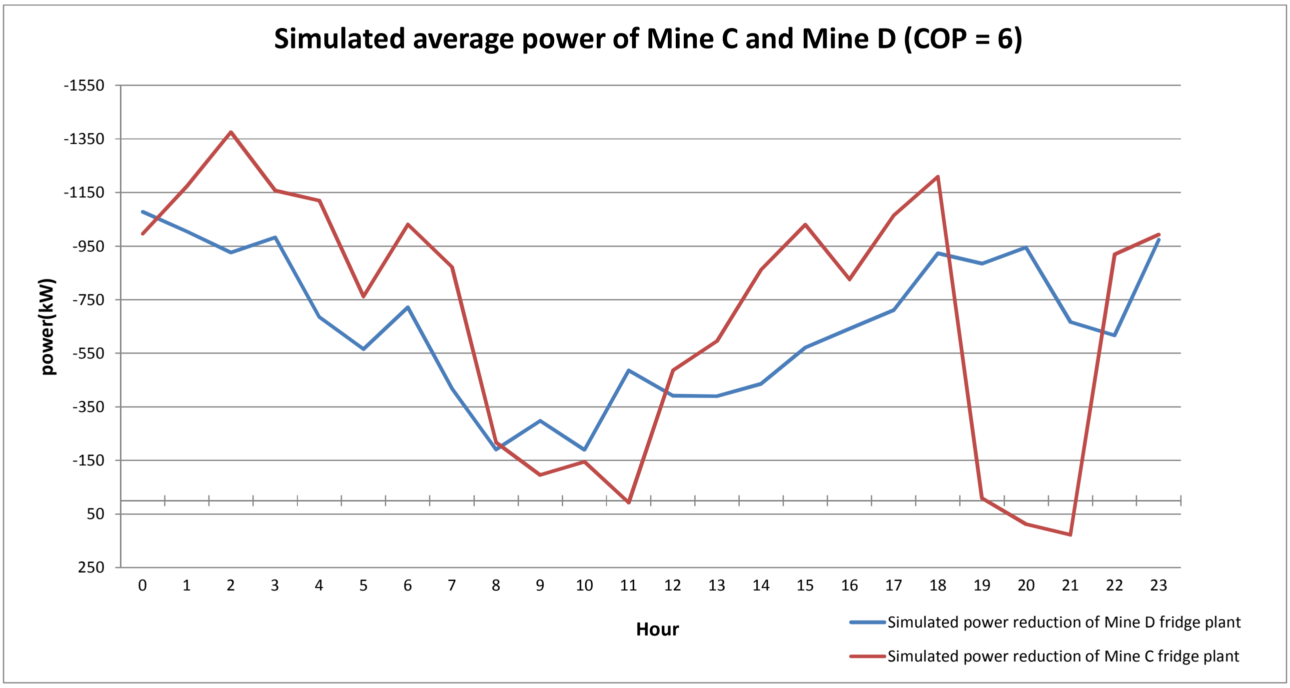


Figure 61: Simulated average power reduction of Mine C and Mine D fridge plant

From the approximated values it was determined that an average power of each surface fridge plant is reduced by 600 kW during weekdays. This contributes to a combined additional saving of approximately R 1.5 million per annum. With regards to the underground components the impact can include the following:

- Reduction in cooling output of the CWC on a specified level.
- Reduction in cooling output of the BAC spray chamber.
- Savings on the refrigeration plant due to the reduced load as a result of less water sent through the cooling circuit.
- Loss in regenerative energy as a result of reduced chilled water.

- Savings on water treatment chemicals.

The possibility exists to reduce the chilled water pressure and subsequently the flow with the WSO project. The effect on the refrigeration plant as well as the cooling units can now be determined and quantified. A possibility exists to optimise savings even more with the quantifications of the thermal impact.

4.5 Conclusion

The simulations were applied to two case studies, namely Mine A and Mine B where DSM WSO projects were implemented to reduce the amount of chilled water used underground. Research showed a reduction in electrical energy usage but also possible reduced cooling effectiveness on the different components.

The reduced cooling effect in underground CWC's and BAC's was approximated using simulations and assumptions. It can now be used to determine how the underground workings may react in terms of temperature as a result of the reduced chilled water but also enables the quantification of savings realised.

These case studies showed positive as well as negative impacts on dewatering and underground cooling and energy recovery systems. The savings realised as well as the reduced energy recovery of the turbines were quantified. The cost associated with the reduction in chilled water to be cooled and dewatered, was determined and a cost breakdown was constructed to show the annual costs loss and annual savings.

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CHAPTER 5: CLOSURE

Thuthukani gold mine headgear and winder ropes [Photo taken in September 2008]

Conclusions are made about the findings as well as some recommendations and notes.

5.1 Overview

In Chapter 4 the effects of reducing the chilled water fed to the relevant mining components in the mine water cycle was quantified. Previously completed WSO projects were analysed on various sites throughout the mining industry each with its own operational configurations.

The effect on the chilled water reticulation system and some energy recovery devices, when chilled water sent underground is reduced, was determined. In this chapter the findings are summarised and conclusions are made from the results obtained in Chapter 4.

5.2 Conclusion

DSM interventions reducing chilled water sent underground has been done in the past. The result is less electrical energy is required to pump less water from the mine. In the literature study the components influenced by this chilled water was investigated. It was found that numerous components uses chilled water, which can be affected by changes in the system. A model of each applicable component was constructed in order to simulate and determine the influence of water reduction. The simulation models have been verified with actual data and showed correlations higher than 0.88.

The influence was categorised through determination of the optimum operations of the WSO projects. Using case studies the cost implications were quantified. Two mines where WSO projects were implemented were used as case studies to apply the simulations.

It was established that systems such as dissipaters and 3CPFS can be operationally affected if the water reduces below the minimum specifications. The cooling system, including BACs and CWCs, experiences a reduced cooling output while the refrigeration plant experiences a reduced electrical energy usage. This resulted in financial savings attributed to the reduction in chilled water supply and savings on the surface refrigeration plant due to reduced electrical energy required to cool the reduced chilled water. The cost comparison is shown in *Table 11* and *Table 12* respectively.

Table 11: Costing comparison between each system of Mine A

Description	Average impact (kW)	Cost (R/per annum)
Mine dewatering system	3150 kW	R 9 640 000.00
Turbines	- 1400 kW	-R 4 710 000.00
Surface refrigeration plant	960 kW	R 3 230 000.00
Total simulated annual saving		R 8 160 000.00

Table 12: Cost comparison between each component of Mine B

Description	Average impact (kW)	Cost (R/per annum)
Mine dewatering system	3500 kW	R 11 800 000.00
Surface refrigeration plant	680 kW	R 2 200 000.00
Total simulated annual saving		R 14 000 000.00

The negative financial impact of the energy recovery systems are outweighed by the cost savings on the other mining components. This is only true up to the point where the operational influences are tolerable.

The cooling components only showed a reduction in cooling output during the non-entry period. In Case study A, the combined average approximated cooling reduction during the non-entry period was 884 kW. In Case study B, the cooling components also showed a combined average cooling reduction of 870 kW during the non-entry period. Respectively, this is approximately 3.1 and 4.3 % of Case study A and Case study B’s surface fridge plant average cooling output.

Arguably the reduction in cooling in specified areas as a result of reduced chilled water takes placed throughout the day when no mining personnel are permitted underground. Thus, the effect on mining personnel will be minimal but re-entry conditions must be ensured and form part of further research opportunities.

5.3 Further research opportunities

Due to the fact that the chilled water reticulation systems on a deep mine has numerous users and are comprehensive, the possibility of other effects must also be noted. The DSM projects provide a platform that can be used to investigate influences of different natures and other possibilities to increase savings.

It is further proposed to investigate the environmental impact the water reduction has on the mine's environmental management plan. It is also suggested to determine to what extent DSM projects such as these can contribute towards environmental standards, requirements and legislation on a typical mine site. This will include research into the reduction of chemicals required to treat the contaminated water.

With regards to the thermal influences of the chilled water on the underground environment, several areas for further study were identified. These are given in the following breakdown:

- In complex piping networks, the chilled water route and flow rates to each component and how this is influenced by a reduction in chilled water pressure. This will further enhance simulation accuracy.
- The underground temperature increases with a reduction in cooling output during non-entry periods. The time required to ensure underground working environment conditions returns to the same conditions before the non-entry cooling output reduction.
- Consideration into the placement of multiple cooling units in series on each level and the resulting effect of reducing water on such a level.

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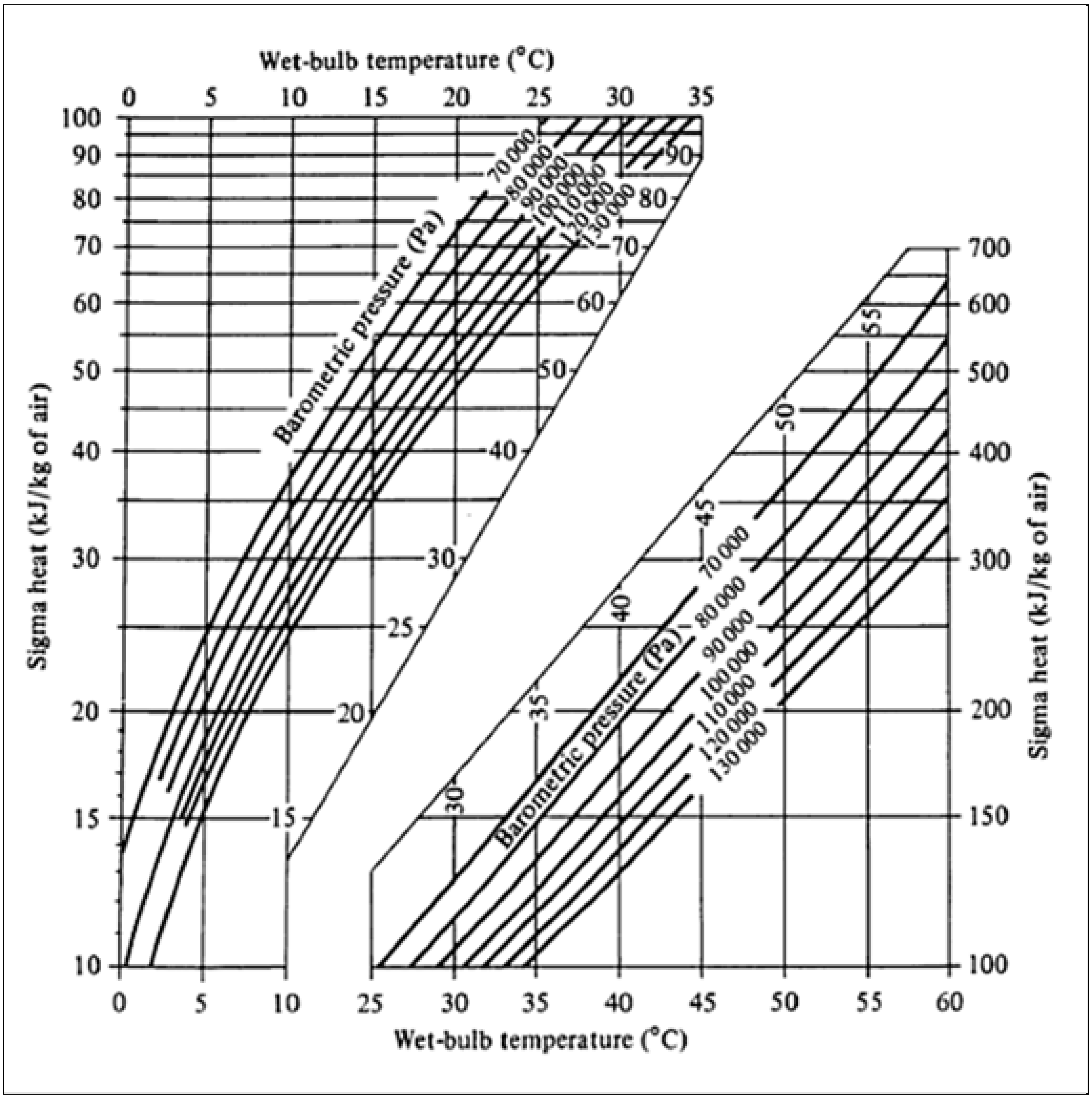
APPENDIX A: Sigma heat chart



APPENDIX B: Thermal properties of water

Temperature - *t* -	Absolute pressure - *p* -	Density - *ρ* -	Specific volume - *v* -	Specific Heat - c_p -	Specific entropy - *e* -
(°C)	(kN/m²)	(kg/m³)	10^{-3} (m³/kg)	(kJ/kgK)	(kJ/kgK)
0 (Ice)		916.8			
0.01	0.6	999.8	1.00	4.210	0
4 (maximum density)	0.9	1000.0			
5	0.9	1000.0	1.00	4.204	0.075
10	1.2	999.8	1.00	4.193	0.150
15	1.7	999.2	1.00	4.186	0.223
20	2.3	998.3	1.00	4.183	0.296
25	3.2	997.1	1.00	4.181	0.367
30	4.3	995.7	1.00	4.179	0.438
35	5.6	994.1	1.01	4.178	0.505
40	7.7	992.3	1.01	4.179	0.581
45	9.6	990.2	1.01	4.181	0.637
50	12.5	988	1.01	4.182	0.707
55	15.7	986	1.01	4.183	0.767
60	20.0	983	1.02	4.185	0.832
65	25.0	980	1.02	4.188	0.893
70	31.3	978	1.02	4.191	0.966
75	38.6	975	1.03	4.194	1.016
80	47.5	972	1.03	4.198	1.076
85	57.8	968	1.03	4.203	1.134
90	70.0	965	1.04	4.208	1.192
95	84.5	962	1.04	4.213	1.250
100	101.33	958	1.04	4.219	1.307

APPENDIX C: Performance assessment report tables

Mine A performance assessment March to May 2011				
	Baseline (kW)	Actual kW profile March 2011	Actual kW profile April 2011	Actual kW profile May 2011
0	13335	9151	8826.4	10638.7
1	12775	8668.7	9072.8	10247.9
2	12791	8433.3	9137.8	10240.4
3	13015	8735.5	9292.3	10473.8
4	13550	9038.4	9025.9	10677.7
5	13564	9242.2	9271.4	10613.1
6	13725	9523.7	9363.8	10627
7	13074	9029.7	9041.2	10384.4
8	10574	9023	8819.1	9367.7
9	10356	8781.5	8688.4	8925.1
10	9772	8691.1	8815.4	10119.6
11	12244	8323.2	9145.8	10130.8
12	13136	8148.3	9338.2	10278.7
13	13362	8992.4	9163.1	10132.7
14	13479	9014.3	8730.7	9854.2
15	13482	9486.1	8880.4	10210.2
16	13242	9497.2	8967.14	10436
17	13557	9160.7	9176	10369.1
18	13309	9492.9	9080.3	10580.5
19	10504	9896.3	9273.8	9979.4
20	10342	9588.8	8997.4	10052.8
21	12541	9403.6	9324.1	10163.4
22	12975	8584.3	8899.5	10448.5
23	13293	8578.4	9035	10276.5

Mine B performance assessment period January to March 2012						
Time [hh:mm]	January Baseline Weekday averages [MW]	January Actual Weekday averages [MW]	February Baseline Weekday averages [MW]	February Actual Weekday averages [MW]	March Baseline Weekday averages [MW]	March Actual Weekday averages [MW]
00:00	15.96	12.36	17.55	13.60	18.37	15.29
00:30	15.83	12.22	17.28	13.33	18.12	15.03
01:00	15.36	11.75	17.03	13.08	18.34	15.25
01:30	14.37	10.77	16.68	12.73	18.10	15.02
02:00	13.58	9.98	15.54	11.59	18.34	15.25
02:30	13.00	9.40	14.75	10.80	18.21	15.12
03:00	13.80	10.20	14.37	10.42	18.00	14.91
03:30	14.19	10.58	14.44	10.49	17.62	14.54
04:00	14.40	10.80	15.19	11.24	16.55	13.46
04:30	15.30	11.69	16.45	12.50	16.69	13.60
05:00	16.52	12.91	17.71	13.76	17.27	14.19
05:30	17.25	13.65	18.85	14.90	17.72	14.64
06:00	17.27	13.67	18.65	14.70	17.35	14.26
06:30	14.17	10.56	15.27	11.32	15.17	12.08
07:00	8.02	4.41	8.51	4.56	9.13	6.04
07:30	7.55	3.94	8.38	4.43	7.75	4.66
08:00	7.57	3.97	8.47	4.52	7.59	4.50
08:30	7.89	4.28	8.62	4.67	7.37	4.28
09:00	8.17	4.57	9.53	5.58	7.87	4.79
09:30	8.25	4.65	11.37	7.43	9.11	6.02
10:00	13.53	9.92	16.33	12.38	14.93	11.84
10:30	17.39	13.79	19.70	15.75	18.71	15.62
11:00	18.85	15.25	20.93	16.98	20.43	17.34
11:30	19.86	16.25	21.28	17.33	20.79	17.70
12:00	20.20	16.59	20.84	16.89	21.56	18.47
12:30	20.12	16.51	21.00	17.05	21.31	18.23
13:00	19.87	16.27	20.96	17.01	20.78	17.70
13:30	19.90	16.29	20.94	16.99	20.27	17.18
14:00	19.47	15.87	19.82	15.87	19.57	16.49
14:30	19.60	15.99	19.43	15.48	19.73	16.64
15:00	19.76	16.15	18.90	14.96	19.52	16.43
15:30	19.39	15.78	19.41	15.46	19.79	16.70
16:00	19.24	15.63	18.26	14.31	19.88	16.79
16:30	18.57	14.96	17.54	13.59	19.26	16.17
17:00	17.25	13.64	16.30	12.35	17.41	14.32
17:30	13.07	9.46	10.09	6.14	14.00	10.91
18:00	8.39	4.78	8.18	4.23	8.76	5.67
18:30	8.26	4.65	7.83	3.88	7.09	4.00
19:00	7.51	3.91	8.41	4.46	7.77	4.69
19:30	8.91	5.31	9.11	5.16	7.45	4.36
20:00	11.36	7.75	13.52	9.57	12.65	9.56
20:30	14.16	10.56	17.90	13.95	15.57	12.48
21:00	15.23	11.62	18.55	14.60	17.17	14.09
21:30	17.00	13.39	19.10	15.15	17.58	14.49
22:00	17.56	13.95	19.33	15.38	17.70	14.62
22:30	17.62	14.01	19.68	15.73	18.23	15.14
23:00	17.58	13.97	19.09	15.14	18.68	15.60
23:30	17.49	13.89	18.73	14.78	18.81	15.72

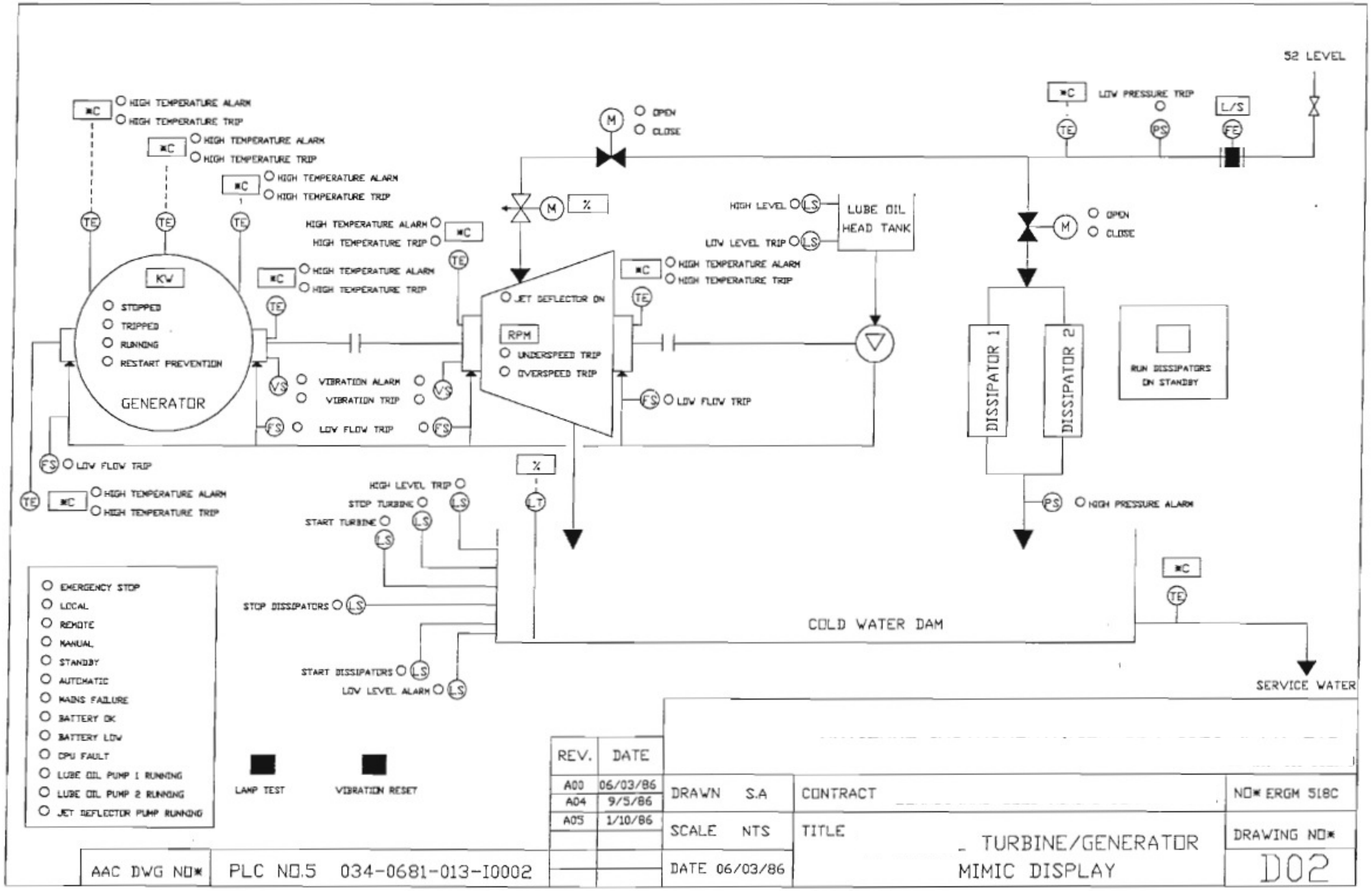
	Mine C Performance assessment March to May 2011			
	Baseline	Actual profile March 2011	Actual profile April 2011	Actual profile May 2011
0	29693.8	25930.2	23506.3	23053.5
1	29152.3	24469.3	23839	19598.1
2	29767	23805.4	21200.3	21410.7
3	29768.7	23898	24349.1	21795.6
4	29215.9	24303.3	22849.8	21855.3
5	28449.6	25262.2	24686.9	22724.4
6	29969.5	25712.2	24392.3	22650.8
7	28692.9	24491.7	26358.4	20717.1
8	16444.5	20629.1	14398	10691.7
9	15922.4	20327.2	14548.1	11299.2
10	16698.5	20595.2	14901.7	12191.7
11	19791.1	23923.3	18564.2	17006.7
12	28451.7	26440.4	26354.8	24466.5
13	30454.7	27220.4	28052.2	26188.4
14	31901.2	27365.4	27205.3	26777
15	32736.2	27238.9	27485.7	26335.6
16	32770.7	26752.4	31040	26780.8
17	32902.5	26496.5	29144.1	25349.9
18	32608.9	24606.7	28050.9	25043.8
19	16276.9	20065.2	15450	13170.7
20	15896.1	20191.1	15475.4	13485.7
21	18585.5	22497.4	19683.9	15697.5
22	27313.1	23121.3	23010.4	20508.5
23	29114.4	25486.1	23303.8	22027.3

	Mine D Performance assessment March to May 2011			
	Baseline	Actual profile March	Actual profile April	Actual profile May
0	34521.8	28120.1	29155.2	25355.3
1	32649	26039.2	27423.9	24980.1
2	33631.6	27530.3	28486.8	26878.1
3	34016.5	27575.8	28632.1	26759.8
4	33488.1	28734.3	29048.1	29377.3
5	33262.1	30276.8	29665.5	28854.4
6	33452.3	28364.2	28205.4	29771.8
7	29152	27929.9	27690.2	23719.3
8	14511.5	18890.1	12285.9	8649.5
9	14951.1	18553	11922.3	8595
10	15900.9	21136.7	13126.6	9752.2
11	30483.3	27437.8	26882.4	27685.6
12	34637	29908	33412.9	32984.7
13	34534.9	30674.3	33121.6	32230.4
14	34148.9	30210.2	32907.3	30856.9
15	34679.3	30798.9	32052.8	30078.7
16	35636.7	31529.4	31864.3	31038.8
17	34631.6	29580.4	31034	29480.4
18	33008.8	29130.1	27970.4	23997.3
19	17855.1	20825.7	11310.4	4247.3
20	19297.9	21277.8	12928.7	5333.2
21	32034.7	29486.5	29317.1	24338.7
22	33964.6	30466.2	30349.2	29092.3
23	34806	28129.7	29802.2	27574.3

APPENDIX D: Mine A turbines information

Level 29 Turbine	**Description**
Model	Sulzer
Installed capacity [kW]	3004
Turbine design flow [l/s]	420
Head [m]	816
Level 52 Turbine	**Description**
Model	Sulzer
Installed capacity [kW]	2400
Turbine design flow [l/s]	420
Head [m]	684
Level 71 Turbine	**Description**
Model	Sulzer
Installed capacity [kW]	2010
Turbine design flow [l/s]	420
Head [m]	574
Level 92 Turbine	**Description**
Model	Andritz
Installed capacity [kW]	3800
Turbine design flow [l/s]	700
Head [m]	620

Mine A turbine P&ID



APPENDIX E: Spray nozzles of typical BAC

Pressure in bar	0.4	0.7	1.5	2	3	4	6	7	15	20	35
Flow(l/min)	10.1	13.3	19.5	23	28	32	39	42	62	71	94
Flow in litres sec	0.2	0.2	0.3	0.4	0.5	0.5	0.7	0.7	1.0	1.2	1.6
65° pray angle (1/4 inch) Veejet®											

APPENDIX F: Test procedure on typical CWC

A test was conducted on the 19th of September 2013 on a typical CWC found underground in a deep mine. The test was initiated to establish which of the three constant flow valves available for fitment to a chilled water car is most suitable. This was tested, but these results do not form part of this study.

One of the testing procedures used a constant water supply with a maximum pressure of 3.6 bar, a portable flow meter, a pressure transmitter, typical CWC and a hand operated valve fitted to the constant water supply. The typical CWC used in the test is shown in Figure A.

Figure A: Chilled water car used in test [photo taken by Mr. C. Kriel]

The testing procedure consisted of connecting the chilled water car to the constant water supply source and directing the used water exiting the CWC to a drain. The pressure supplied to the chilled water car was measured downstream of the connected hand operated valve. This pressure was varied using the hand valve and the flow to the drain was measured and noted for each interval. With the maximum pressure of 3.6 bar, a flow of 12.1 litres per second was recorded. With the reduction in pressure in intervals to a minimum of 0.5 bar, the flow measured was 4.6 litres per second. The CWC test results are tabulated in Table A.

Table A: Chilled water car test results with change in pressure

Pressure into CWC (kPa)	Flow through CWC (l/s)
360	12.1
320	11.3
240	9.7
200	9
178	8.4
150	7.8
100	6.8
50	4.6

APPENDIX G: Megaflex tariff structure

Megaflex tariff

Non-local authority

2013/2014

Transmission zone	Voltage	Active energy charge [c/kWh] High demand season [Jun - Aug] Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Low demand season [Sep - May] Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Transmission network charges [R/kVA/m]	VAT incl
≤ 300km	< 500V	204.55	233.19	62.23	70.94	33.97	38.73	66.98	76.36	46.22	52.69	29.46	33.58	R 5.85	R 6.67
	≥ 500V & < 66kV	201.33	229.52	60.99	69.53	33.12	37.76	65.68	74.88	45.20	51.53	28.68	32.70	R 5.35	R 6.10
	≥ 66kV & ≤ 132kV	194.96	222.25	59.06	67.33	32.07	36.56	63.60	72.50	43.77	49.90	27.77	31.66	R 5.21	R 5.94
	> 132kV	183.75	209.48	55.66	63.45	30.23	34.46	59.94	68.33	41.25	47.03	26.18	29.85	R 6.58	R 7.50
> 300km and ≤ 600km	< 500V	206.21	235.08	62.48	71.23	33.93	38.68	67.27	76.69	46.31	52.79	29.38	33.49	R 5.90	R 6.73
	≥ 500V & < 66kV	203.34	231.81	61.60	70.22	33.45	38.13	66.34	75.63	45.65	52.04	28.96	33.01	R 5.40	R 6.16
	≥ 66kV & ≤ 132kV	196.88	224.44	59.64	67.99	32.38	36.91	64.22	73.21	44.19	50.38	28.04	31.97	R 5.25	R 5.99
	> 132kV	185.58	211.56	56.22	64.09	30.52	34.79	60.53	69.00	41.66	47.49	26.43	30.13	R 6.65	R 7.58
> 600km and ≤ 900km	< 500V	208.27	237.43	63.08	71.91	34.25	39.05	67.94	77.45	46.76	53.31	29.66	33.81	R 5.97	R 6.81
	≥ 500V & < 66kV	205.38	234.13	62.22	70.93	33.79	38.52	67.00	76.38	46.11	52.57	29.25	33.35	R 5.44	R 6.20
	≥ 66kV & ≤ 132kV	198.88	226.72	60.25	68.69	32.71	37.29	64.87	73.95	44.65	50.90	28.32	32.28	R 5.29	R 6.03
	> 132kV	187.45	213.69	56.78	64.73	30.84	35.16	61.15	69.71	42.08	47.97	26.70	30.44	R 6.74	R 7.68
> 900km	< 500V	210.36	239.81	63.74	72.66	34.61	39.46	68.63	78.24	47.23	53.84	29.97	34.17	R 5.99	R 6.83
	≥ 500V & < 66kV	207.43	236.47	62.83	71.63	34.11	38.89	67.66	77.13	46.56	53.08	29.54	33.68	R 5.51	R 6.28
	≥ 66kV & ≤ 132kV	200.88	229.00	60.85	69.37	33.04	37.67	65.52	74.69	45.10	51.41	28.61	32.62	R 5.32	R 6.06
	> 132kV	189.29	215.79	57.37	65.40	31.17	35.53	61.78	70.43	42.53	48.48	27.00	30.78	R 6.79	R 7.74

Distribution network charges

Voltage	Network access charge [R/kVA/m]	VAT incl	Network demand charge [R/kVA/m]	VAT incl	Urban low voltage subsidy charge [R/kVA/m]	VAT incl
< 500V	R 11.63	R 13.26	R 22.05	R 25.14	R 0.00	R 0.00
≥ 500V & < 66kV	R 10.67	R 12.16	R 20.23	R 23.06	R 0.00	R 0.00
≥ 66kV & ≤ 132kV	R 3.81	R 4.34	R 7.05	R 8.04	R 9.39	R 10.70
> 132kV	R 0.00	R 0.00	R 0.00	R 0.00	R 9.39	R 10.70

Voltage	Reliability service charge [c/kWh]	VAT incl
< 500V	0.27	0.31
≥ 500V & < 66kV	0.26	0.30
≥ 66kV & ≤ 132kV	0.25	0.29
> 132kV	0.23	0.26

Customer categories	Service charge [R/account/day]	VAT incl	Administration charge [R/POD/day]	VAT incl
> 1 MVA	R 133.50	R 152.19	R 60.17	R 68.59
Key customers	R 2 616.06	R 2 982.31	R 83.55	R 95.25

Reactive energy charge [c/kVArh] High season	VAT incl	Low season	VAT incl
9.40	10.72	0.00	0.00

Electrification and rural network subsidy charge [c/kWh] All seasons	VAT incl	Affordability subsidy charge [c/kWh] payable by non-local authority tariffs All seasons	VAT incl
5.20	5.93	2.07	2.36