Reconfiguring deep-level mine dewatering systems for increased water volumes

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PREFACE

To my parents Piet and Rita Venter:

Nothing can be built successfully without a strong foundation. Thank you for all you have done through the years.

To my brother Louw Venter:

Our frequent talks, laughter and exiting plans for the future has kept me positive. Thank you.

To my fiancé Cheryl-Ann Smit:

Your constant support, motivation and positivity regarding my studies have been a blessing this past 5 years, thank you. I look forward to discovering what He has planned for us in future.

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Thank you for your guidance, valuable inputs and time spent throughout the completion of this study.

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To Enermanage (Pty) Ltd and its sister companies:

Thank you for the opportunity and financial support to complete this study. Your support has opened doors in the lives of many.

- Psalm 121

ABSTRACT

Title:	Reconfiguring deep-level mine dewatering systems for increased water volumes
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Deep-level mines are faced with a host of challenges that can pose a threat to the safety of underground mine employees. Significant among these threats is the risk of underground floods as a result of fissure water flowing into mine shafts. Neighbouring mine shafts are frequently connected at certain underground levels, allowing flood water to overflow from one shaft to another. Damage of equipment and loss of production are also risk factors to be considered if a mine is to flood.

As mining depth increases the initially installed water reticulation system becomes outdated and ineffective at distributing and removing water from a mine. Inevitably the reconfiguration of older mine water reticulation systems becomes a necessity for the effective and efficient management of water within mines.

Previous studies have investigated the reconfiguration of mine water reticulation systems. These studies mainly focused on reconfiguration for the purpose of energy cost saving, decreased water wastage and improved cooling system operation. The identified studies did not, however, focus on reconfiguration of a mine water reticulation system for the management of excessive water volumes.

The primary objective of this study is to focus on possible solutions for the reconfiguration of a deep-level mine water reticulation system to compensate for excess water. The secondary objective is to improve the water reticulation system after reconfiguration occurred. System improvements after reconfiguration can consist of water demand optimisation, energy cost optimisation and pump automation.

A five-step method was developed to reconfigure a deep-level mine water reticulation system for excess water management. The five steps within the developed methodology can be listed as:

1. Data acquisition of mine WRS and problem identification
2. Solution development
3. Validate the proposed reconfiguration solution
4. Implementation and system improvement
5. Results quantification

The five-step method developed for this study was successfully tested on two case studies that involved four different mine shafts. Completion of the first case study proved that the involved mine could remove an additional volume of 0.7 ML (29%) of excess water per day. In the second case study the amount of water that had to be pumped to surface by the involved mine was reduced by 1.74 ML (31.4%) per day. This allowed better performance of the mine's water reticulation system. Implementation of proposed system improvements made to two mines, in the form of system automation and load shift projects, realised a total cost saving of R1.28-million within the first year.

Results attained from applying the developed methodology proved that mine water reticulation functionality was improved, excess water volumes could be removed, and solved the identified problems unique to each of the two case studies. These aforementioned results proved that the study objective had been successfully met because possible solutions for the reconfiguration of a deep-level mine water reticulation system, to compensate for excess water, had been attained.

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3CPFS	Three chamber pipe feeder systems
BAC	Bulk air coolers
COP	Chronic obstructive pulmonary
DSM	Demand Side Management
ESCO	Energy service company
FP	Fridge plant
GWP	Gold worker’s pneumoconiosis
HX	Heat exchanger
L	Level
PLC	Programmable logic controller
PPE	Personal protective equipment
PRV	Pressure reducing valves
RAW	Return air way
REMS	Real-time energy management system
SA	South Africa
SCADA	Supervisory control and data acquisition
TOU	Time-of-use
WRS	Water reticulation systems

CHAPTER 1 INTRODUCTION AND LITERATURE OVERVIEW

Chapter 1 is the introduction and literature overview section of this study. Here the focus is to research all the relevant fields for the purpose of this study. These fields include South African deep-level mining, deep-level mine water reticulation systems (WRS), excess water within mines, and WRS reconfiguration methods for excess water volumes. Gold mines will be focused on mainly as these include the deepest mines [1]. Relevant previous studies will be discussed. A study need, problem statement and study objective will be developed.

1.1 South African gold mining sector

Africa is home to 42 % of the world's known gold reserves [2]. Of all African countries, South Africa is the largest producer of gold and ranks as the 6th largest producer in the world [3]. The Witwatersrand Basin is a geological formation within the Witwatersrand gold-producing area of Southern Africa. This basin stretches over an arc of 400 km and traverses across the North West, Free State and Gauteng provinces of South Africa, making it the world's largest gold resource [4]. Figure 1 displays a map of South Africa with all the main regions of gold mining activity marked on the map.

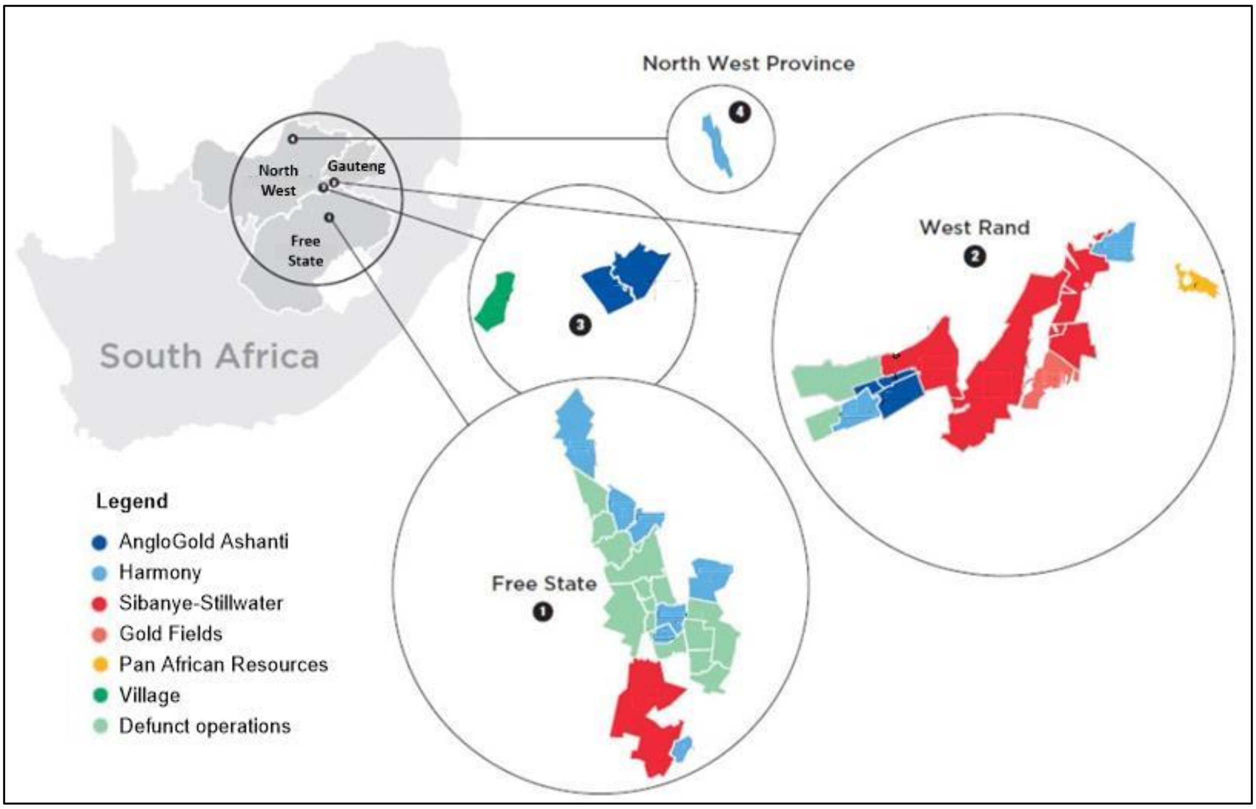

Figure 1: South African main gold mining regions (adapted from [4])

The South-African mining industry has for many years been the mainstay of the South African economy. Major mining sectors in SA include gold, coal, platinum group metals and diamonds. Other minerals mined include vanadium, chrome, titanium and other lesser minerals [4]. Of these minerals, platinum and gold are mined at the deepest levels underground, with platinum and gold found at vertical depths reaching up to 2 km and 4 km respectively [1]. South Africa hosts eight of the world's ten deepest mines and mining at these depths becomes very labour-intensive and physically demanding [5].

As the leading supplier of electricity to South Africa, Eskom is responsible for most of the country's power supply [6]. The mining industry is responsible for the consumption of 15 % of Eskom's annual output. Of the mining industry the gold mining sector is the largest user, consuming 47 % of the industry's electricity [7].

1.2 Consumers within a mine

Large and reliable systems are required to keep underground conditions bearable for mine workers. The main systems required to keep a deep-level mine functional are the pumping, ventilation, refrigeration and compressed air systems. These four main systems are also considered to be among the most energy intensive as they consume the largest amounts of electricity. Figure 2 displays the electricity consumption distribution of different systems of a typical deep-level gold mine.

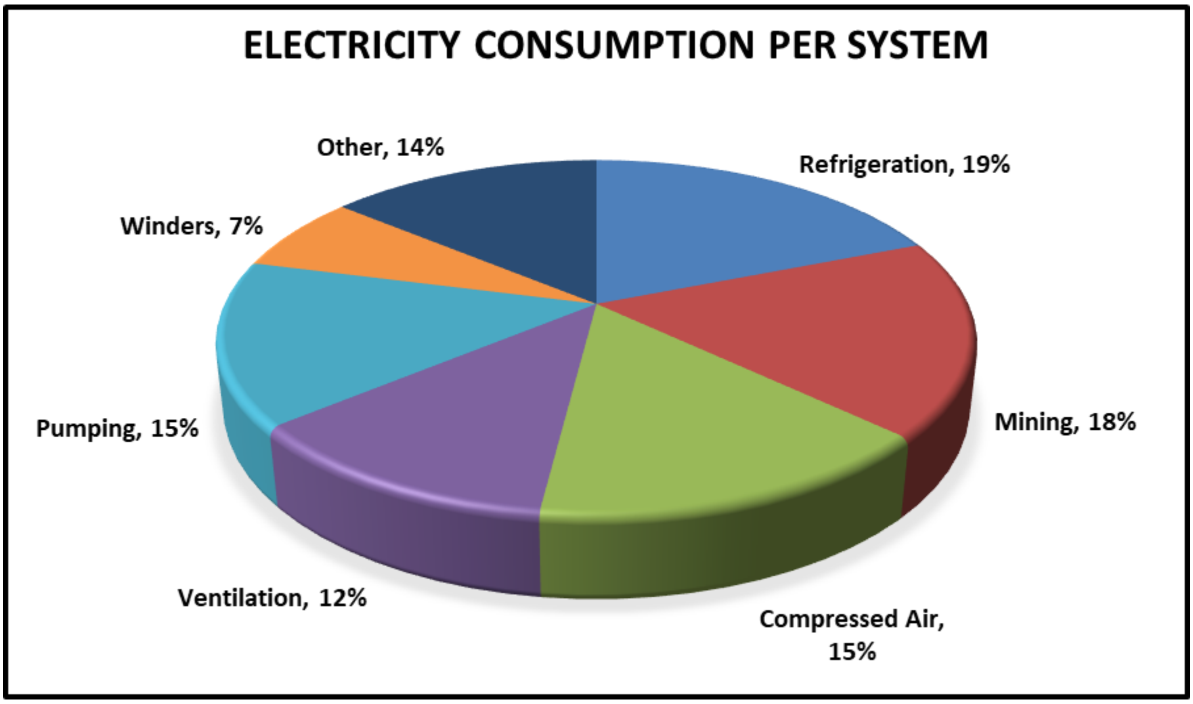

Figure 2: Average electricity usage of typical gold mining systems [8]

Two of the largest consumers in a typical deep-level gold mine are the refrigeration and pumping systems. Pumping and refrigeration each form part of a mine's WRS. As displayed in Figure 2, these systems consume 19 % and 15 % respectively. This makes the WRS the largest consumer of electricity on a typical gold mine as these systems consume a total of 34 % of the total energy.

Pumping forms part of the dewatering sub-system of the WRS and most of it will be discussed in Section 1.3.3 of this study. Whilst refrigeration forms part of the WRS, it could be viewed as a system on its own. The refrigeration sub-system of a mine will be discussed in detail in Section 1.3.4 of this study.

Proper maintenance and the correct use of these systems are of paramount importance as the safety of underground workers and mine productivity are directly dependent thereon. These systems are in many ways linked to one another and therefore can influence each other's performance. A typical example would be: if feed pumps were not maintained properly, water would not be distributed efficiently through the refrigeration systems and this could cause an increase in temperature throughout the mine.

1.3 Deep-level mine water reticulation systems

Section 1.3 will explain the functionality of typical deep-level mine's WRS. The WRS can be sub-divided into three sub-systems, which are the water supply, dewatering and refrigeration sub-systems. A general overview of a typical deep-level mine WRS will be given and then followed by an in-depth discussion of each of the three sub-systems and their relevant key components.

1.3.1 A general overview

A deep-level mine WRS can be an intricate system. The main purpose of the system is to distribute chilled water to key working areas underground where it will be used for the following purposes [9]:

- Dust suppression within haulages and stopes
- Flushing away rock during drilling
- Cooling down warm air and equipment
- Sweeping
- Powering hydraulic equipment such as hydro drills

A simple depiction of a general mine WRS is displayed in Figure 3.

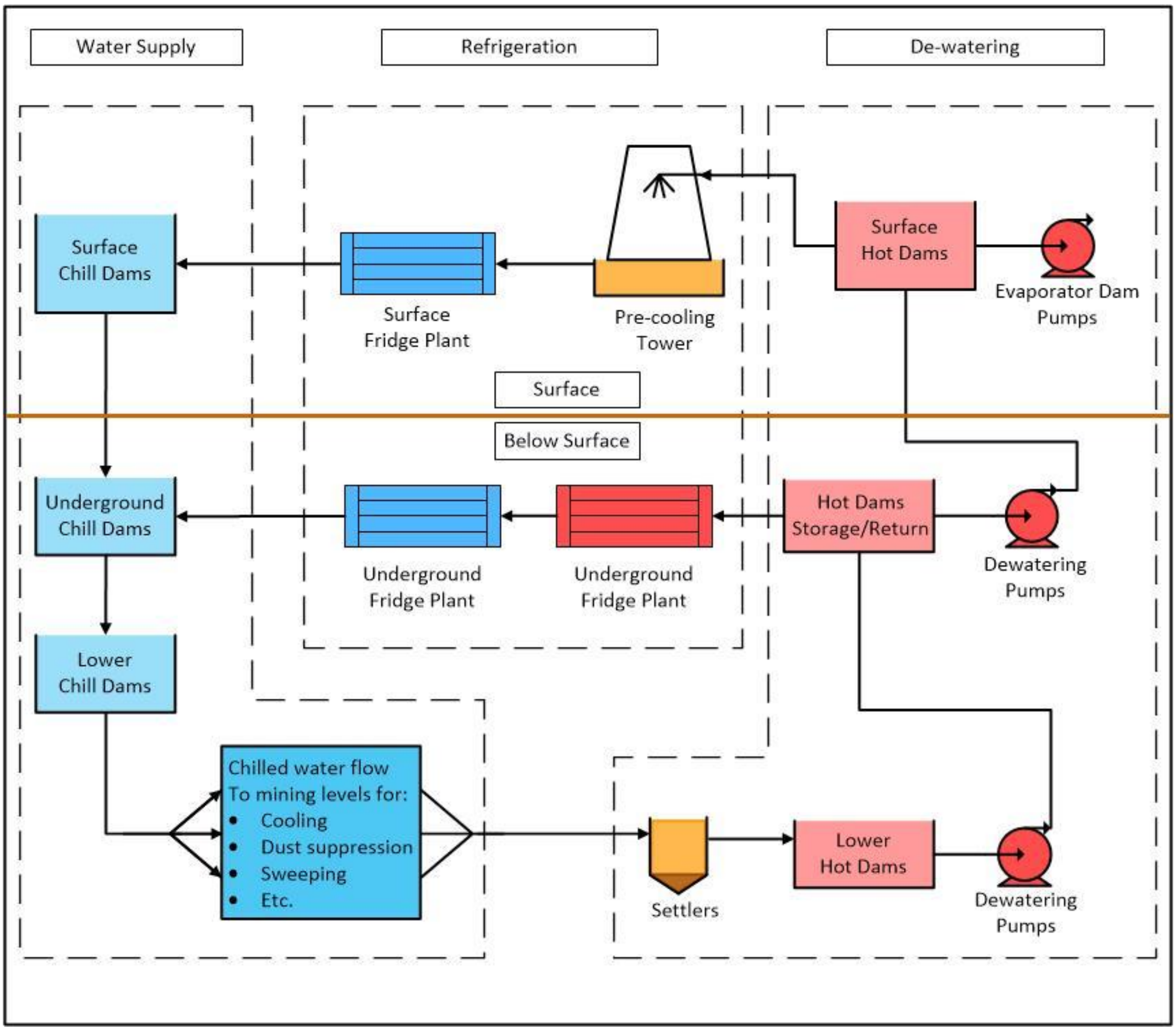

Figure 3: Typical WRS and its main elements (adapted from [9])

As displayed in Figure 3, the water supply sub-system consists of chilled water dams on surface and underground along with all the needed pipe lines and valves to transport chilled water where needed. In this sub-system of the WRS chilled water is supplied to working areas, cross-cuts and cooling equipment on all working levels. The dewatering sub-system consists of hot water dams, pump stations, valves, settlers and pipelines to move warm water from underground to surface. It also consists of the pumps that move fissure water to the settlers, to then be pumped to surface. Settlers will be discussed within Section 1.3.3 of this study.

The refrigeration sub-system has the main purpose of cooling warm water down both on surface and underground. This chilled water can then be linked back into the water supply sub-system. The refrigeration sub-system consists of fridge plants and pre-cooling towers.

1.3.2 Water supply sub-system

After being cooled through the surface refrigeration system, water flows to surface chill dams. The chilled water is of great importance to the functionality of a deep-level mine and is typically gravity fed down to working areas. Gold mines in South Africa reach depths of up to 4,000 m below surface. With water pressure accumulating at approximately 10,000 kPa for every 1,000 m immense pressures is generated within pipelines. This means that pressures must be reduced by making use of pressure reducing valves (PRVs) or cascade dams [10].

In South African mines, water is supplied using cascading dams and shaft column water supply systems [11]. Within a cascading dam system, water is gravity fed from surface to a main receiving dam. From this dam water overflows to different dams on lower levels and the head difference between the dam and the lower levels creates the required pressure [10]. Figure 4 displays a comparison between the cascading dam water supply and the shaft column water supply methods.

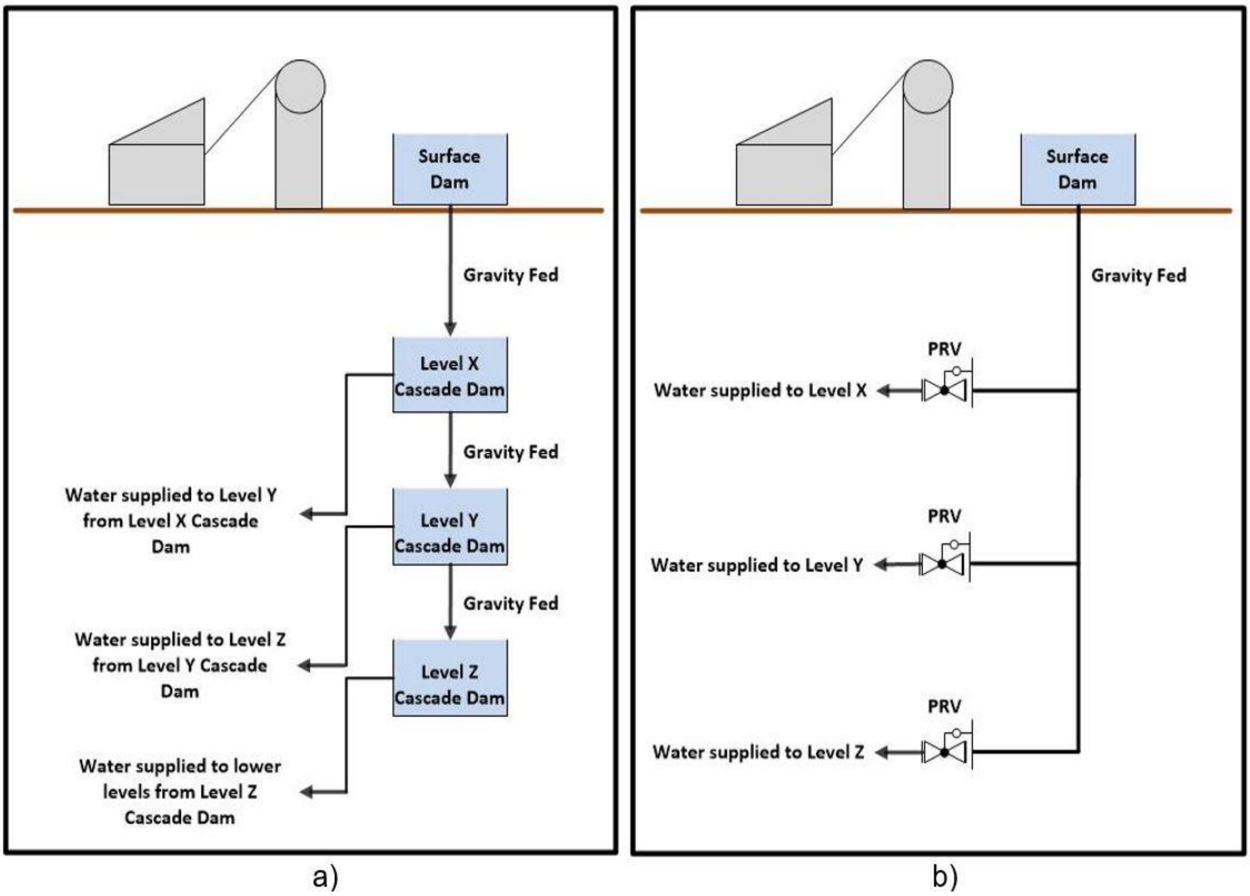

Figure 4: a) Cascading dam **b)** and shaft column water supply methods (adapted from [11])

Within the shaft column system, water is gravity fed down a main column and is then taken from the main column on different levels. PRVs are installed to break the pressure on each level. Figure 4b displays this method with the use of a basic representation.

Once underground, chilled water is distributed to where it is needed and is then used for several purposes including dust suppression within haulages and stopes, flushing away rocks during drilling, cooling and sweeping.

Cooling:

As mines deepen, temperatures increase drastically. This is mainly due to the fact that virgin rock temperatures can reach 60 °C at depths of 4,000 m below surface [10]. Virgin rock temperatures refer to the temperature of the rock face after blasting. Along with this, auto-compression of air contributes to an increase of temperatures as mines reach deeper levels [12].

Acceptable working conditions are considered by the mining industry in South Africa as wet-bulb temperatures less than 27.5 °C at the station and 32.5 °C at the stopes [13]. The application of cooling methods is thus of paramount importance in creating and maintaining acceptable underground conditions.

For shallow mines, acceptable working temperatures can be achieved by circulating ambient air from surface [14]. As mines reach depths of more than 700m, the use of primary cooling methods becomes necessary and upon depths passing 1.4 km, secondary and tertiary cooling methods may be required [15]. Figure 5 displays a schematic representation of the use of primary, secondary and tertiary cooling methods to supply deeper segments of a mine with cool air.

Primary cooling consists of bulk air coolers (BACs) on surface that cool down ambient air before moving underground. Chilled service water is used to cool down the air using evaporative cooling. A surface ventilation fan is connected to a return air way (RAW) which links up with the main shaft. The ventilation fan extracts hot air from underground creating a negative pressure underground, drawing mixed air from the main shaft and BAC [16]. This in turn creates chilled ventilation underground.

There are two kinds of BACs, vertical or horizontal forced draft BACs [17]. The heat exchanger (HX) used within a BAC underground may either be a direct-contact spray HX or a closed-circuit cooling-coil HX. BACs used on surface, for primary cooling, usually make use of direct-contact spray HXs for the cooling down of ambient air.

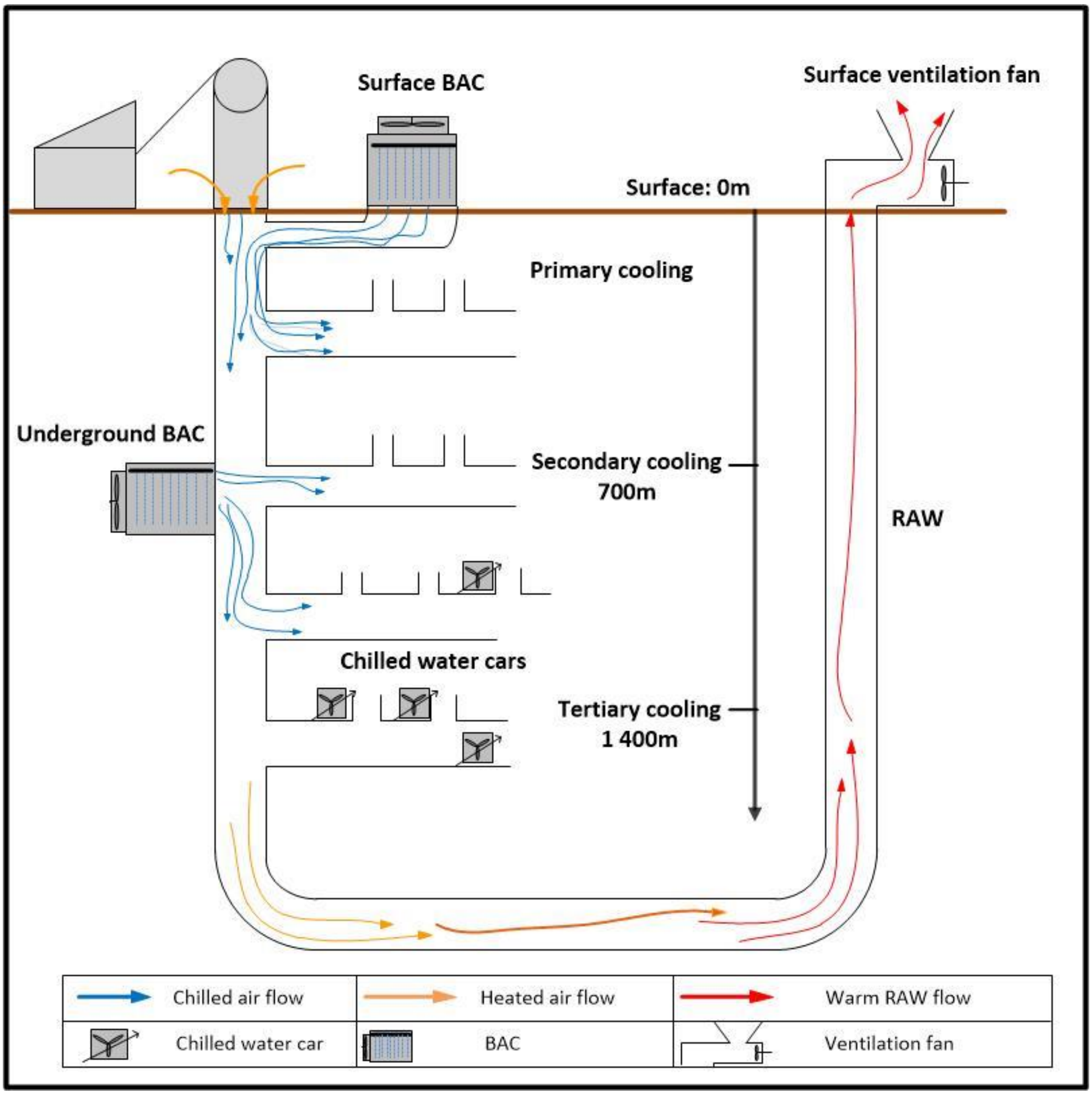

Figure 5: Primary, secondary and tertiary cooling within a mine

Vertical forced draft BACs with direct-contact spray HXs are used on surface to serve as primary cooling. This is due to the fact that vertical forced draft BACs are the least expensive method of cooling underground air [18] and also have a greater cooling capacity [19].

Horizontal forced draft BACs are typically used underground as secondary cooling. Cold service water is sent through the inlet of the cooling-coil banks. Warm air is blown across the cooling-coil banks transferring heat from the warm air to the cooling-coil banks and thus the water. Air exits the BAC as cool air to be sent to work places.

Whilst vertical forced draft BACs can achieve cooling capacities of more than 20 MW, a highly efficient horizontal forced draft BAC can only achieve cooling capacities of about 3.5 MW giving horizontal BACs a major disadvantage [20]. Horizontal forced draft BACs are, however, preferable underground as they easily fit into existing haulages. Figure 6 displays an underground horizontal forced draft BAC using direct-contact spray HX.

Figure 6: Underground horizontal forced draft BAC with direct-contact spray HX[1]

Tertiary cooling is usually required where mining activities are too deep or too far into a level for primary and secondary cooling methods to have an effect [21]. Cooling cars are then installed in haulages or cross-cuts where temperatures are too high for suitable working conditions. A cooling car makes use of chilled water from the supply pipe lines which flow through a radiator or cooling-coils. A booster fan is connected to the cooling car, blowing air over the radiator and in turn blowing cooled air into working places. This is referred to as in-stope or remote cooling. Figure 7 displays a brand-new cooling car before underground installation.

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[1] Photo courtesy of “BBE Group”, Internet: http://www.bbegroup.ca/gallery/. [Accessed: 29-Aug-2019].

Figure 7: Brand-new cooling car[2]

Drilling:

For ore to be extracted from mines, holes must be drilled into the virgin rock face. Explosives are placed in these holes and the rock blasted free. Mines typically make use of pneumatic drills although hydraulic drills can also be used [22]. Chilled water is used to cool down both the drill bit and rock face, and it also acts as a dust suppressant during drilling. Figure 8 shows a photograph of a mine worker making use of a pneumatic drill to drill holes into the rock face. These holes will then be packed with explosives to blast ore free from the rock face. Water can be seen forming a dam around the mine worker’s feet.

Dust suppression:

Dust within the underground working environment can pose a great threat to mine workers. This is since the ore has a high silica content that can cause silicosis when inhaled over long periods of time. Dust can also cause gold worker’s pneumoconiosis (GWP) and chronic obstructive pulmonary (COP) disease when inhaled [23]. Thus, it is important that dust suppression methods are used and correct personal protective equipment (PPE) are worn in underground areas, especially in stopes where blasting takes place.

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[2] Photo courtesy of “Manos.”, Internet: http://www.manos.co.za/. [Accessed: 29-Aug-2019].

Figure 8: Mine worker operating a pneumatic drill [24]

As previously mentioned, chilled water is used to suppress dust whilst drilling [25]. Mine workers also spray working areas with chilled water after blasting to cool down rock surfaces before re-entry of the areas. An example of this is shown in Figure 9.

Figure 9: Mine worker spraying work place with chilled water [26]

Sweeping and flushing away of rock:

After blasting has commenced and the rock faces have cooled, mine workers can now gather the ore scattered from the blast. Larger pieces are easily moved by hand or with the use of a loader, but smaller particles of rock and gold are more tedious to move to loading boxes. High pressure water cannons are used to do this. Figure 10 displays a mine worker making use of a water cannon to move ore to loading boxes.

Figure 10: Mine worker operating a water cannon [26]

1.3.3 Dewatering sub-system

Service water sent down a mine along with fissure water amounts to large water volumes underground. To prevent flooding the water must be removed to surface. The main purpose of the dewatering system is to remove warm water from the mine. Secondary tasks include the prevention of flooding and the regulation of water levels in underground storage dams.

The dewatering system consists of the settlers, dewatering pumps, hot water storage dams, mud dams, mud pumps, valves and pipes needed to move water and mud from underground to surface. Figure 11 displays a schematic representation of a typical dewatering sub-system of a mine WRS.

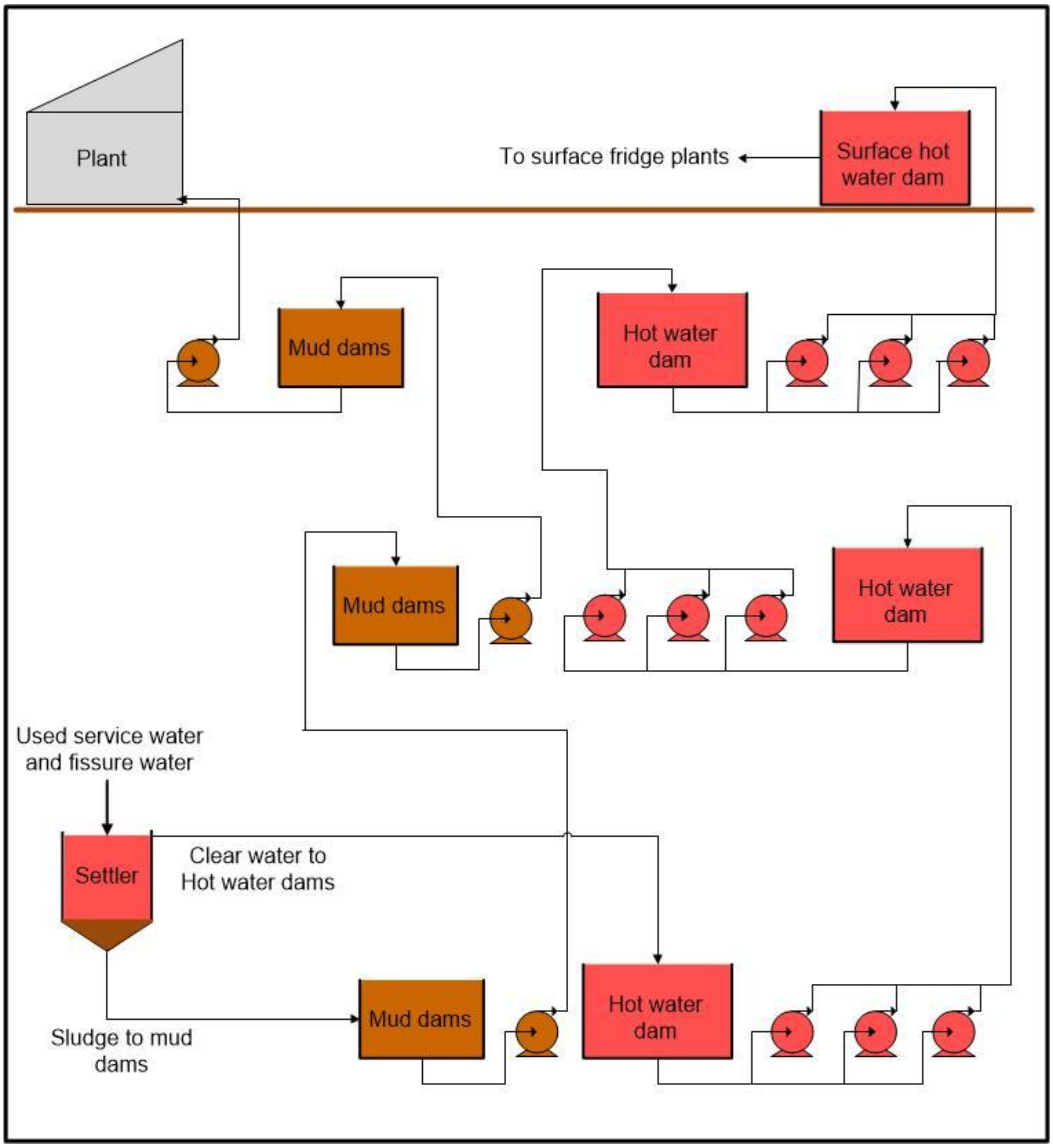


Figure 11: Typical mine dewatering system

As displayed in Figure 11, used service water gathers in the settlers where sludge is separated from clear water. The sludge is pumped to mud dams and clear water to clear water dams for storage before being removed from the mine. From here sludge and clear water are pumped, through cascading dam systems to surface where sludge is sent to the plant for processing and clear water is stored in surface hot water dams. Clear water on surface can be used for any purpose the mine needs.

Settlers:

After serving its purpose within the cold water supply sub-system of the WRS, service water is found on the floor of each level. Used service and cooling water along with fissure water is then channelled from various levels to underground settlers. The accumulation of water is the first step of the dewatering process. Separation of rock particles and dust (sludge) from the water is needed before water can be removed from underground. This is done by settlers. Figure 12 displays an underground settler.

Figure 12: Mud settler used in a mine [26]

Once accumulated in settlers, water is separated from mud (or sludge). This is done with the addition of flocculant to the water. Flocculant is a chemical that reacts with solid particles and causes them to stack together to form larger particles [27]. Gravitational forces then force large particles to descend to the bottom of a settler as sediment [28].

Sludge accumulated at the bottom of the settlers is drained to mud dams underground. Mud pumps are then used to pump sludge to surface metallurgical plants where mineral extraction takes place to remove any remaining gold. Processed sludge is then pumped to evaporative slime dams on surface. Clear water separated from the sludge particles spills over the settlers into columns where it is deposited into hot water dams.

Hot water dams:

Hot water dams are built underground for the storage of warm water after use within the mine; from here warm water is pumped to surface hot water storage dams. Surface hot water dams serve as storage for warm water to either be recirculated through the WRS or be pumped to evaporator dams. As displayed in Figure 11, hot water dams are cascaded on different levels before water is pumped to surface. This is done to allow for a smaller head to be pumped from one dam to the next.

Hot water dams have large capacities to ensure that water can be stored for a long enough time before the use of dewatering pumps becomes necessary. Dams can typically have volumes of 3,500 m^3 or more and have large vertical heights to create a U-tube effect for dewatering pumps [11].

More than one dam is typically built in one location. This is done to ensure enough storing capacity for when dams must be cleaned. Cleaning of dams becomes necessary as not all sludge is extracted in the settlers. Fair amounts of sludge move into hot water dams, causing a build-up on dam floors. Sludge can cause significant harm to dewatering pumps. Therefore, the minimum water-level limit of a dam increases with the presence of sludge to avoid sludge entering the pumps. Sludge thus reduces the storing capacity of hot water dams.

Warm water is pumped through cascaded dam systems underground up to hot water dams on surface. Here water is sent to fridge plants to be cooled and recirculated in the WRS or excess water is pumped to surface evaporation dams.

Dewatering pump stations:

Pump stations cascade along with hot water storage dams to form multiple levels of pump stations throughout a mine. This results in larger flow rates as pumps can be connected in parallel. Pumps connected in parallel will produce an increase in flow rate, whilst pumps connected in series will have an increase of overall head [29].

Mines prefer to make use of large multistage centrifugal pumps within dewatering systems [30]. This is because centrifugal pumps can achieve high head pumped when connected in series [29]. Multistage refers to a centrifugal pump consisting of more than one impeller.

Pumps used in mine dewatering systems are typically within the installed capacity range of 1 to 3.5 MW and pump heads range anywhere from 500 m to 1,000 m, depending on mine depth. A pump station can house anywhere from two to twelve pumps. Dewatering pumps of a single level usually feed off a common supply manifold.

Care must be taken as to the number of pumps connected to a common discharge manifold. Although the addition of a pump to a common discharge manifold does increase total flow rate, this also amounts to increased discharge friction and pressure. Pumps operating at higher discharge pressures will experience a decrease in efficiency [9]. This will cause each pump added to a parallel configuration to deliver a smaller flow compared with what the pump can deliver when operating individually. Figure 13 shows this.

Thus, if too many pumps are added to the same discharge column, the flow contribution of newly added pumps will become negligible. Determining the maximum number of pumps that a discharge column can handle will therefore be beneficial. In some cases, mines have more than one column installed within their dewatering system to avoid this effect.

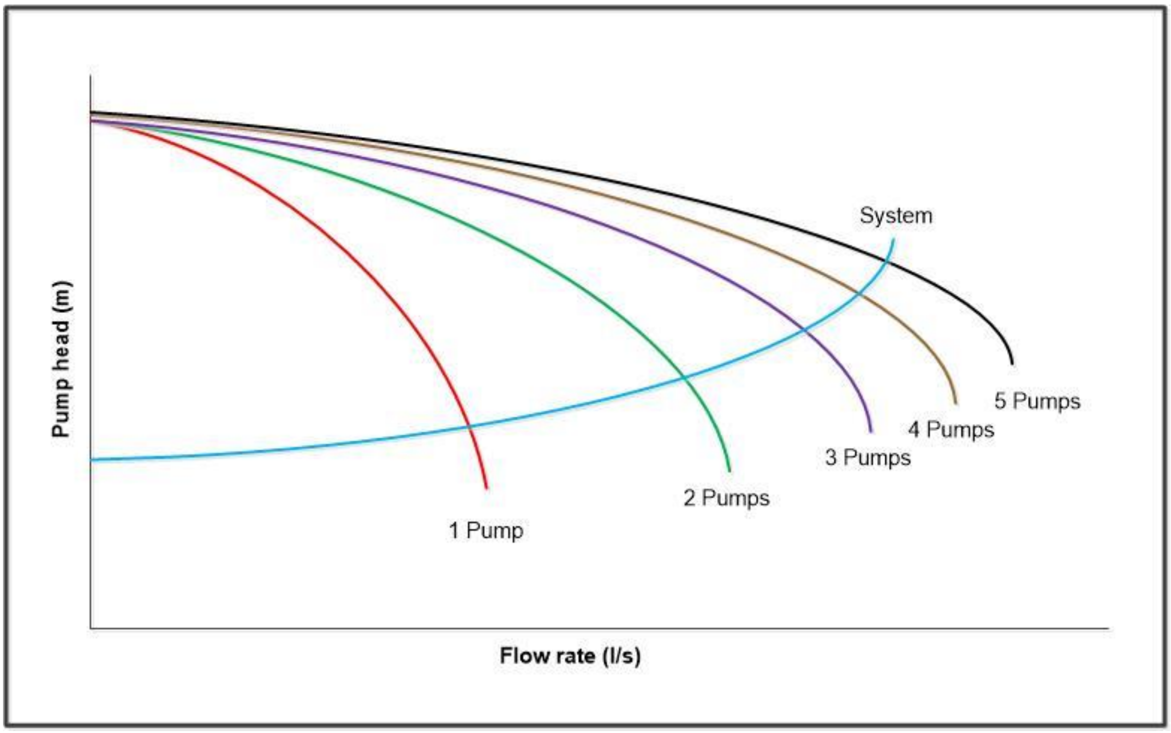


Figure 13: Flow contribution of multiple pumps in parallel configuration (adapted from [31])

1.3.4 Refrigeration sub-system

The refrigeration sub-system of the WRS refers to warm water being cooled on a large scale. Water is cooled to be used for mining as well as the cooling down of air for ventilation purposes [32]. The refrigeration sub-system consists of pre-cooling towers, fridge plants (FPs), dams, pipes and valves. For this study BACs and cooling cars will not form part of the refrigeration sub-system as they heat water up and are a consumer of water. Figure 14 displays a basic schematic resembling the refrigeration sub-system of a WRS.

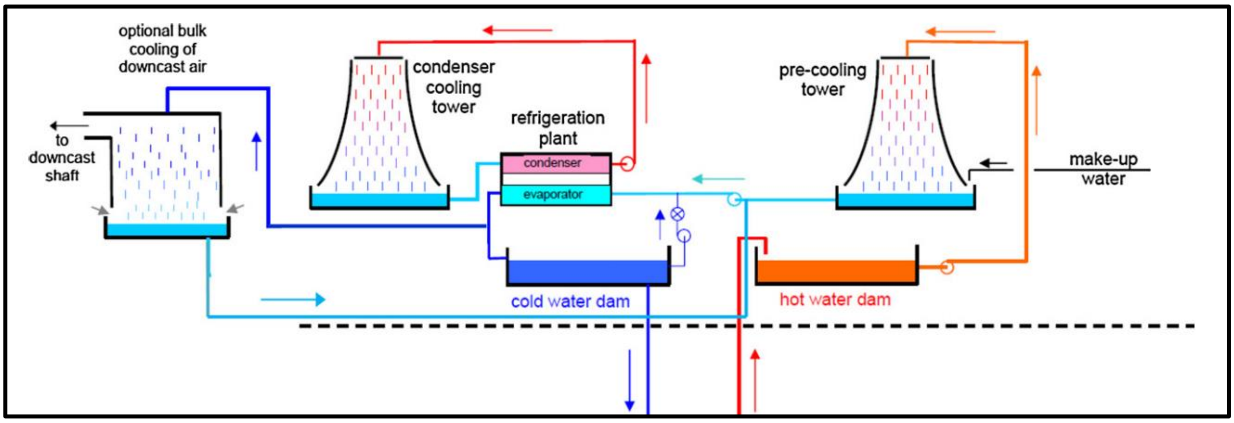


Figure 14: Refrigeration sub-system of WRS [33]

Pre-cooling towers:

Warm water is pumped from underground into a hot water dam on surface. After use warm water reaches the surface hot water dams at temperatures between 25 °C and 30 °C. From here the hot water is pumped to a pre-cooling tower to cool it down to a temperature typically between 15 °C and 20 °C. Figure 15 displays a practical example of pre-cooling towers.

Figure 15: Practical example of pre-cooling towers [34]

The main difference between pre-cooling towers within refrigeration and cooling of mining areas is that cooling of mining areas makes use of water to cool down ambient air and pre-cooling towers makes use of ambient air to cool down water.

Fridge plants:

From the pre-cooling towers water is pumped to surface fridge plants where it is cooled down to anywhere between 3 °C and 5 °C. FPs are installed both on surface and underground at certain mines. Within a FP water is cooled using a standard vapour-compression cycle [35]. For more information regarding the functionality of a vapour compression cycle, please refer to [35]. After exiting the fridge plants, the chilled water is stored in chilled water dams on surface or underground where it can be used for mining purposes as discussed in Section 1.3.2 of this study.

1.4 Excess water within deep-level mines

A typical gold mine in South Africa will pump more than 4 Ml of water from underground to surface daily. Within the gold mining industry some 5,500 Ml of water is in circulation [25]. Typically, a larger volume of water is pumped out of a mine than that which is sent down for use. These additional volumes of water that must be removed are most likely the result of fissure water added to the WRS.

Fissure water is water accumulated in subsurface cracks and fractures, dependent on geology and the movement of the earth’s crust [36]. The amounts of fissure water released by mining activities underground differ between mines. Data analysis of the water readings of a mine in the Free State region of South Africa have shown that fissure water can have an average flow of 40 l/s into a mine WRS. Analysis done by Cilliers [11] proved that flows of as much as 100 l/s are possible in other mines.

Not only do these large amounts of water lead to increased pumping costs, but they also create the risk of flooding if dewatering systems are not well enough equipped. Flooding of mining operations poses a great threat to the safety of underground mine workers. Damage of equipment and loss of production are also risk factors to be considered if a mine was to flood. The effective and efficient management of fissure water within mines is thus of great importance.

There are numerous cases of gold mines flooding, either due to no control measures being in place or old abandoned mines being left to flood [37]. After the closing of multiple mines within the West Rand region, dewatering of these abandoned mines stopped. In 2002 this led to the discharge of acidic water that negatively affected the downstream environment, underground and surface water [37].

Mine flooding has also led to numerous deaths with the most recent case being the flooding of a mine southwest of Harare, Zimbabwe [38]. Along with the risk of flooding, fissure water may have a negative impact on the temperatures of an underground working environment due to extensive moisture in refrigerated areas, humidification of ambient air temperatures and heat transfer from fissure water into the environment [39].

Fissure water temperatures, in South African mines, can increase by a temperature gradient of 1.7 ^{o}C / 100 m, reaching temperatures of 50 ^{o}C at depths of 2,685 m [39]. The refrigeration system is then negatively impacted because warmer water must be cooled, and cooling is negatively impacted as working areas are heated up.

Underground water quality changes can occur as a result of actual mining operations and mixture with fissure water. These changes lead to the following quality problems [25];

- Dissolved salts – Leading to corrosion that results in increased friction loss in pipes, increased erosion and abrasion and blocking of equipment.
- Acidity changes – Acidic water will cause corrosion, whilst alkaline water will reduce settling and flocculation ability.
- Suspended solids – Causing erosive wear on pumps, silting up of clear water dams and loss of efficiency in heat exchangers.
- Cyanide – Draining of water from underground backfill paddocks may contain cyanide. This is poisonous to humans and can leach gold.

As acidic fissure water flows through old mining haulages and interconnecting tunnels, shale rock is weakened [50], [41] and can lead to the decay of underground tunnelling and the weakening of the structure of the mine. This decay may lead to unwanted seismic activities if flooded tunnels are pumped too empty and the internal support of fissure water is lost. Large risk of seismic activity then exists, posing a threat to the safety of mine workers as seismic activity underground can cause fall of ground and the collapse of tunnels.

Gold mines within proximity of one another are often linked through a range of interconnecting tunnels. This is done to allow for escape routes to other mine shafts, among other reasons. As older mines are shut down the dewatering of fissure water within that shaft ceases. As these older shafts flood, water can then flow to other active mines along these interconnected levels, increasing the risk of flooding.

1.5 System reconfiguration and improvements

Reconfiguring and improving a WRS can be a long and sometimes expensive exercise. It is not, however, as expensive as total failures of any part of the WRS leading to the standstill of mining activities and loss of production. Avoiding the risk of flooding on mine workers' safety is also a top priority. The reconfiguration and improvement of mine WRS can be done in many ways. In this study, reconfiguration and improvements will be viewed in terms of water demand management, energy management and system automation.

1.5.1 Water demand management

Demand management implies the reduction of chilled water use within a mine, leading to a decrease in water sent through the dewatering sub-system of the WRS. This will not only reduce the cost of running the energy intensive centrifugal pumps within the dewatering sub-system but will also lead to the possibility of larger amounts of fissure water displaced through the dewatering system. The management of a mine’s chilled water demand can include leak management, stope isolation and pressure set-point control.

Leak management:

A prominent contributor to water wastage underground is leaks within pipe lines and columns. These pipes are typically made of steel and can easily deteriorate and rust in harsh and humid underground conditions. Small cracks start to form along these pipe lines because of this deterioration. This leads to leaks. Worn gaskets within flanges tend to leak large amounts of water under high pressures. A lack of maintenance allows these leaks to gain size until the total failure of a water column can occur.

Large amounts of energy are used to cool service water down to suitable temperatures for underground use. Due to the wide range of uses for water within mines, the total failure of a column will not only result in the total standstill of mining activities but could also waste energy [8]. Leak management will also reduce the amount of water wasted leading to a reduction in demand.

The only way to identify leaks is by performing a leak audit. This involves mine workers and/or personnel of an energy service company (ESCO) to physically go underground to check each section of the WRS for leaks. It is of importance that the type, size and location of each leak found are recorded. During these audits it is frequently found that mine workers leave cold water hoses open. Figure 16 displays a pipe flange leaking and Figure 17 displays a chilled water hose left open.

Figure 16: Leaking pipe flange [42]

Figure 17: Open chilled-water hose [8]

Stope isolation:

The areas of the mine where the actual mining activities take place are referred to, by mine personnel, as the stopes. From either the main shaft or sub shafts entering a certain level underground, main haulages lead to the location of the mined reef. Closer to the reef cross-cuts branch out from the main haulages and eventually lead to stopes where the gold reef is mined. Here water can be used for multiple purposes, including flushing away rock and cooling drills. Daily mining activities can generally be categorised into three mining shifts:

- Morning shift (Drilling) – The drilling of the reef takes place to make way for explosives to be inserted.
- Afternoon shift (Blasting) – Blasting takes place to free ore from the reef.
- Evening shift (Sweeping/extraction) – Ore is collected, moved to loading boxes and extracted to surface.

Water is only required within the stope areas during the drilling and sweeping shifts. Stope isolation thus entails the termination of the water supply to stopes during blasting shifts. Blasting shifts usually occur within the time slots of 18:00 to 22:00 daily. This can either be done by installing manual or automatic valves to cut off water supply to the stopes.

Automatically actuated valves are preferable as they eliminate human error, because mine workers frequently do not close the valves after finishing a morning shift. Installation of manual valves, with no actuators, requires less capital expenditure, because actuators are not installed, but lead to larger water wastage due to human error.

Pressure set-point control:

Pressure set-point control involves the control of water pressures to a set level. Pressure control was tested on certain South African municipal water distribution lines with great success. It resulted in reduced water leaks, reduced water wastage and a significant reduction in system failures [43].

The pressure of the fluid along with the size of the leak determines the flow rate of the fluid through a leak. Reducing the pressure will then reduce the amount of water wasted within a column. Figure 18 displays the results of a test conducted by Volsoo [31] to show the flow of water through a pipe column at different pressures.

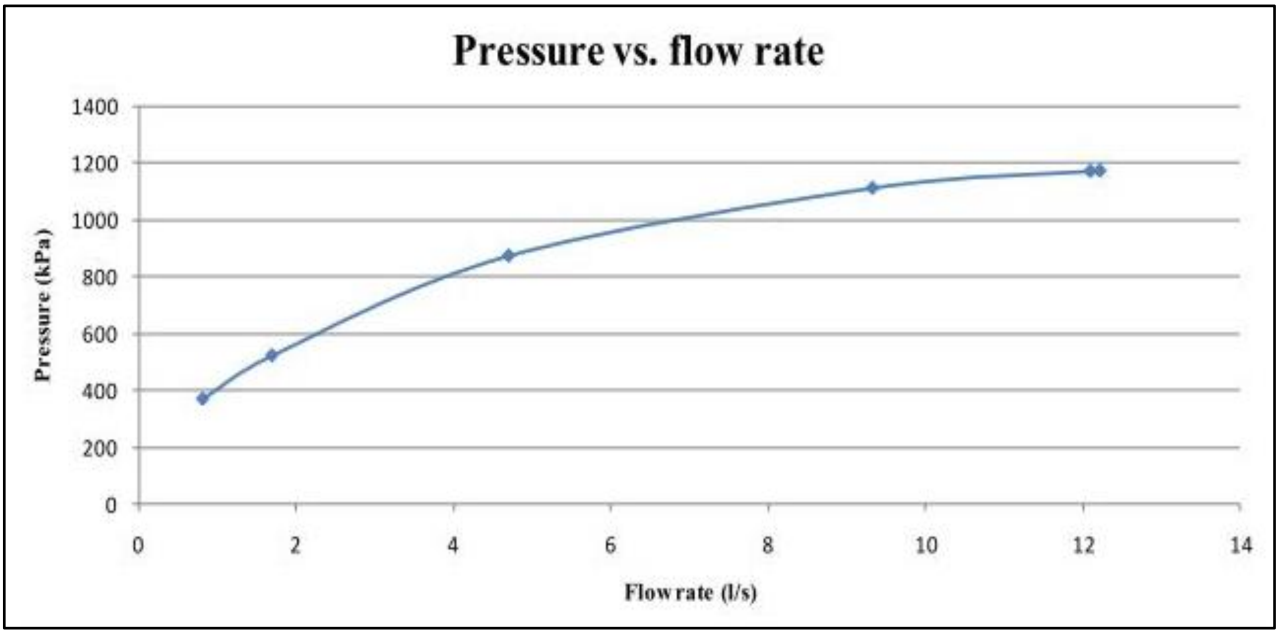


Figure 18: Water pressure vs flow on a mining level (adapted from [31])

It can be seen in Figure 18 that the flow rate starts to increase by larger increments as pressure increases. This means that a reduction in pressure will cause the flow rate to decrease significantly. The use of pressure control on levels could thus be of great advantage to water demand reduction.

Pressures will typically be reduced during shifts where less water is required, such as blasting shifts. It must be taken into consideration that water is still needed for cooling purposes among other things, and pressures must be adjusted accordingly. During production shifts, pressures must be high enough as to not interfere with drilling and sweeping activities.

1.5.2 Energy management

Energy management plays a large role in the reconfiguration of mine WRS and usually aims at reducing the cost of running the WRS by means of a reduction in electricity consumption. The management of energy can either be done by means of energy recovery systems or energy demand management. Because of the vast amount of electricity used by industrial and mining companies in South Africa, Eskom introduced a time-of-use (TOU) structure [11]. TOU implied that customers are billed different amounts for the electricity used during different times of the day [44]. Customers with a notified maximum demand of more than 1 MVA fall into the Megaflex tariff structure. Mines are usually amongst these clients [44].

There are three TOU periods within the Megaflex tariff structure, namely off peak, standard and peak time. Eskom charges different amounts for each of these periods as well as different amounts during winter (June – August) and summer (September – May) months. Tariffs also differ according to the line size and the client’s distance from Johannesburg, South Africa [44]. Please refer to Appendix A for the winter and summer months’ Megaflex tariff time schedules.

Figure 19 displays the prices of a Megaflex client with a 500 V - 66 kV line within 300 km of Johannesburg [45]. It is clear to see from Figure 19 that the use of electricity within the peak periods of a day will amount to higher costs. The first step to identification of electricity wastage would then be to determine whether the mine consumes large amounts of electricity within these peak times. Demand Side Management (DSM) is the term used to refer to the planning and implementation of projects that are used to manipulate or alter the electricity load profile at the end-user’s side.

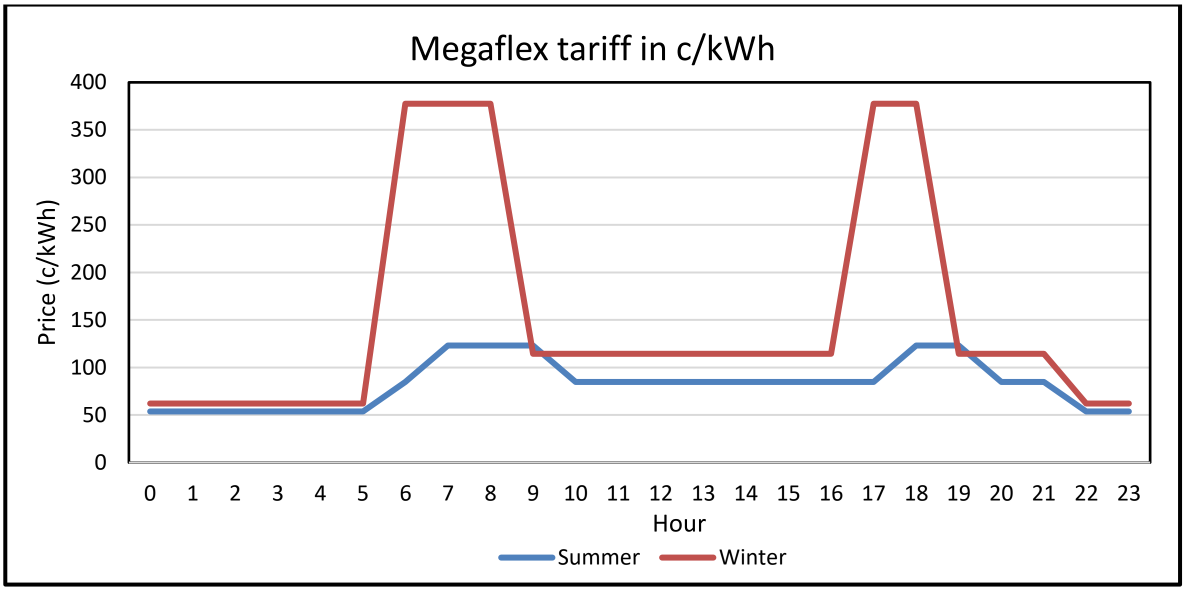


Figure 19: Megaflex tariff of a 6.6 kV line 300 km from Johannesburg

Load shifting:

Load shifting is a DSM tool used to lower electrical consumption during Eskom peak hours. The purpose of load shifting is not to use less electricity during the day, but rather to move the load to less expensive times during the day [46]. This project is of benefit to both Eskom and the client as the client pays less for electricity and Eskom will have more capacity during peak hours. Figure 20 displays a typical load shift profile (blue) compared with a normal profile (red) with the area beneath the graphs representing the electricity used.

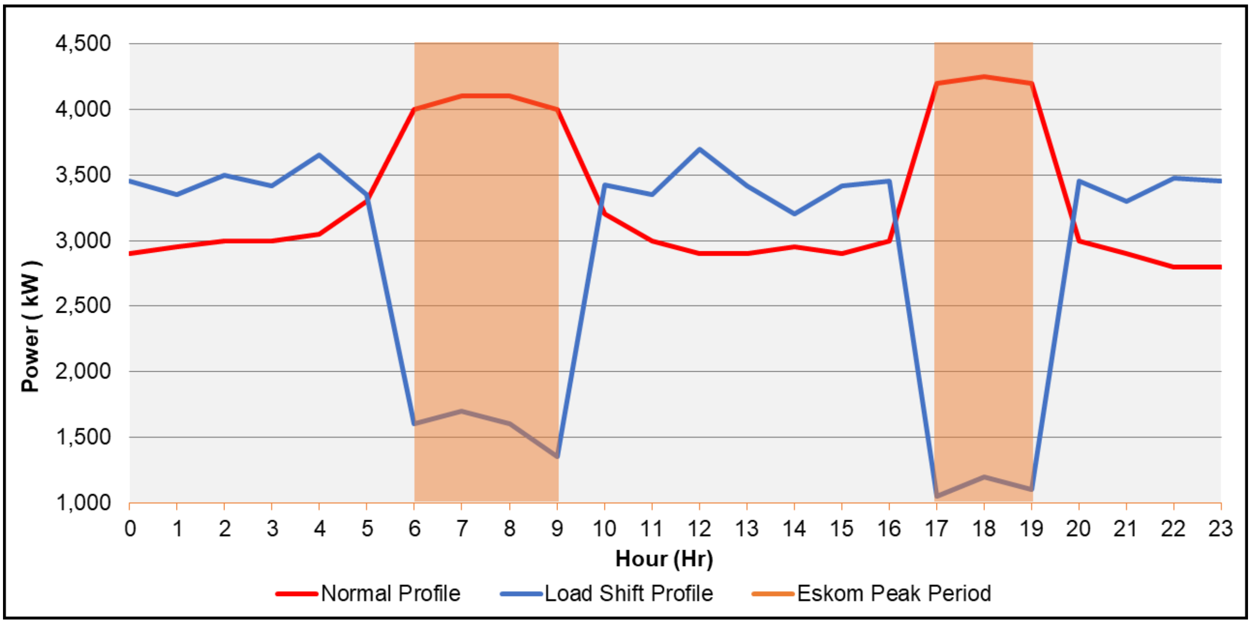


Figure 20: Typical load shifting profile

Peak clipping:

Peak clipping refers to the practice where processes or systems are stopped or shut down to alter the load during the maximum or peak demand times within a day, reducing the demand. The total electricity demand is then reduced without influencing production negatively. Peak demand times can occur during any time of the day, but clipping is usually done during Eskom peak hours.

Figure 21 is a depiction of a typical peak clipping profile where the normal profile is represented with a red line and the peak clipping with a blue dotted line. It can be seen that the profiles remain the same, except for peak hours where the peak clipping occurs.

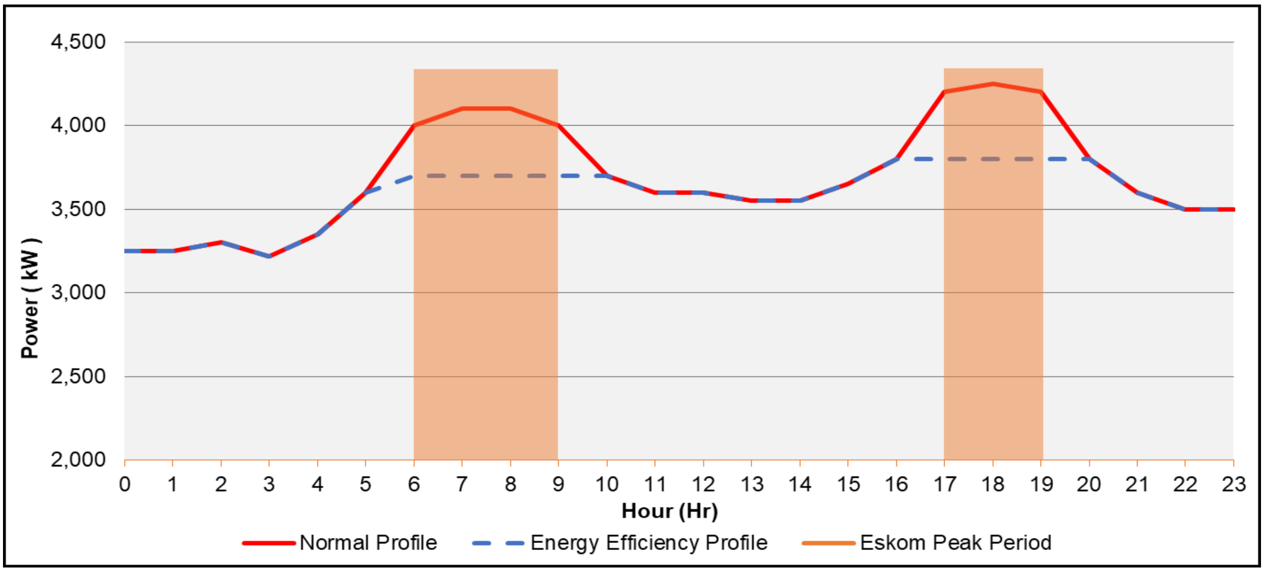


Figure 21: Typical peak clipping profile

Energy efficiency:

Energy efficiency refers to the practice of using electricity more efficiently. This is done by either switching to a more efficient process or making use of more energy efficient equipment. A typical energy efficiency load profile is displayed in Figure 22. Here the normal profile is represented with a red line and the energy efficiency with a blue line. It can be seen that the profile remains the same, but with a reduction in power consumption.

The installation of energy efficient dewatering systems such as three chamber pipe feeder systems (3CPFS) and turbines can reduce the electricity demand on a mine. If identifying inefficiencies within a mine, it would be wise to determine if the mine makes use of these systems.

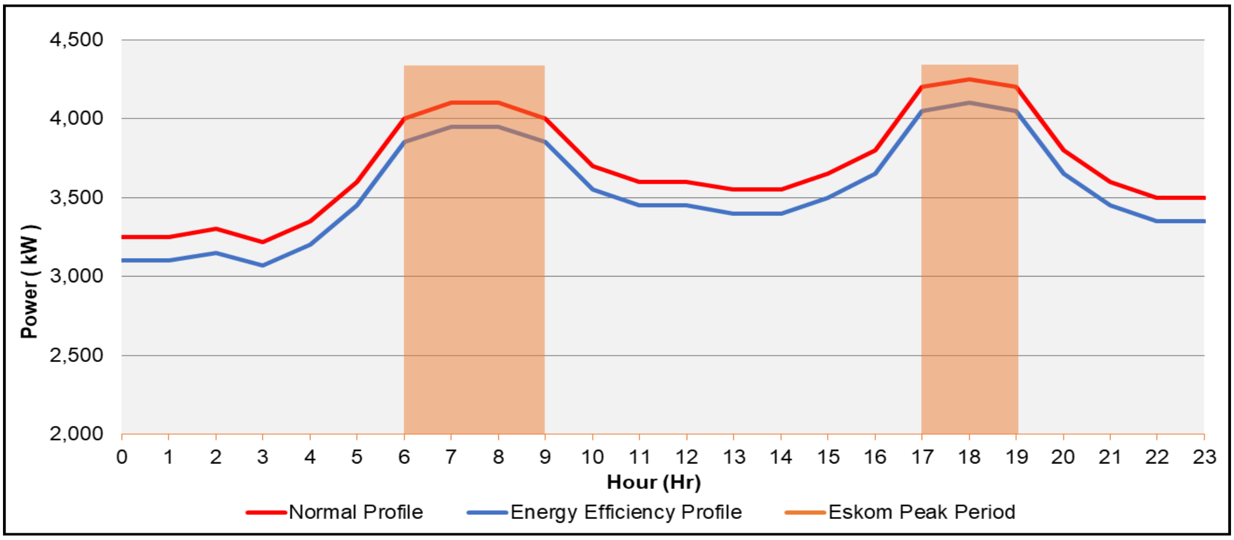


Figure 22: Typical energy efficiency load profile

Proper maintenance of equipment, utilising more efficient equipment and changing to more efficient processes play a large role in efficient electricity usage. Wasted chilled water amounts to wasted energy, since large amounts of electricity are used to cool water down within fridge plants and pre-cooling towers. Identifying the amount of chilled water wasted along with a study of the efficiency of equipment and processes used should be a crucial step in the identification of inefficiencies.

1.5.3 System automation

System automation entails the installation of instrumentation that enables the client to actively monitor and control a system from surface. Automation of the WRS enables mining operations to adapt to numerous situations without having to negatively affect production, and all whilst achieving energy cost savings. Automation of pumps enables the implementation of load shift projects on mine dewatering systems [47]. Some of the main benefits of implementing system automation within the WRS include:

- Improved control of equipment
- Remote management of systems
- Elimination of errors caused by human intervention error leadings to improve reliability
- Effective monitoring of dam levels
- Enabling preventative maintenance and pump protection procedures
- Effective application of load shifting projects to realise cost savings

The basic instrumentation needed for pump automation includes programmable logic controllers (PLCs), temperature and vibration transmitters, flow meters, valves, pressure transmitters, dam level indicators and servers [48].

SCADA:

The supervisory control and data acquisition (SCADA) is an installed program on a mine server located within the control room. The SCADA serves as the interface that a control room operator uses to control pumps from surface. It is also used to indicate schedules and log data [49]. The SCADA sends instructions from the control room to the underground PLCs. Figure 23 displays a typical gold mine SCADA.

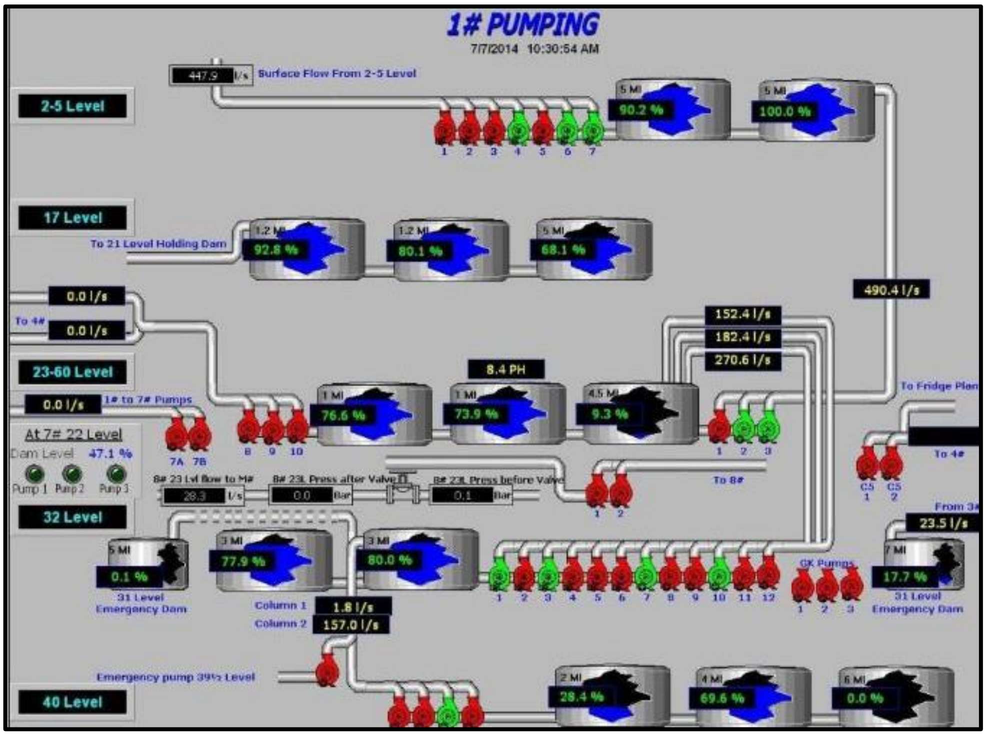


Figure 23: Example of a gold mine SCADA [48]

Energy management systems:

An example of an energy management system is Real-time Energy Management System (REMS). REMS is a simulation system as well as an energy management system used to control mine dewatering pumps in real time. It serves as a powerful simulation package that can be used to accurately simulate possible outcomes and implement them on the mine. Implementation of this system will make use of real-time data from underground PLCs to control dewatering systems.

Many energy management systems exist that will be able to control the dewatering system of a mine. REMS was considered as it was already implemented on some of the mines applicable to this study. Some of the benefits of using REMS on a mine dewatering system include:

- Full automation of equipment underground along with system reliability
- Easy to monitor the condition and status of underground equipment (for example dam levels, pump running status, vibration of equipment, temperatures and valve positions)
- A built-in historian saves the historical data of specified equipment
- Specified alarms can be sent to mine personnel via SMS or email (for example high pump temperature, high dam levels and excessive vibration of equipment)
- Can be programmed to perform load shifts on dewatering equipment
- Eliminates human error

The REMS platform, used for automated pump control and monitoring, of a gold mine dewatering system in the Free State region of South Africa is displayed in Figure 24.

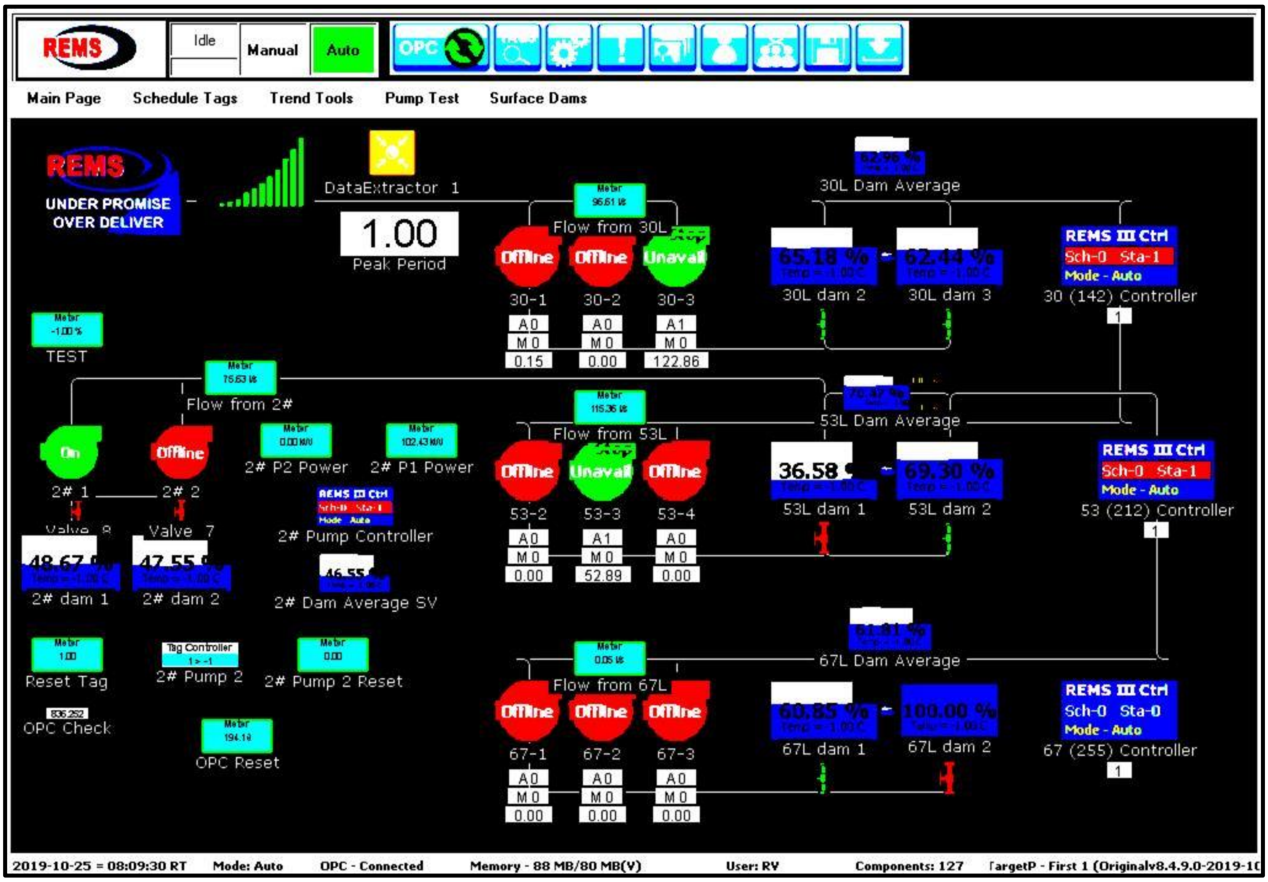


Figure 24: REMS platform of a gold mine dewatering system

Some of the negative aspects of making use of REMS for the control of mine dewatering systems are that it is not available to all and it is not very user friendly. Furthermore, pumps can be switched to lock-out position, thus not enabling REMS to have full control of the system. The benefits of making use of REMS far outweigh the negative aspects. For that reason, REMS will be the only energy management system discussed and made use of within this study.

1.6 Previous studies and the need for this study

The purpose of Section 1.6 of this study is to give a critical analysis of previous studies concerning the reconfiguration of a mine WRS. Additionally, attention will be given to whether these studies included certain system improvements after or during reconfiguration. These improvements are **system automation**, **demand management** and **energy management**. The studies will be reviewed according to the **objective, method** and **results** of the study.

1.6.1 Studies regarding the reconfiguration of mine WRSs

For the purpose of this study, reconfiguration of a WRS referred to changes made to the WRS of the specific mine, or surroundings of the mine, that led to improvement of the mine’s WRS functionality and/or improved water distribution and control. Many studies were identified that included the reconfiguration of mine WRSs in some way or another. Most of these studies revolve around the implementation and/or improvement of DSM projects (load shifts and peak clipping) on gold mines in South Africa.

Studies revolving around DSM projects usually have the main goal of cost saving via energy demand reduction and do not always aim at improving WRS functionality or removing excessive water. For this reason, studies that mainly focused on the improvement of existing DSM projects were not considered. The nine relevant studies identified are discussed below. Newer studies could not be identified.

Study A: [9]

Conradie [9] conducted a study on the reconfiguration of mine WRS systems to achieve cost savings throughout the entire day. This was done by reducing the amount of water transferred through the dewatering sub-system via reduction of chilled water supply and demand. Supply and demand reduction were achieved through the removal of cooling cars and replacing them with strategically placed centralised BACs [9].

A method was developed and used to evaluate the cost and energy savings of a reconfigured mine’s dewatering system with accuracy. Actual data obtained was verified and used as inputs to calculate the energy cost of both the original and reconfigured dewatering systems. The developed methodology was applied on the reconfigured mine WRS of a South African gold mine. After the first month of implementation an energy saving of **4,095 MWh** was achieved. The predicted energy and cost savings, if performance of the reconfigured WRS could be sustained, was predicted as **49.1 GWh** and **R31.8 million** per annum, respectively [9].

Study B: [50]

Oosthuizen [50] completed a study that focused on the reconfiguration of the complete dewatering system of five mine shafts, within the same gold mining complex, for cost saving purposes. Various possible pumping options concerning the WRS of the five separate shafts and the interconnected network as a whole were investigated, simulated and then verified. From the results of this simulation the dewatering systems were automated and optimised by means of load shift implementation.

REMS was used for the simulation of the different pumping possibilities. The average load shifted out of peak periods per day along with the annual financial saving for each of the scenarios are displayed in Table 1.

Table 1: Study B main results

	Mine A	**Shaft C**	**Mine D**	**Mine E**
Daily load shifted from peak (kWh)	61 997	32 818	25 995	11 082
Annual savings (R)	18.7-million	11.1-million	7.5-million	1.8-million

Study C: [8]

Botha [8] opted to reconfigure mine WRSs by means of reducing water wastage and to minimise water consumption during less water intensive periods of the day, such as blasting shift. The three main methods identified to reduce water wastage and consumption were leak management, stope isolation control and supply water pressure control.

Botha conducted tests on two different mines. On Mine 1 pressure control was applied and led to a daily reduction of 1.4 Ml of water leading to 9.6 MWh electricity reduction and R 513 700 saved annually. All three of the identified techniques were implemented on Mine 2. A daily reduction of 7 Ml water was realised by leak management whilst 1.6 Ml water was reduced daily by pressure control and stope isolation. This led to a 92 MWh reduction in electricity consumption and estimated cost saving of R 5.6-million per annum.

Study D: [51]
Oberholzer [51] focused on the reconfiguration of the cooling systems of mines for optimal operation. Inefficient cooling and refrigeration equipment were identified by comparing the date of installation with the life expectancy of equipment. Old equipment was deemed inefficient. A universal method to obtain optimal operation of a mine's cooling sub-system was developed and the effects of reconfigurations were predicted by means of simulation.

Implementation of the suggested reconfigurations to a mine's cooling sub-system was predicted to realise a power reduction of 9 MW on the mine's total power usage whilst delivering a chilled water temperature of 5°C. The simulation set-point was changed to 3 °C and results proved that the cooling sub-system would be able to maintain a chilled water outlet temperature of 3.2 °C whilst obtaining a reduction in power consumption [51].

Study E: [33]
Vosloo et al. [33] conducted a study that focused on the reduction of a mine's energy use through applying load shifts to the mine's FPs and dewatering system for cost saving purposes. A surplus of cold water was generated before peak periods to improve load shift performance of FPs whilst pump automation and scheduling along with turbine utilisation were used to improve pumping load shifts. A reduction in peak demand load together with optimising the refrigeration system and its auxiliaries achieved a 4.8 MWh daily electrical energy saving. A morning load shift of 3.3 MW and an evening load shift of 4 MW was achieved. REMS was used to monitor and control mine WRS equipment.

Study F: [52]
Roberts and Stothert [52] conducted a study on the development and improvement of an integrated control system to enable centralised management of the WRS of Elandsrand gold mine in South Africa. The study described the development of the system to date along with research done on further improvement to the system. The main objectives of the implementation of the management system were to reduce operating costs and optimise production of chilled service water supplied to the mine.

The installation of PLCs and pump status monitoring equipment was completed to allow for better pump control and maintenance. This would allow the mine to control dewatering pumps from surface and by so doing, pump less water during high cost periods of the day. Although specific figures were not mentioned in the study, the system yielded benefits, as electrical demand charges were reduced and water distribution between underground levels could be co-ordinated.

Study G: [53]

Gao et al. [53] focused on the development of a system that can analyse and explore different strategies for managing a mine WRS. The developed systems model integrated a process-based mine WRS simulator with multi-objective optimisation for assessing mine water management strategies. The system was specifically designed for coal mines and made use of four principal indicators to describe and evaluate the effect of seven identified water management strategies.

Objectives of the best identified management strategies included decreasing raw water use, improving water use efficiencies, reducing water use cost, eliminating unregulated discharge, and minimising risks associated with water quantity and quality (particularly salinity) in worked water stores [53]. The developed system was used to assess the water management strategies on a coal mine in Queensland, Australia. Results of the simulation indicated that tested strategies could result in a reduction of 40 % in water use costs along with a 50 % reduction in raw water needed.

Study H: [54]

Côte et al. [54] developed and calibrated a systems model that can be implemented to simulate the impact of implementing water management strategies on coal mines. Management strategies would help reduce the amount of water being used and improve the amount of water re-used within the WRS. The developed model was applied and compared with the water balances of 7 coal mines in Queensland, Australia.

Results proved the developed systems model as an appropriate tool to assess mine performance, providing guidance to improve performance through strategic planning and to compile the water management information that can be reported as sustainability performance indicators.

Study I: [55]

Gunson, Klein, Veiga and Dunbar [55] conducted a study that demonstrates the most energy-cost effective method to operate a mine or mill WRS. A linear programming algorithm was developed to determine the most cost-effective way to supply water to a mine or mill’s water consumers. The method used was to determine a detailed water balance of the specified mine/mill, followed by the identification of all water sources and consumers.

The energy requirements of all water sources (i.e. pumps, treatment and cooling) to supply water to all consumers is calculated and applied to the algorithm to minimise power consumption. An example was used to describe the developed method and resulted in an 50 % energy-cost reduction. No actual results attained by implementation of the method are discussed within the paper.

1.6.2 Need for the study

The findings of the nine relevant studies are summarised within Table 2. As seen in Table 2, none of the reviewed studies have been regarding the reconfiguration of a mine WRS for the management of increased water volumes. Only one of the studies included reconfiguration, automation, energy management and water demand management in one study. The need thus exists for a study regarding the reconfiguration of a mine WRS for the management of increased water volumes.

Table 2: Criteria of relevant studies

Study	Reconfiguration purpose	System Automation	Demand management	Energy management
A	Cost saving through entire day		X	
B	Multiple mine shafts for cost saving	X		X
C	Decreased water wastage and consumption		X	
D	Optimal cooling system operation			X
E	Decreased energy use through load shifts	X	X	X
F	Reduce operating costs and optimise production of chilled service water			X
G	Identify improved water management strategies of coal mines		X	X
H	Identify the effect of applying water management strategies on coal mines		X	X
I	Most cost-effective way to operate mine/mill WRS			X

1.7 Problem statement and study objectives

Gold mining in South Africa is a large industry that consists of several gold mine groups spread across several regions. One region will usually consist of several mine shafts located along the gold reef of the mined area. These shafts are, in most cases, connected through a vast network of underground tunnels. Along with access to escape routes to other shafts, these connections create the risk of flooding as fissure and flood water can now flow from one shaft to another.

Fissure water can enter a mine with a temperature gradient that increases by 1.7 ^{o}C / 100 m of depth below surface, reaching temperatures of 50 ^{o}C at depths of 2,685 m [39]. These high temperatures can have a large negative impact on the refrigeration and ventilation systems due to extensive moisture in refrigerated areas, humidification of ambient air temperatures and heat transfer from fissure water into the environment [39]. Along with this, fissure water has a negative impact on the water reticulation system as additional water must permanently be pumped out of the shaft to avoid flooding of active working areas.

As gold mines deepen over time the original systems put in place for ventilation, refrigeration and water reticulation rarely remain effective. Inevitably a large-scale system reconfiguration becomes a necessity to keep working conditions underground bearable. Alternatively, secondary pumping systems must be put in place to keep flooding water from reaching active mining areas.

This study will focus on **possible solutions for the reconfiguration of a deep-level mine water reticulation system to compensate for excess water**. The summarised **objectives** can be listed as follows:

1. Identify problem areas within the water reticulation system.
2. Develop a reconfigured system to compensate for excess fissure water and simulate the system to confirm the viability of the solution.
3. Implement the reconfigured system.
4. Improve the already reconfigured system.

1.8 Overview of the study

Section 1.8 of this study describes the main purpose of each of the following chapters within this study.

Chapter 2:

Chapter 2 describes the five-step method used to reconfigure a mine water reticulation system to better manage high water volumes. This method was developed for the purpose of this study and the five steps are as follows: data acquisition, solution development, validation of solution, implementation and system improvement, and results quantification. Each of the five steps is discussed in detail and will give a universal solution as to the reconfiguration of a deep-level mine water reticulation system to manage higher quantities of water than initially designed for.

Chapter 3:

The five-step method developed in Chapter 2 was applied to two case studies, Case Study A and Case Study B. The process and main findings of the two case studies are discussed in Chapter 3 of this study. This serves as the results chapter of this study.

Chapter 4:

Chapter 4 will give a well-rounded conclusion of the literature, methodology and results chapters of this study.

CHAPTER 2 MINE RECONFIGURATION PROCEDURE

A universal process to reconfigure a mine's WRS, for improved management of high-water volumes and improved performance, was developed. This process was derived and adapted from reconfiguration processes described in multiple studies [9], [51], [56], [57].

Here the generic five-step method developed to reconfigure a deep-level mine WRS, for the management of excess water, will be discussed. Methods to improve WRS performance after reconfiguration will also be discussed.

2.1 Introduction

Figure 25 is a graphic representation of the steps described within this methodology to achieve the reconfiguration of a deep-level mine WRS to manage high water quantities.

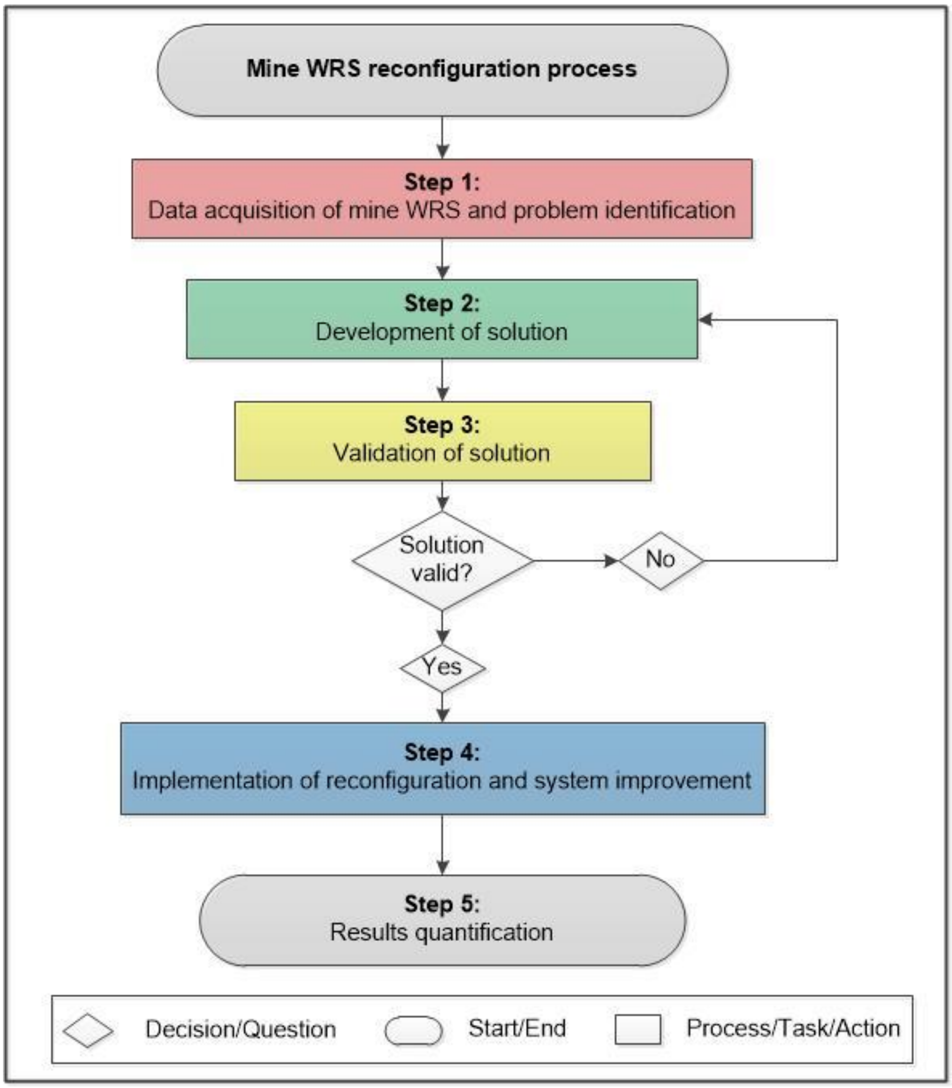


Figure 25: Mine WRS reconfiguration process

As seen in Figure 25, the processes consist of five main steps. Each of these five steps can be an iterative process to ensure the best possible solution is attained after the completion of the final reconfiguration. Evaluation will take place during each of the five steps to ensure the feasibility or correctness of the step.

A short description of each of the five steps is provided below:

Step 1: Data acquisition of mine WRS and problem identification is to acquire all the necessary data regarding the needed specifications of the mine's WRS and problems within the WRS. Analysis of the attained data will aid with gaining familiarity of the applicable mine WRS and the problems at hand.

Step 2: Development of solution. Here the main purpose will be to utilise the information gathered during the first step to devise a solution for the management of the excess water within the mine. This developed reconfigured system/solution will be applied to the WRS of the applicable mine, the surroundings of the mine, or both. Surroundings of the mine can be neighbouring mine shafts or interconnected tunnels between mines.

Step 3: Validation of solution is the validation of the proposed reconfiguration solution. Validation will be done by means of a simulation to serve as proof that the proposed reconfigured system will be up to the task at hand.

Step 4: Implementation of reconfiguration and system improvement can only commence after validation and will be the physical implementation of the proposed reconfigurations to the system and/or surroundings. After or during implementation, the possible system improvements as discussed in Section 1.5 of this study, can commence where possible.

Step 5: Results quantification is the final step of the developed method. Results will be quantified by comparing the relevant measured flow rates before and after implementation of the proposed reconfigurations. Quantification of results can start during the implementation stage as possible results can already be attained during implementation.

Sections 2.2 through to 2.6 will consist of in-depth discussions of each of the five steps of the reconfiguration process. Possible expectations and guidelines will be given to each of the steps, but it is important to note that cases will differ depending on the applicable mine and the problems faced. The process followed to complete each step was derived through hands on experience and availability of processes, equipment and guidance from experienced mine personnel and mentors.

2.2 Step 1 - Data acquisition of mine WRS and problem identification

Data acquisition refers to the gathering of information regarding the mine WRS itself and all the problems within the current WRS. This will firstly enable one to be completely familiar with the WRS on the given mine along with its problem areas. Familiarity will bring about a broader perspective when developing a solution during the second step of the process. Figure 26 is a graphic representation of the data acquisition process.

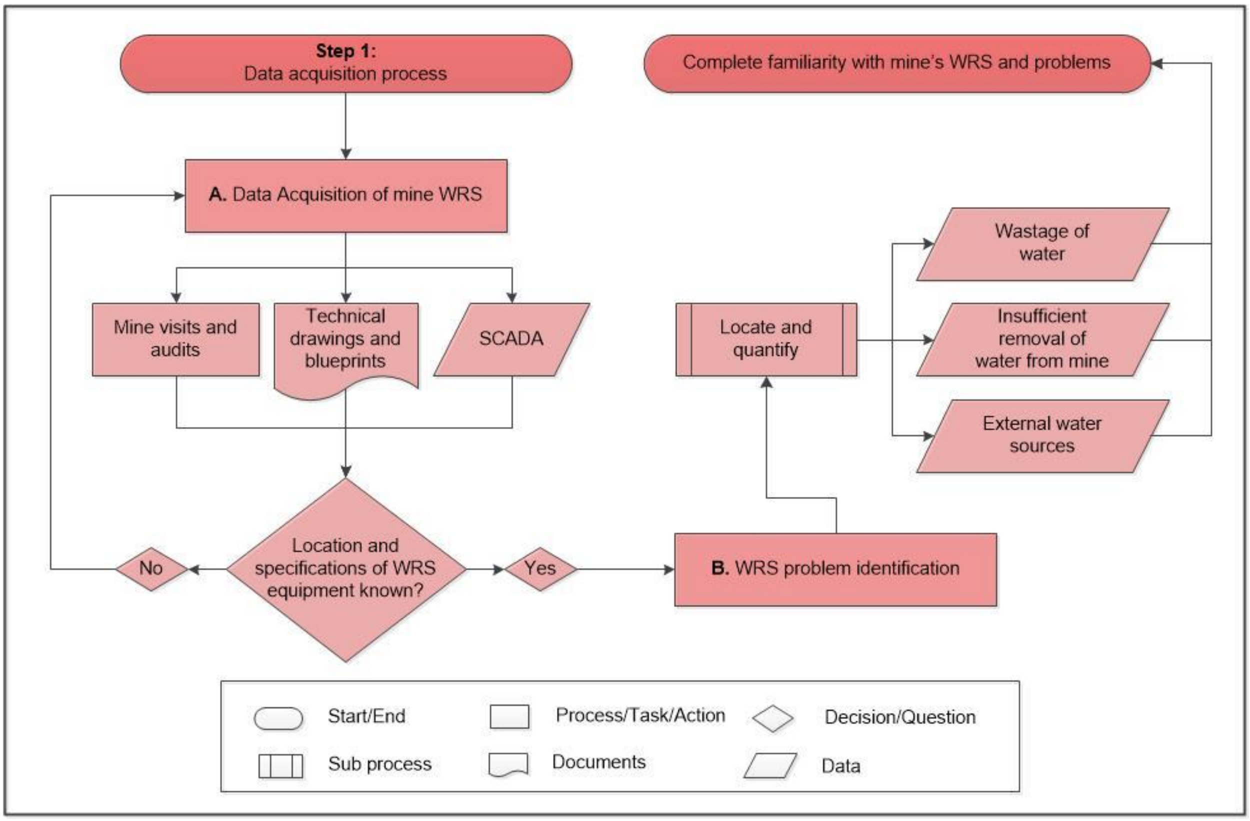


Figure 26: Data acquisition process

It is frequently found that a SCADA system is present on deep-level mines. As mentioned in Section 1.5.3, the SCADA logs data of mine equipment and processes by means of installed instrumentation. Mine equipment (such as PLCs and flow meters) all have a given address by which it can be identified. Tag names are used by the SCADA to reference to different equipment addresses.

A vast array of measurements can be logged by the SCADA of which flow rates, dam levels, vibration measurements, temperatures and open or closed positions are only a few. Making use of a mine's SCADA system within the data acquisition process can be of great benefit.

In cases where a SCADA is not present on the investigated mine, equipment with logging capabilities must be installed to record the desired readings. An example of this would be the installation of a flow meter on a certain pipe line to log the flow rates throughout the day. This recorded data can then be analysed manually.

A. Data acquisition of mine WRS:

It is firstly required that the locations and specifications of all major components of the WRS are known. Main components housed within the WRS of a deep-level mine can be listed as follows:

- Hot water-, cold water- and mud storage dams
- Fridge plants
- Bulk Air Coolers
- Cooling towers
- Settlers
- Pumps
- Valves
- Pipelines
- Water cars

Where applicable, the following specifications must be gathered for different components within the WRS:

- Flow rates in and out of a component
- Power requirements of the component
- Efficiencies
- External flow rates entering system
- Depth below surface
- Head to be pumped
- SCADA tag names
- Length, diameter and material of pipe sections
- Pressures
- Volumes of dams

All the above-mentioned data and specifications can be acquired by means of extensive underground audits, mine blue prints, measurements, calculations and the mine’s SCADA. Talking to experienced mine personnel during a visit to the site will also help a great deal in familiarising oneself with the WRS layout.

B. WRS problem identification:

With the WRS and all its components' locations and specifications known, the next part of the data acquisition step is to gather information regarding all the problems within the WRS. It was found that if a mine has a problem with excessive water, it could be the result of any combination of the following:

- Wastage of water within the mine
- Insufficient removal of water from the mine
- External sources adding water to the mine (such as fissure water)

Water wastages in a mine will allow more water to be used within the WRS thus adding to the water demand. Unnecessary water volumes must still be removed, adding to the work load of the dewatering sub-system. Insufficient removal of water from a mine can be due to damaged pumps, increased water demand or outdated infrastructure for the removal of water. With mines expanding and deepening, fissure water added to the mine WRS increases, as explained in Section 1.4. Problem identification must thus be done with the three main reasons in mind.

The most common problem occurring within mine WRSs is the wastage of water in the form of leaks. Identifying all the leaks within the system would be the first step toward the identification of system problems. This is done by performing an extensive audit of the pipelines and all water users within a mine's WRS. Audits along the WRS are usually performed by groups, or individuals, auditing separate areas or levels of the mine. Dividing the workforce covers more ground and is preferable, as mines can be large, consist of multiple levels and have a vast number of tunnels.

Alternatively flow rates can be measured at the start of a pipe line leading to a certain level or haulage, as well as the ends of the pipe line. Using the calculated water volume flow rates of each pipe segment, a water balance can be calculated to determine the areas of water wastage and amounts of water wasted.

A typical audit will focus of identifying the amount or rate of water wasted, the exact location of the leak/wastage and the type of leak. Pipe material and diameter are also recorded. Table 3 displays a typical table used to identify leaks and wastages within a WRS audit. The most common suspects found in water wastages were flanges, T-Pieces, rusted pipes and poor connections between pipes.

Table 3: Typical WRS audit table

No.	Position	Description	Diameter ['']	Material
1	71L, Chair lift cross-cut	Leak	2	Steel
2	71L, Haulage – north	T-Piece leak	4	Steel
3	First split after 71L Haulage – north	Hole	4	Plastic
4	80L East 8 cross-cut, Fish plate 203	Coupling	4	Plastic

Once leaks are identified, the flow rate of each leak can be quantified using Bernoulli's theorem.

$$Q = a\,A_t\sqrt{\frac{2(P_i - P_o)}{\rho_w}} \tag{1}$$

Here the following holds:

Q = Volumetric flow rate (m^3/s)

P_i = Pipe internal pressure (Pa)

P_o = Pressure outside of the pipe (Pa)

A_t = Area of the leak (m^2)

a = Fluid flow coefficient (-)

ρ = Fluid density (kg/m^3)

Figure 27 displays the different flow rates according to different leak sizes. For this exercise, a flow coefficient of 0.7, water pressure of 1,400 kPa within the pipe and air pressure of 110 kPa outside of the pipe were assumed.

It is clear to see that water wasted increases exponentially with an increase in leak diameter. Calculating the total flow rate of water wasted will result in a better understanding of the problem at hand. This is because an accurate prediction can now be made as to the amount of unused water that must be removed within the mine's WRS.

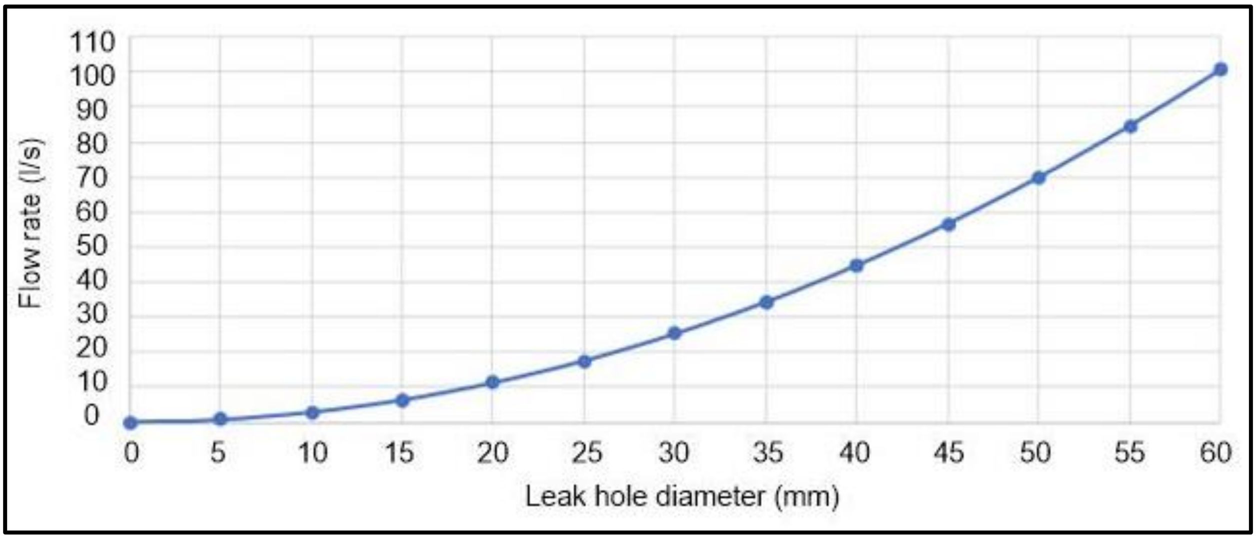


Figure 27: Flow rate of different leak sizes using Bernoulli's theorem

Quantifying the amount of fissure water added to the system can be done with a simple water balance. This implies measuring the water flows in and out of a mine. Table 4 is a water balance example, displaying the water readings of a medium sized gold mine (1.37 km depth) within the Free State province of South Africa. The readings were the total over a one-week period and displays all the water sent down and pumped out of the mine.

Table 4: Water flow readings of a medium sized gold mine over a one-week period

Water flow to	**Volume reading (m^3)**
Down interconnected shafts	488
Service water down	4,707
Drinking water down	1,228
Sum of water sent down mine	**6,423**
Dewatering	29,776
Waste water to evaporative dams	150
Sum of water pumped out of mine	**29,926**

Table 4 shows that the total amount of water sent down the mine and its interconnected shafts amounts to 6,423 m^3, whilst a total of 29,926 m^3 of water was removed from the mine within that week. A total of 23,503 m^3 of the water removed can thus be accounted for as fissure water. This is equivalent to a fissure water inflow of 3.35 ML per day or a constant flow of about 39 litres per second. Upon completing the first step of the mine reconfiguration process, a clear understanding of the mine WRS and its problems will have been gained, and solution development can begin.

2.3 Step 2 - Solution development

Solution development can be a complex part of the process as there are many factors to consider when implementing changes to a mine WRS. These factors are, for example, the required flow rates and pressures needed for different areas of the mine, cooling and refrigeration must not be negatively influenced, floods must be avoided. Factors are mine dependent and will vary with each different scenario faced. A few basic ideas and possibilities as to the development of a general solution are discussed within Section 2.3 of this study.

Figure 28 is a visual representation of the solution development process.

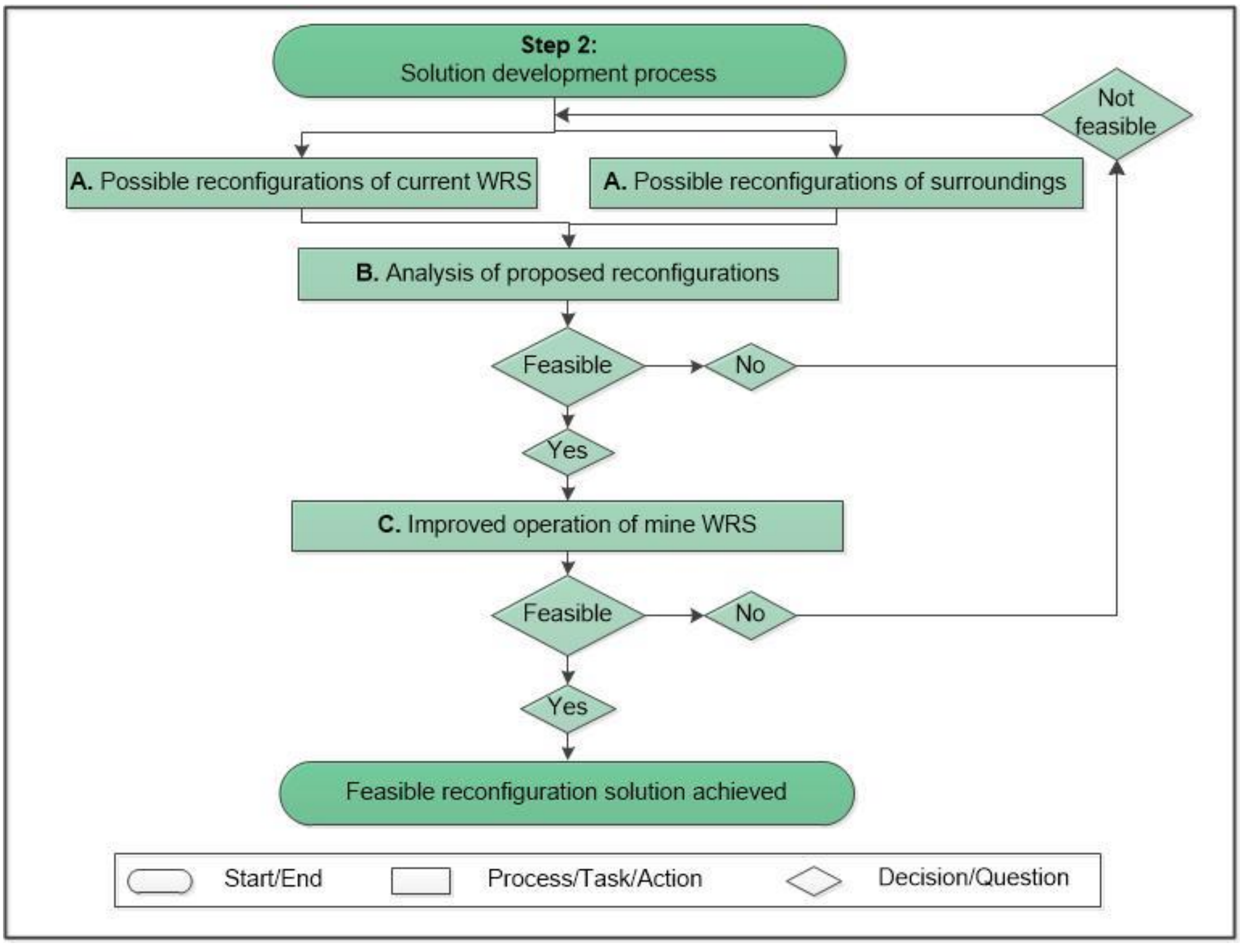


Figure 28: Solution development process

As seen in Figure 28 the solution development process will consist of three main steps that lead to achievement of a feasible reconfiguration solution. These steps are:

A. Possible reconfigurations of both the current mine’s WRS and surroundings
B. Analysis of the proposed reconfigurations
C. Improved operation of the mine’s WRS

With multiple reconfiguration solutions available, it is important that the correct solution is developed. Therefore, each step of the solution development will be analysed to ensure the feasibility of the proposed step. If the proposed solution is found to be impractical at any stage, the process will be repeated until a feasible solution is developed.

A. Possible reconfigurations of mine WRS and surroundings

Step 2 of the solution development will start by firstly inspecting ways in which to reconfigure the WRS of the relevant mine or the surroundings of the mine. Identifying the source of the excess water (Step 1) will help direct focus to reconfiguration solutions of the current system or the surroundings.

For any mine with an excess of water it will be beneficial to firstly reduce the amount of water consumed by the WRS. This reduction in water sent down the mine will allow scope for more fissure water to be pumped out. As discussed in Section 1.5.1, the three main methods of achieving a decreased water demand are leak management, pressure set point control and stope isolation.

From the audits performed during Step 1 the areas of water mismanagement in the mine must be recorded for rectification. Water balances of the mine before and after repairs must be measured and recorded to measure the change in water use.

Next is to ensure that all equipment used within the WRS is running efficiently and is up to date. Old outdated equipment such as damaged pumps, clogged up heat exchange elements and damaged valves add to the inefficient use of water within the WRS.

Critical to the reconfiguration solution development is the removal of fissure water before reaching active mining areas. High water volumes, usually caused by fissure water, can be removed by implementing new pump stations to remove water from old working areas that are flooded. In some cases, water flows between interconnected levels of neighbouring shafts. Here a dewatering pump station can be implemented within an inactive mine to remove water before it reaches active mine shafts.

Planning of proper flow and storage to ascending levels within the dewatering system is of great importance. If the pumping capabilities of a lower level's dewatering pumps are larger than that of the higher level's pumps, the risk of flooding the higher level becomes imminent. In such a scenario large enough storage dams on either level along with proper pump scheduling and dam preparation is necessary.

B. Analysis of proposed reconfigurations

For every possible reconfiguration solution developed (as mentioned in Part A of Step 2), the next step of solution development can begin, namely an analysis of the proposed solution. Analysis of the proposed solution will involve further investigation of the proposed WRS reconfiguration. This investigation can be performed either by means of simulation or calculations. It may even involve acquiring the opinion of an experienced person.

This is only the analysis of a theoretical solution for the reconfiguration of the mine's WRS. Analysis will allow a broader understanding of the situation to unfold and will allow for any unseen errors or details to be noticed.

If, after analysis, the proposed reconfiguration was found not to be feasible the process must restart, and a different reconfiguration solution must be developed. Alternatively, if the solution is still deemed feasible after analysis, part C of the second step of solution development can commence.

C. Improved operation of mine WRS

This step will consist of developing methods to improve WRS operation after reconfiguration. These improvements will not focus on dealing with the main problem that the mine is faced with (excessive water), but rather additional benefits added to the WRS functionality. As mentioned in Section 1.5, system improvements can be done in two main ways, namely:

- Energy management
- System automation

With the possible methods of improving the WRS operation in mind, the feasibility of the implementation of these improvements on the mine's WRS must be investigated. If found that the proposed improvements are not feasible, the solution development step will restart.

Once all the parts of Step 2 are found to be feasible the step is complete. The feasible reconfiguration solution has now been attained and Step 3 of the reconfiguration process can commence.

2.4 Step 3 – Validate proposed reconfiguration solution

Figure 29 represents the third step, namely the proposed reconfiguration validation process.

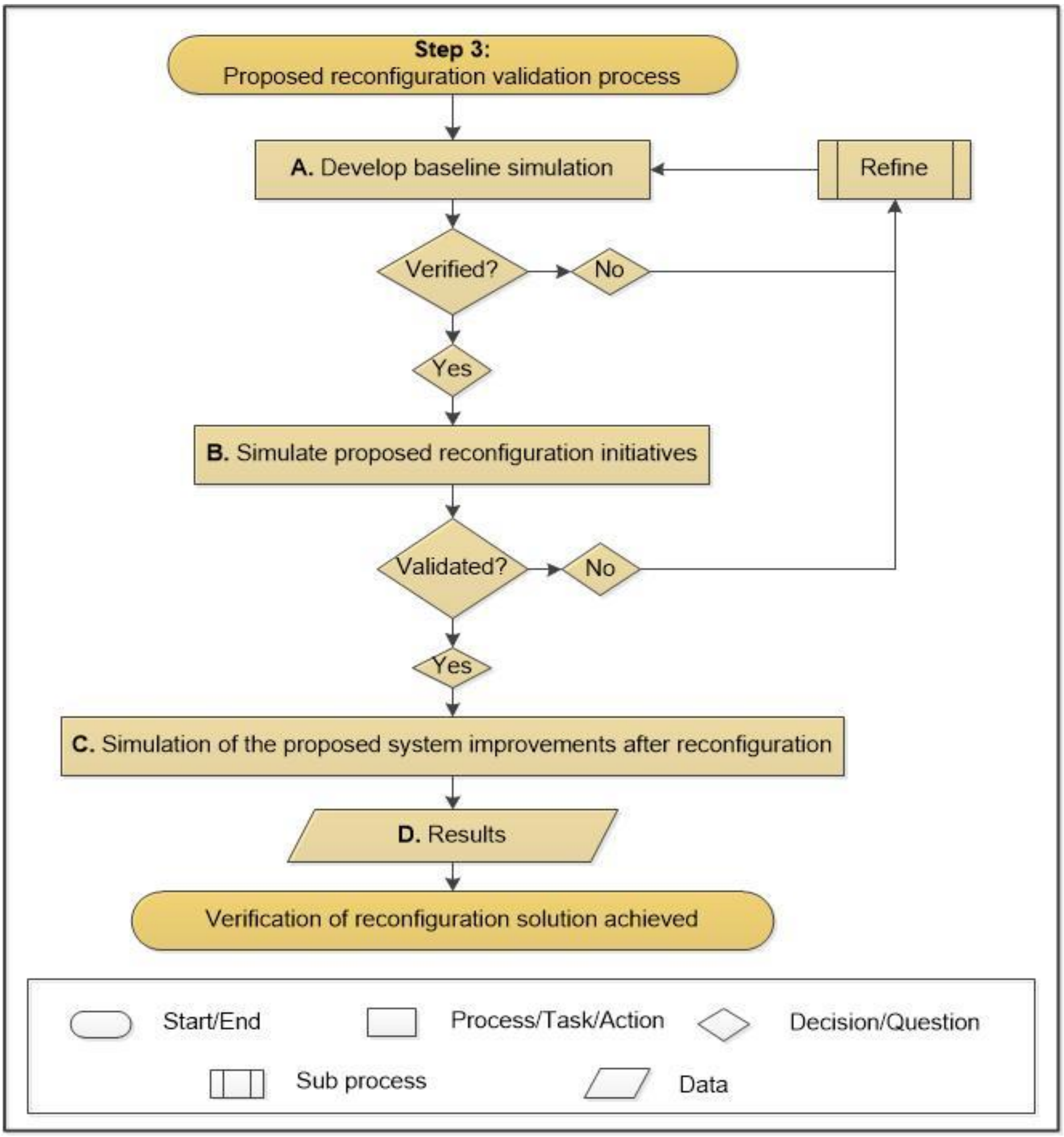


Figure 29: Validation process of proposed reconfiguration

The feasibility of the WRS reconfiguration will have to be validated by means of a simulation model. Proving the validity of the reconfigured system model would mean proving that the model can effectively remove all excess water from the mine. Volumes of unwanted water within the mine can be calculated by means of a water mass balance similar to the one shown in the first step of the process (Section 2.2) and will form part of the simulation input range.

As seen in Figure 29 the validation of the proposed reconfiguration can consist of four main parts, namely:

A. Development of a baseline simulation
B. Simulation of the proposed reconfigurations (as attained in Step 2)
C. Simulation of the proposed WRS improvements (i.e. load shift simulation)
D. Results of the simulations

The developed baseline simulation will be verified as will the simulation of the proposed reconfigurations. If found not to be accurate the simulation will be refined, and the step repeated until favourable simulations are attained.

For a simulation to be successfully built, the following requirements must be met:

- Programming of inflows and outflows leading water to and away from dams, respectively
- A long enough time period must be simulated (i.e. three consecutive days)
- Simulation of pump statuses and flows
- Simulation of starting and stopping of pumps
- Simulate linkage of pumps to upstream and downstream dams
- Simulate dam level changes due to flow
- Simulation of valve control to dams made available for water storage

As mentioned in Section 1.5.3 of this study, REMS is a powerful simulation package that is capable of accurately simulating a mine's WRS and can predict the viability of the developed reconfiguration solution. REMS software has been applied and validated on mines' water reticulation systems by preceding researchers Botha and Janse van Vuuren [8], [58].

A. Develop baseline simulation

The validation step will start with the construction of a baseline simulation of the WRS before reconfiguration. As discussed, the baseline simulation will be a model of the relevant section of the mine WRS created in REMS. The baseline simulation will be compared with and verified with actual measurements or readings attained from site visits and remote monitoring systems. This verification of the simulation will prove the accuracy of the simulation baseline model.

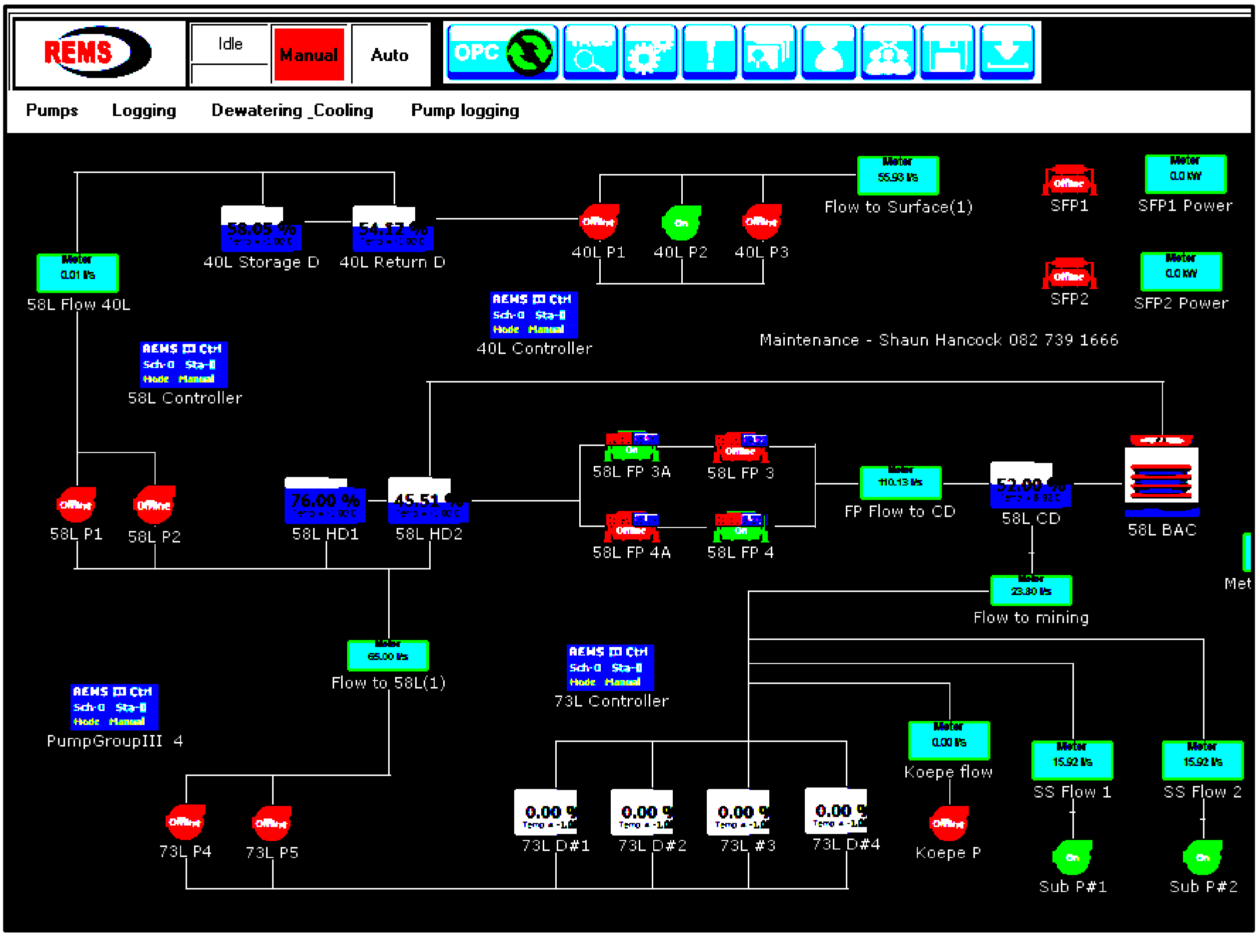


Figure 30: REMS simulation baseline of a mine WRS

An example of a REMS baseline simulation model of a current mine WRS is displayed in Figure 30. As seen in Figure 30, the simulation displays the main components of a mine WRS from the bottom level (73L all the way to surface). Dewatering dams, cold water storage dams, all pumps, BACs and fridge plants are included within the simulation. This gives a good sense of the capabilities of REMS.

If the baseline simulation results are inaccurate the simulation will be refined and re-iterated until accurate results are attained. Once the baseline model is validated the next step of the validation process can start.

The baseline simulation must be very accurate when compared with the actual scenario underground. Accuracy is needed in order to attain good results when simulating the proposed reconfiguration initiatives. All relevant flows of water to and from dams, dam volumes, pump flows and volume flow of fissure water must be accurate.

B. Simulate proposed reconfiguration initiatives

Next the proposed reconfiguration changes, as attained during Step 2 of the process, will be made to the baseline model and simulated. Here the test can be made to see if the proposed reconfigurations to the mine WRS would be able to eliminate the identified problems. The proposed solution would also have to be able to remove excess water from the mine as effectively as possible, without compromising the functionality of any of the WRS equipment.

This part of the reconfiguration process is of great importance and will predict the results attained from implementing the proposed reconfiguration solution. As mentioned in the first paragraph of Section 2.4, validation of the reconfigured model would mean that water is distributed effectively throughout the WRS and removed effectively from the mine.

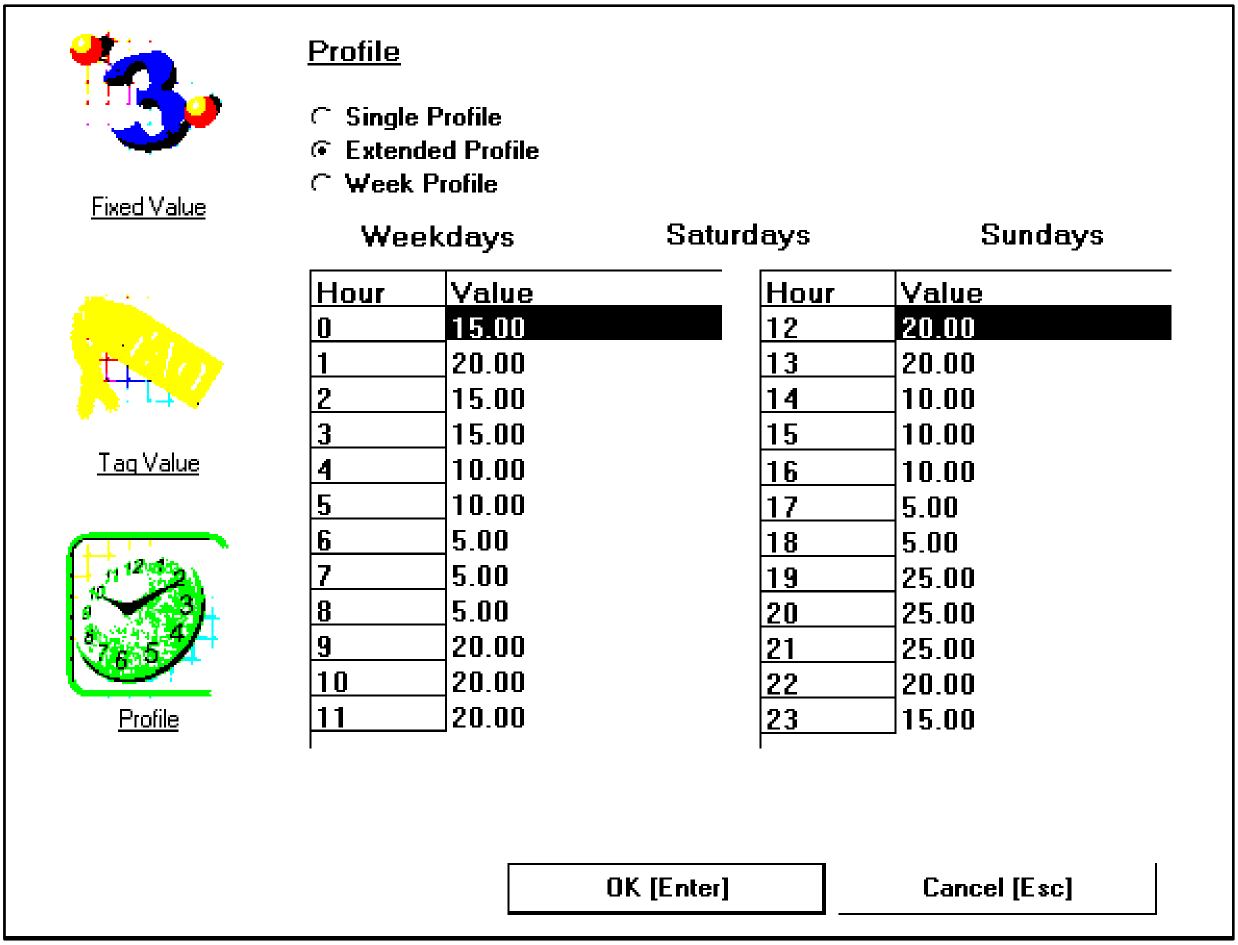
C. Simulation of the proposed system improvements after reconfiguration

With the proposed reconfiguration solution to the WRS simulated, the system improvements after reconfiguration, as decided in part C of Step 2, can be simulated. This will determine the added benefits and improvements to the reconfigured system. Of the proposed improvements mentioned in Section 1.5.3 of this study, load shift is most commonly performed on dewatering systems.

This would involve simulating dam preparation on the relevant pump station where the load shift is to be performed. Dam preparation involves the control of dam levels to the extent that levels are empty enough, before Eskom peak times, not to overflow if pumping is ceased during peak hours. This is especially difficult during morning peak times as the morning peak is one hour longer than the evening peak. Programming of the dam preparation is done by means of setting up a control range within REMS. Figure 31 displays a typical example of the REMS control range setting.

Each pump simulated within REMS can have a specified control range table assigned to it. Pump control ranges are set according to desired dam levels. Control ranges can be set to control the dam levels of upstream dams (the dams that the pump is pumping water from) or downstream dams (the dams the pump is pumping water to). For the purpose of this study, upstream dam control will be the preferred choice as the control range can control the amount of water removed from a specified dam.

The purpose of the control range is to control dam levels for different hours of the day. This is done to allow dam preparation, i.e. emptying dams before peak hours to allow for additional water volumes to flow into the dam without having to start pumps (to empty dams) during peak hours.



Profile

○ Single Profile
● Extended Profile
○ Week Profile

Weekdays Saturdays Sundays

Hour	Value
0	15.00
1	20.00
2	15.00
3	15.00
4	10.00
5	10.00
6	5.00
7	5.00
8	5.00
9	20.00
10	20.00
11	20.00

Hour	Value
12	20.00
13	20.00
14	10.00
15	10.00
16	10.00
17	5.00
18	5.00
19	25.00
20	25.00
21	25.00
22	20.00
23	15.00

Figure 31: REMS control range settings

As mentioned in Section 1.3.3, sludge moves into dewatering dams and causes build-up to form. Build-up sludge can be harmful to pumps and therefore bring about a change in minimum dam level. The control range value is set with the minimum dam level added. The allowed dam level, outside of peak hours, can thus be calculated as follows:

Max allowed dam level (outside peak) = Minimum dam level + Control range value (2)

During peak hours the control range is subtracted from the dam's maximum capacity to specify the maximum allowed dam level before pumping occurs. This means that the dam cannot be filled passed a certain limit and the control range is set to a specified value below that limit. The allowed maximum dam level before pumping commences, during peak hours, can be specified as follows:

$$\text{Maximum dam level (during peak)} = \text{Dam max limit} - \text{Control range value} \qquad (3)$$

Setting the control range from the top during peak hours allows for the dam to fill up as much as possible before pumping must commence. In the example shown in Figure 31 dam levels could rise to 5 % below the maximum dam level.

D. Results

The results of all simulations performed can now be processed and a final decision as to the validation of the reconfiguration solution made. The results can be presented to relevant mine personnel for approval of the decided-upon reconfigurations and improvements. With the reconfigured model validated and approved by the relevant mine personnel, the implementation phase can commence.

2.5 Step 4 - Implementation and system improvement

Implementation of the reconfigured model can be the most time-consuming part of the reconfiguration process. Here the needed adjustments, changes and repairs proposed within the reconfiguration model must be implemented at the mine.

Critical to the implementation phase is that follow-up audits be performed along with follow-up meetings with the relevant mine personnel. Keeping track of the progress and monitoring improvements, along with reporting back to the relevant people, is important.

Figure 32 represents the implementation and improvement phase of the reconfiguration process. This phase has two main objectives: firstly, implementation of the proposed reconfiguration solution; and secondly, the improvement of the reconfigured system. Follow-up audits and measurement quantifications will take place during the implementation of both objectives until completion. Final results can then be obtained.

As seen in Figure 32, the implementation phase will firstly start by handing over the complete report of the proposed reconfiguration solution (Step 2) and results from the validation process (Step 3) to the relevant mine personnel. Once approved and a project kick-off meeting has been held, implementation of the reconfigured solution can commence. Progress of project implementation can be monitored and reported throughout the entire implementation process (Step 4).

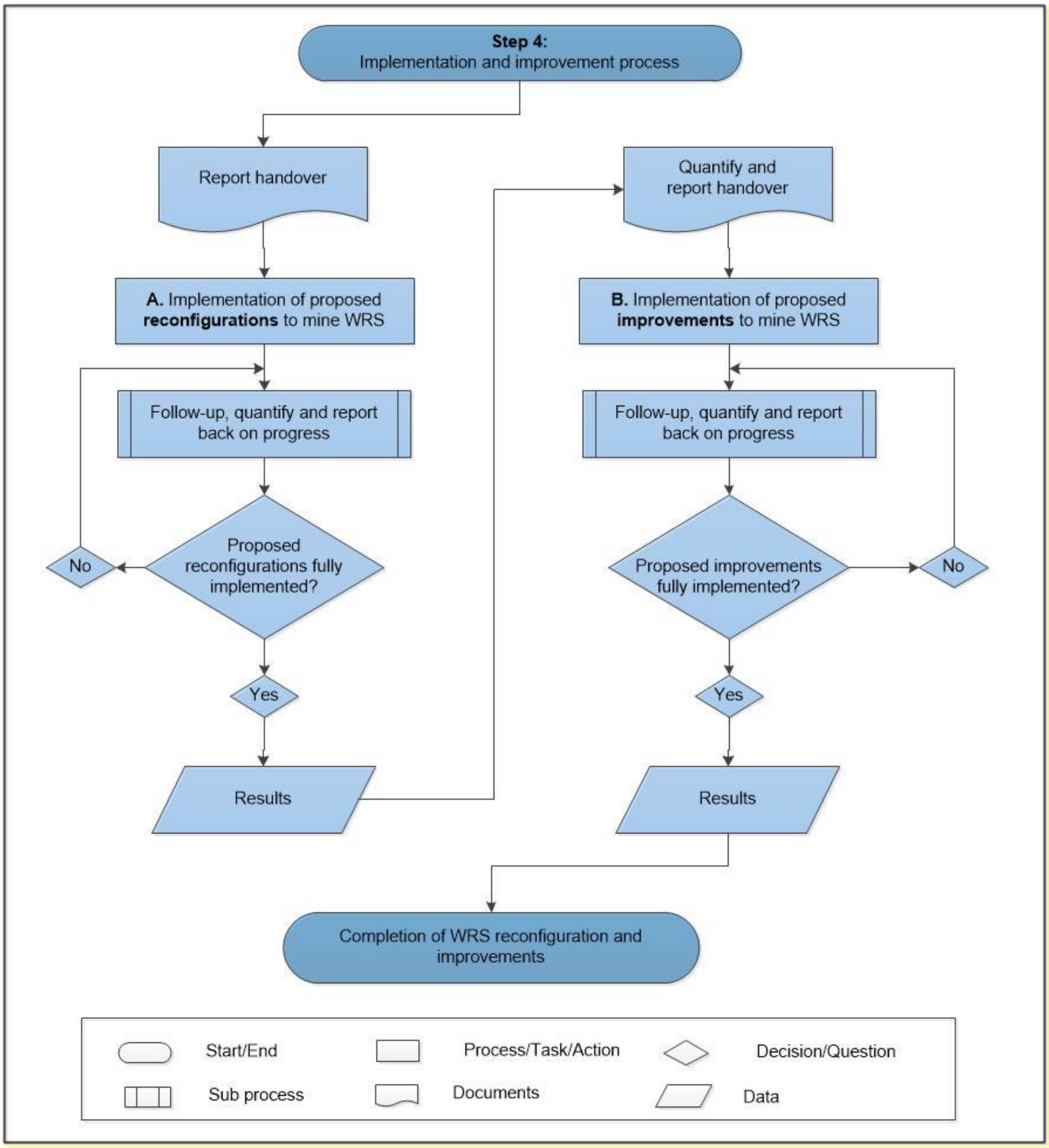


Figure 32: Implementation and improvement process

A. Implementation of proposed reconfigurations to mine WRS

With the solution proposition and quantification report signed, the implementation of the proposed reconfigurations to the mine WRS can now begin. As mentioned, this can be a time-consuming process and relies solely on the available workforce of the mine along with the time available to shut down systems for repairs and changes to take place.

Weekly, bi-weekly or monthly follow-up audits will be performed during the implementation phase to monitor progress and quantify changes in water management and usage. Progress can then be reported back to the relevant personnel. This process will continue until completion of the implementation of the proposed reconfigurations.

After completion a final quantification audit can be performed. This will allow quantification of the changes brought about to the WRS by the proposed reconfigurations. A clearer understanding of the possibilities regarding system improvements can also be attained.

B. Implementation of proposed improvements to mine WRS

After implementation of the newly reconfigured system, system improvements can be made. As mentioned in Section 1.5, system improvements can be made in terms of demand management, energy management and system automation methods. Because water demand management will form part of the reconfiguration model, energy management and system automation are the most likely options for improvement.

As discussed in Section 1.5.2, energy management involves the application of load shifting, peak clipping and energy efficiency techniques to avoid the consumption of electricity within Eskom Megaflex peak periods. Application of these methods will amount to cost savings within the use of a mine’s WRS.

If the mine is equipped with a fully operational SCADA, as discussed in Section 1.5.3, automation of the dewatering system can be applied. REMS will be used for WRS automation for this study. Automated control of dewatering systems allows for efficient execution of energy management techniques and can be of great benefit for many reasons, as mentioned in Section 1.5.3. With the implementation and improvement phase underway, the results quantification phase can commence.

2.6 Step 5 - Results quantification

Figure 33 is a graphical representation of the fifth and final step of the reconfiguration process, namely the results quantification phase. Results quantification can start during the completion of the implementation and improvement phase. This will involve performing extensive audits on site as well as via monitoring equipment. All relevant information must be gathered that concerns the implemented changes to the WRS. Results will be quantified for both the implemented reconfiguration to the WRS and the improvements after system reconfiguration.

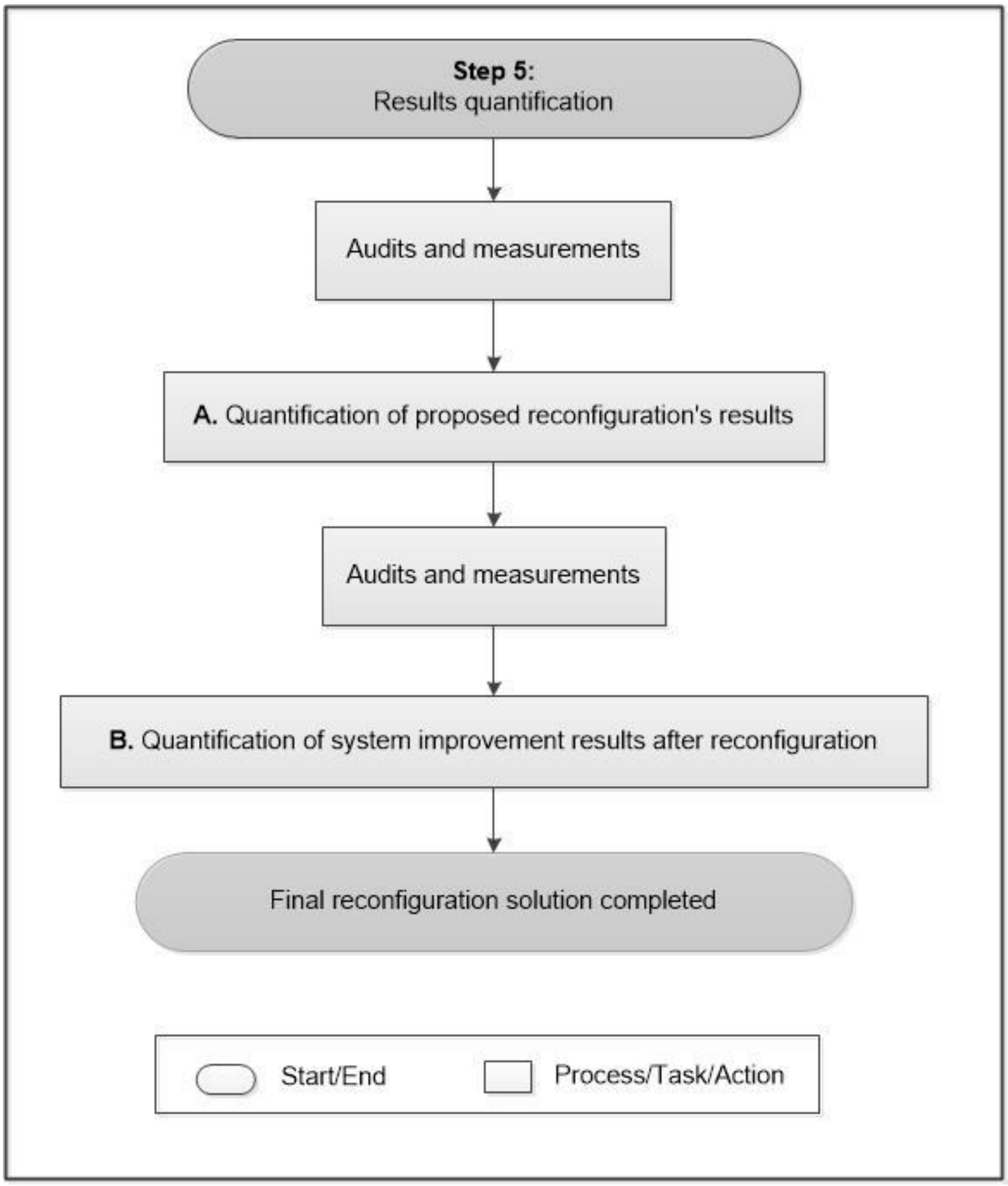


Figure 33: Results quantification phase

As can be seen from Figure 33, results quantification will take place for both the implemented reconfiguration solution to the WRS and the improvements after system reconfiguration. Results quantification may be a timely process as it involves the monitoring of all relevant WRS components along with flows, volumes and functionality of said components. This is especially relevant to the quantification of system improvements after reconfiguration.

A. Quantification of proposed reconfiguration's results:

Reconfiguration results will focus on the results obtained by the implementation of the proposed reconfiguration solution. This will primarily concern the distribution, consumption and removal of water within the mine. Water balances and measurements will be used to quantify the amount of water used by and removed from the mine before, during and after the implementation phase. Distribution loads and movement of water within the mine will also be monitored.

As mentioned in Section 2.4, this will be done to prove that the surplus amount of water within the mine was successfully reduced and removed after implementation of the proposed solution. A general idea of the success of the reconfiguration project will then be clear.

B. Quantification of system improvement results after reconfiguration:

The second part of results quantification will focus on the improvements made to the already reconfigured system. Main quantification will be of cost savings due to a decrease in electricity consumption within Eskom peak periods as well as improved system performance and water distribution. This will be quantified before and after improvement implementation.

As discussed in Section 1.5.2, electricity tariffs change for different hours of the day. The cost of electricity used by the relevant parts of the WRS will be calculated by multiplying the amount of energy used within a given hour by the matching tariff. Taking the sum of each 24-hour day, the average daily cost will be calculated.

The quantification of system improvements may carry on for a time after the completion of the overall reconfiguration project. This is because systems must be monitored and optimised after implementation. The implementation of a load shift project on dewatering pumps along with system automation is a good example of such a case. System performance must be monitored for at least a month after implementation to quantify proper results. Slight changes might also be made to the control range of the automated dewatering system after system implementation.

2.7 Conclusion

A five-step method was developed to reconfigure a deep-level mine water reticulation system for the management of excess water volumes. General guidelines were given as to what can be expected within each step of the process. The five steps to be followed are: data acquisition, solution development, validation of the developed solution, implementation of the solution and results quantification.

Along with this, methods to improve the reconfigured system are discussed within the second step of the process. Validation of these improvements is discussed in the third step and the implementation is discussed in step four. The five-step method is a generic method that can be applied to most deep-level mines.

CHAPTER 3 IMPLEMENTATION AND RESULTS

Chapter 3 of this study is the results and findings section of the document. Here the aim is to describe the findings and results attained from two case studies by making use of the five-step method described within the second chapter of this study.

3.1 Introduction

The five-step method was implemented on two case studies that involved multiple mines. The two case studies will, for the purpose of this study, be named Case Study A and Case Study B. In the case studies the following took place:

- **Case Study A** – The existing water reticulation system of Mine A was reconfigured to compensate for fissure water pushing up from the bottom of Mine A.
- **Case Study B –** Implementation and reconfiguration of Mine B-2 and B-3 pumping system components to prevent fissure water from flowing to Mine B-1. Furthermore, the operation of Mine B-1 and B-2 WRS was improved.

System improvement after reconfiguration can consist of the following:

- **Demand optimisation** - Consisting of leak management, stope isolation and pipe restriction removals.
- **Energy cost optimisation** - Through the implementation of TOU pumping schedules.
- **Pump automation** - Allowing for effective remote management and the elimination of human error.

3.2 Case Study A

Case Study A took place on a large gold mine, Mine A, within the Free State region of South Africa. Mine A was originally mined to a depth of approximately 3.5 km and in recent years started with localised mining of the pillar due to the gold reef being depleted at the deeper levels of the mine.

As mining localised and moved up to shallower levels, the deeper abandoned levels flooded and pushed fissure water up into the mine. This posed a great threat to the active levels and reconfiguration had to occur as the current dewatering system could not keep up with the needs of the mine. An in-depth discussion of the mine WRS before reconfiguration will follow within the data acquisition phase.

3.2.1 Step 1 – Data acquisition

All the information gathered for the complete familiarisation of Mine A's WRS and problems within the WRS, is discussed within Step 1 of Case Study A.

A. Data acquisition of Mine A WRS

Firstly, knowledge of the basic overview of Mine A and its external influences had to be gathered. Figure 34 displays a basic overview of Mine A.

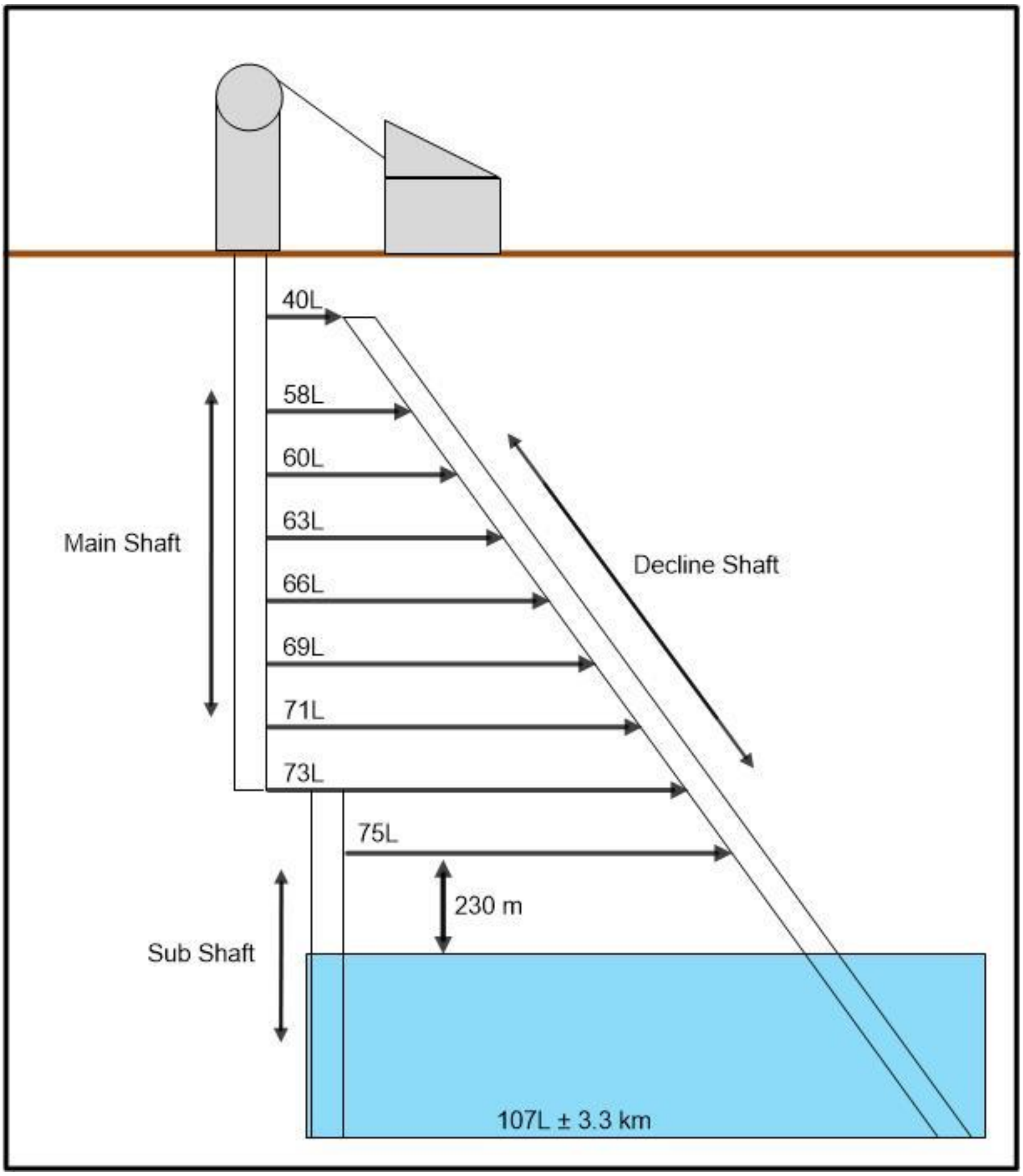


Figure 34: Basic overview of Mine A

As seen in Figure 34, Mine A's levels are numbered from 40L down to 107L. Levels are named according to the depth of the level below surface, measured in feet and divided by 100. Thus, 40L would represent 4,000 ft below surface. The main shaft was sunk down to 73L where a sub-shaft was then sunk from 73L down to 107L. A 45-degree angle decline shaft connects all the mine's levels from 40L down to 107L.

The deepest active level mined after localisation occurred is 75L. Below 75L the sub-shaft, decline shaft and lower levels are flooded by fissure water. For safety reasons the flood-water level must be maintained at approximately 230 m below 75L. This is done via the implementation of two submersible pumps placed within the sub-shaft at a depth of 230m below 75L.

Figure 35 displays the basic layout of all the main components within Mine A's WRS. As displayed in Figure 35, the main components of Mine A's WRS are located on 40L, 58L and 73L. Other smaller pumps, valves, refrigeration equipment and WRS relevant equipment are included within the mining levels between 58L and 73L, but these were not relevant to the study.

Starting at 73L DAM 1 to 4; all the water within the WRS gather in these dams after serving its purpose within the WRS. From there, water is pumped by PUMP 1 to 3 up to 40L storage dams and by PUMP 4 and 5 up to 58L DAM. From 58L DAM water flows to the main fridge plants for cooling purposes and then stored in a chill dam.

Cooled water can then be distributed to all the active mining levels via gravity feed from 58L chilled dam. After use water is pumped back to the settlers on 71L. From the chill dam water is also pumped through 58L BAC for mine refrigeration and the warm water returned to 58L hot dam.

From 40L storage dam water flows to a return dam where a portion of the water is gravity fed back to 58L dam and recirculated through the WRS. The remaining amount of water is pumped to surface where it can be used within the refrigeration sub-system or be pumped to evaporation dams.

It is not required for Mine A to send down additional water from surface for WRS functionality. This is because enough water is added to the WRS from the flooded sub-shaft's fissure water. All of the gathered information regarding the pumps, dams and flow rates within Mine A's WRS (as displayed in Figure 35) is displayed in Table 5, Table 6 and Table 7, respectively.

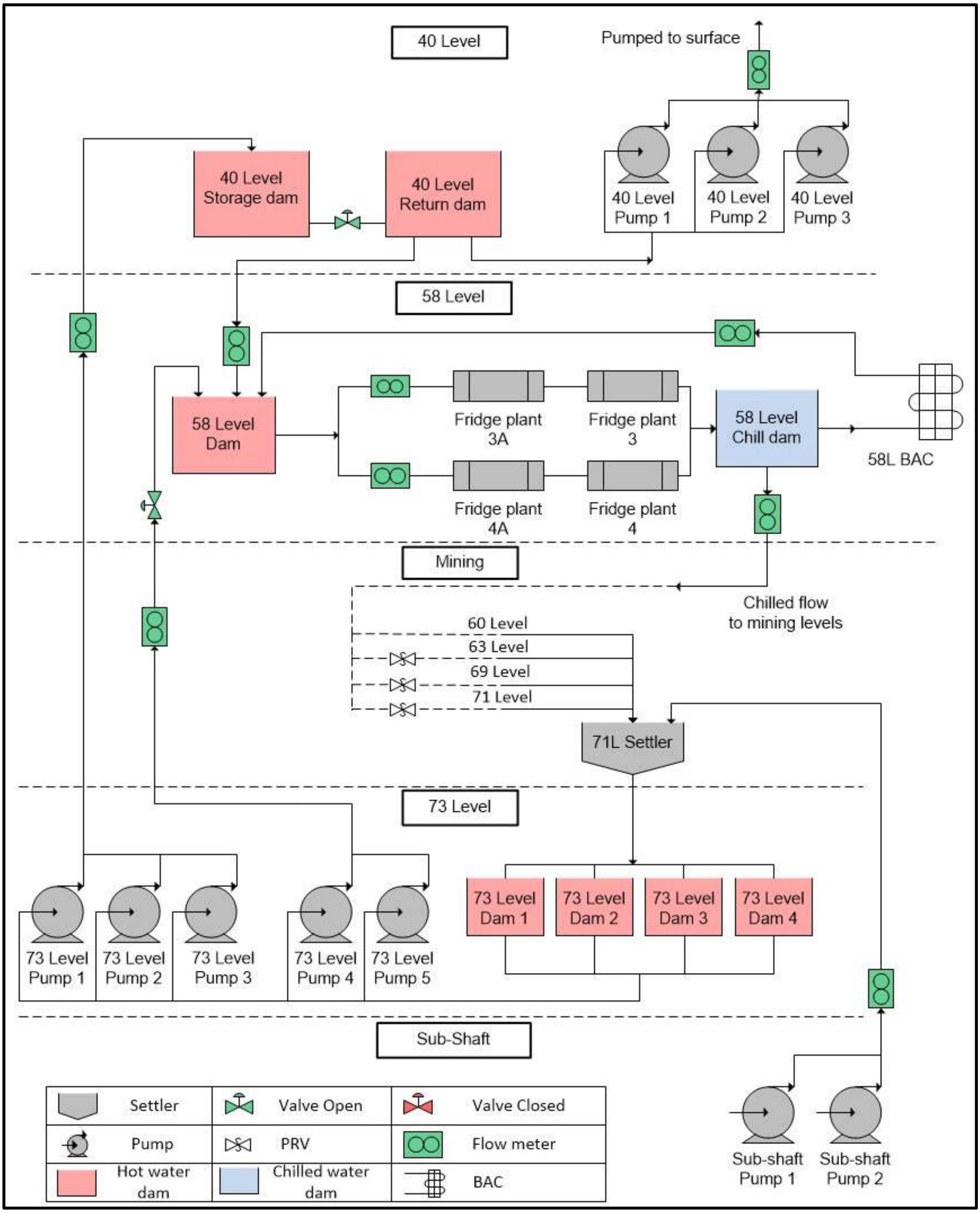


Figure 35: Basic layout of Mine A WRS before reconfiguration

Table 5: Mine A WRS pump specifications pre-reconfiguration

Pump	**Installed capacity** (kW)	**Flow rate supplied** (L/sec)	**Head to pump** (m)	**Purpose**
40L Pump 1	1,440	62	1,219	Hot water from 40L return dam to surface
40L Pump 2	1,440	62	1,219	Hot water from 40L return dam to surface
40L Pump 3	1,440	62	1,219	Hot water from 40L return dam to surface
73L Pump 1	1,200	66	1,066	Hot water from 73L dams to 40L storage dam
73L Pump 2	1,200	66	1,066	Hot water from 73L dams to 40L storage dam
73L Pump 3	1,200	66	1,066	Hot water from 73L dams to 40L storage dam
73L Pump 4	1,200	76	460	Hot water from 73L dams to 58L hot dam
73L Pump 5	1,200	76	460	Hot water from 73L dams to 58L hot dam
Sub shaft Pump 1	500	16	290	Fissure water to 71L settler
Sub shaft Pump 2	500	16	290	Fissure water to 71L settler

Table 6: Mine A WRS dam specifications pre-reconfiguration

Dam	**Capacity** (m^3)	**Purpose**
40L storage dam	567.5	Holding dam for water from 73L
40L return dam	567.5	Holding dam for water returned to 58L and water pumped to surface
58L hot dam	1,540	Holding dam for water pumped to 40L and cooling
58L chill dam	2,543	Holding dam for chilled water sent to mining
73L dam 1	558	Machine water holding dam for pumping to 40L & 58L
73L dam 2	696	Machine water holding dam for pumping to 40L & 58L
73L dam 3	696	Machine water holding dam for pumping to 40L & 58L
73L dam 4	684	Machine water holding dam for pumping to 40L & 58L

Table 7: Mine A WRS flow rates pre-reconfiguration

Flow	**Flow rate** (L/sec)	**Average daily volume flow** (ML/day)
From 40L to surface	62	2.4
From 73L to 40L	66	3.3
From 73L to 58L	76	4.6
Flow to 58L BAC	24	2.1
Sub shaft to 71L settlers	32	2.76
40L to 58L	16	0.9
To 58L fridge plants	107	7.6
Chilled water from 58L chill dam to mining	59	5.1

With all the needed information regarding Mine A's WRS acquired and complete familiarity gained, the identification of problems within the WRS of Mine A could commence.

B. Mine A WRS problem identification

Upon inspection it was found that Mine A did not have a large number of leaks within the WRS, thus wastage in the form of leaks was not of concern. As displayed in Table 7, an average of 2.76 ML of water was being pumped from the flooded sub-shaft to 71L settlers. This shows that at least 2.7 ML of fissure water is being added to the WRS per day.

Figure 36 displays the basic layout of Mine A's WRS with the two main identified problems circled in red and numbered 1 and 2. Problem 1 involves the large pipe column connecting 40L storage dam and 73L Pumps 1 to 3. Problem 2 was regarding the water sent from 40L return dam to 58L dam.

With a head difference of 1,005 m between 73L pumps and 40L storage dams, the service water pipe column connecting these levels experienced water pressures of more than 10,000 kPa. This high water pressure along with 73L pumps frequently pumping water to 40L storage dams caused the pipe column to frequently burst at the bottom. With the pipe column between 40L storage dams and 73L pumps out of action, the entire functionality of Mine A was affected until repairs were done. This impacted Mine A's production negatively.

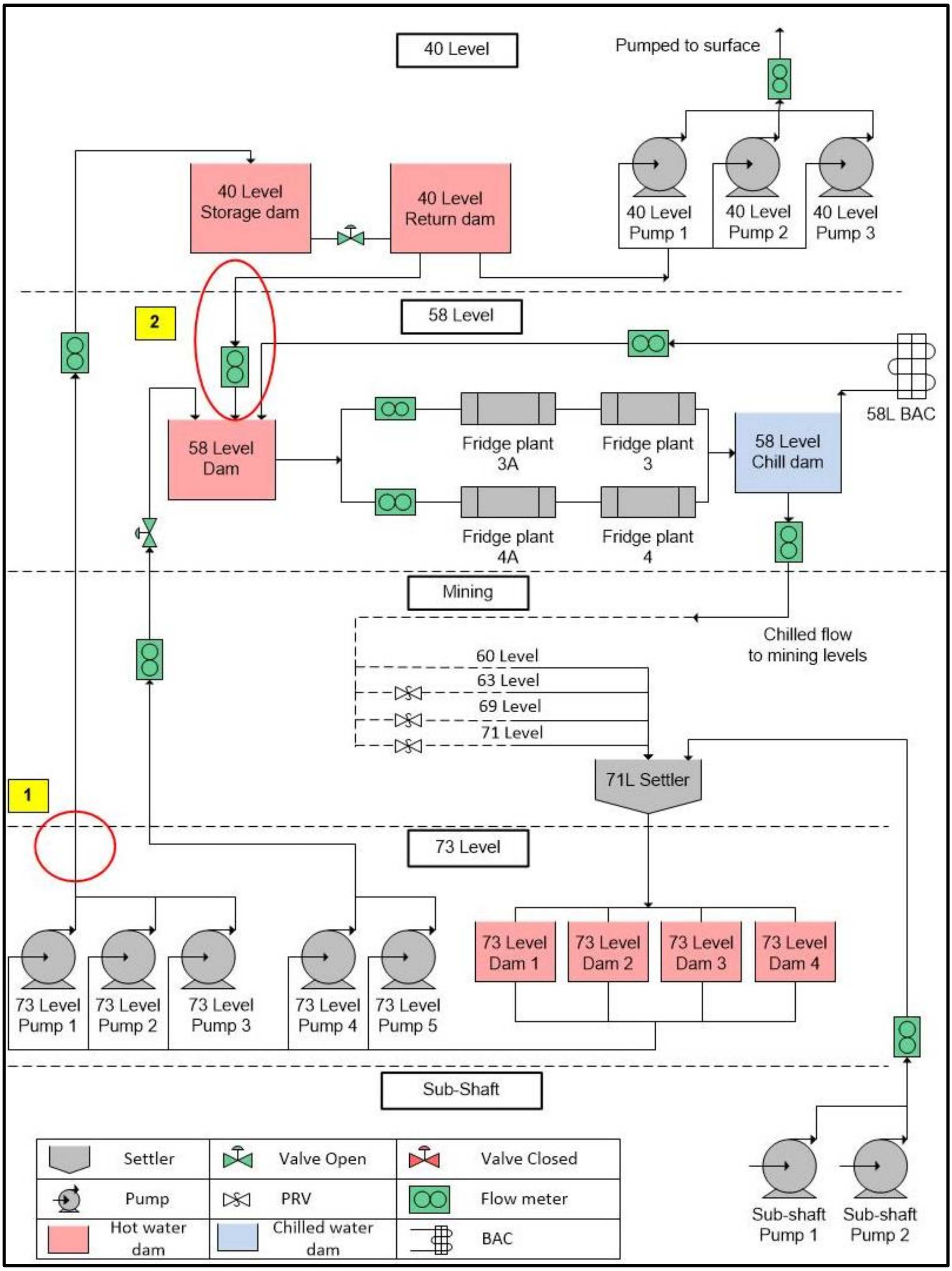


Figure 36: Mine A WRS - problem identification

As displayed in Figure 36, Problem number 2, a pipe column connecting to 40L return dam allowed water to flow to 58L dam. Additional water was recirculated back into the WRS, increasing volumes of water to 58L dam, feeding the fridge plants. The additional amount of returned water, along with the added fissure water meant that Mine A’s WRS was handling more water than its design capacity, causing dams to flood and pipe lines to be overloaded.

Larger quantities of water flow through the settlers into 73L dams and this resulted in more strain on the 40L to 73L pipe column due to larger quantities pumped. Overloading the WRS increased the risk of damage to the WRS equipment, flooding and loss of production.

3.2.2 Step 2 – Solution development

A solution was developed for the reconfiguration of Mine A’s WRS. This was done with the two main problems in mind along with the longevity of Mine A’s WRS. The proposed solution consisted of four main changes. The proposed changes only involved the WRS of Mine A as there were no influences or problems arising from the surroundings of Mine A. Figure 37 is a basic layout of Mine A’s WRS displaying the proposed solution to the problems identified within Step 1 of Case Study A. These changes are numbered 1 to 4 and are circled in green.

Proposed Change 1 was to close off the pump column that connected 73L pumps to 40L storage dam. This meant that the column did not have the risk of frequently bursting, thus eliminating the risk of a standstill in production. With the column sealed off 73L pumps 1 to 3 would not be needed any more and could be used as spare pumps or moved to a different location within the mine.

Since water would not be pumped directly to 40L from 73L dams any more, larger quantities of water would have to be pumped to 58L hot dams through 73L pumps 4 and 5. Proposed Change 2 was then to implement two pumps on 58L that would help empty 58L hot dams into 40L storage dam. These could either be new pumps, or the pumps previously used on 73L to pump water to 40L storage dam. A flow meter would then have to be installed in the pipe line in order to monitor the amounts of water sent to 40L storage dam.

Proposed Change 3 was to seal off the pipe line connecting 40L return dam to 58L hot dams. This would mean that less water was recycled back into the system and that more water could now be removed from the mine via 40L pump 1, 2 and 3. 58L hot dams did not run the risk of emptying as more water was being pumped from 73L to 58L.

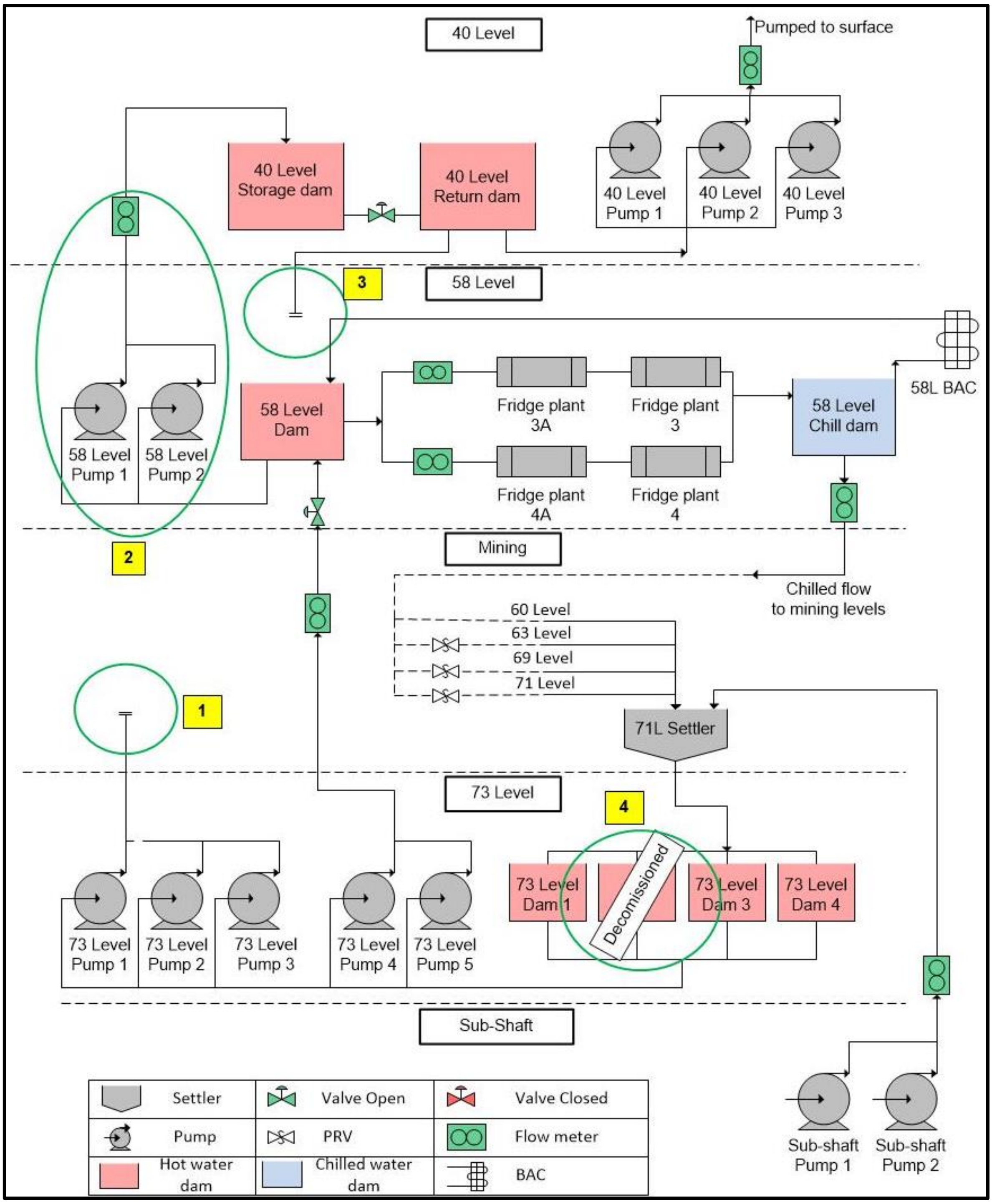


Figure 37: Proposed solution for the reconfiguration of Mine A WRS

With less water recycling through the WRS the need for water storage would be reduced. Proposed Change 4 was to decommission one of the 73L storage dams. This would mean less maintenance as only 3 dams would have to be cleaned and maintained. Validation would have to prove that enough dam capacity remains for normal WRS functionality. Although a fourth dam would assist with additional storage capacity for cleaning and maintenance proceidures, mine personnel decided that removing Dam 2 was still necessary.

The proposed reconfiguration changes were analysed and discussed with the relevant personnel on Mine A. These personnel included the senior shaft engineer, mechanical foreman, general manager of the mine, and other engineers working at Mine A.

The proposed improvements of Mine A's WRS after system reconfiguration were to implement an automatically controlled load shift project on the dewatering pumps and fridge plants. This would be achievable since Mine A already had a functioning SCADA installed that had access to most of the equipment within the WRS. Furthermore, the proposed improvements after reconfiguration included leak management, pressure set-point control for the dewatering system and pump automation.

3.2.3 Step 3 – Validate proposed reconfiguration solution

Validation of the proposed solution for the reconfiguration of Mine A's WRS consisted of two main steps which are listed from A to B within Section 3.2.3 of this study. The steps are, firstly, to develop the baseline simulation of Mine A's WRS before reconfiguration, and secondly, a simulation of Mine A's WRS with the proposed reconfigurations implemented.

Final results of the proposed improvements to Mine A, after reconfiguration, will not be included within this study as the implementation of the improvements was not complete during writing of this study.

Both simulations were created and refined successfully. The final versions of the simulations and their findings will, however, only be discussed within Section 3.2 of this study. The BAC on 58L was not included within either of the simulations as it creates a water-flow loop that remains on 58L and does not remove much water from the level.

Furthermore, for the purpose of the simulations the storage and return dams on 40L were simulated as one dam with a similar volume as both dams combined. The same was done for 73L dams 1 to 4. This could be done as the aforementioned dam pairs are, in reality, connected with valves and act as a single unit with a larger volume.

A. Baseline simulation

The WRS of Mine A, before reconfiguration changes occurred, was simulated with a REMS model. The main purpose of the baseline simulation was to simulate the WRS of Mine A, pre-reconfiguration, and to determine simulation results compared with measured results. Figure 38 displays the dashboard of the REMS model that served as baseline simulation of Case Study A.

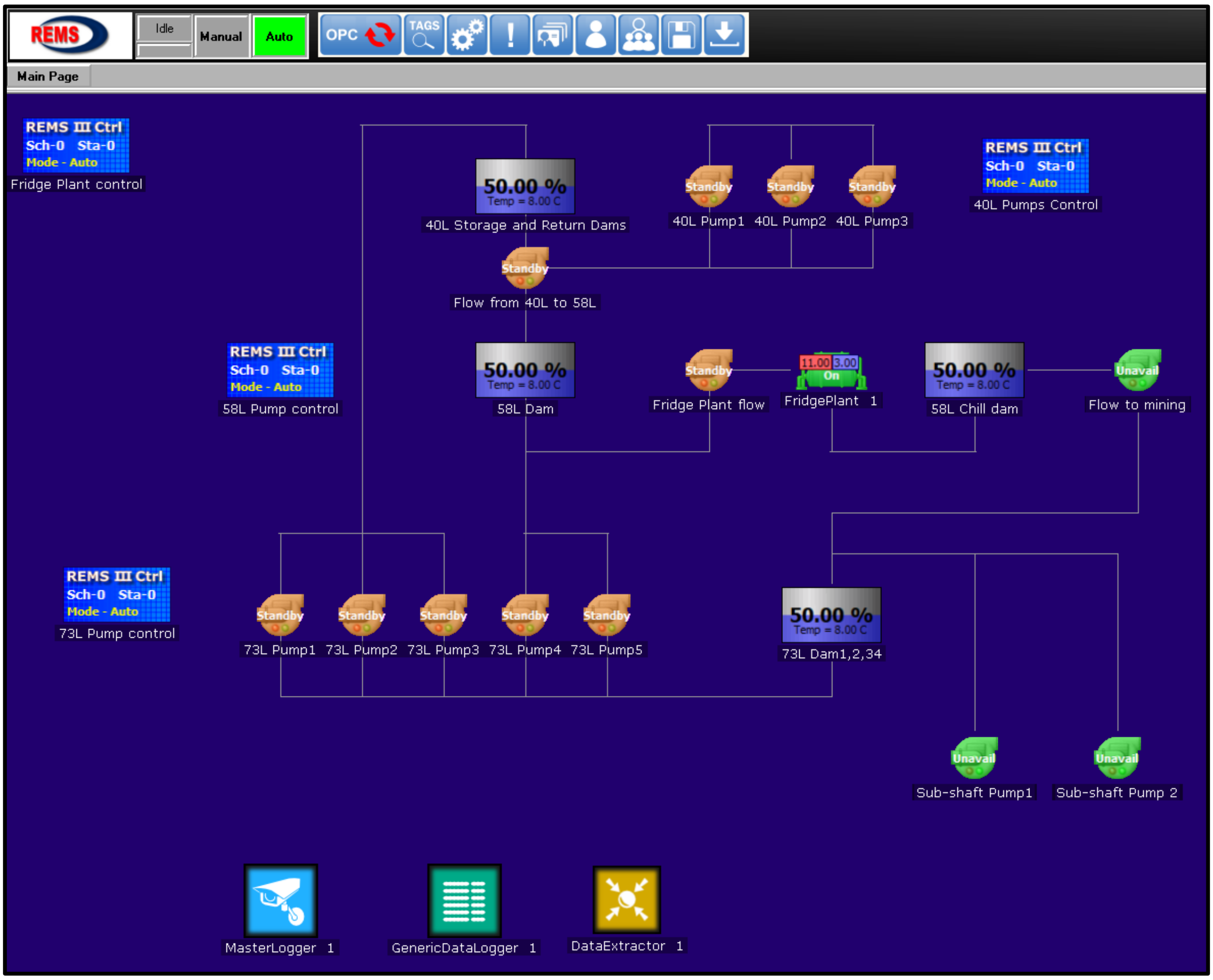


Figure 38: Case Study A baseline simulation model

Certain measured flows and specifications were used as inputs and the attained results compared with the actual measured values. Table 8 displays the inputs used within the baseline simulation as displayed within Figure 38. As can be seen in Table 8, the attained data displayed within Table 5 and Table 6 was used as main inputs for the baseline simulation.

Table 8: Inputs of Case Study A baseline simulation

Level	Component	Specification (unit)	Value/Result
40		Combined volume (m^3)	1,135

	Storage and Return dam	Inflows (-)	73L Pump 1, Pump 2 & Pump 3
		Outflows (-)	40L Pump 1, Pump 2 & Pump 3
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
	Pump 1, Pump 2 & Pump 3	Power (kW)	1,440
		Flow rate supplied (L/s)	62
	Flow to 58L	Flow rate (L/s)	16
58	Hot dam	Volume (m^3)	1,540
		Inflows (-)	73L Pump 4 & Pump 5
		Outflows (-)	Fridge plants
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
	Chill dam	Combined volume (m^3)	2,543
		Inflows (-)	58L Fridge plant
		Outflows (-)	Chilled flow to mining
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
	Fridge plant	Instantaneous flow rate (L/s)	107
	Flow to mining	Average day flow rate (L/s)	59
73	Pump 1, Pump 2 & Pump 3	Power (kW)	1,200
		Flow rate supplied per pump (L/s)	66
	Pump 4 & Pump 5	Power (kW)	1,200
		Flow rate supplied per pump (L/s)	76
	Dams 1, 2, 3 & 4	Combined volume (m^3)	2,634
		Inflows (-)	Sub-shaft pump 1, sub-shaft Pump 2 & Chilled flow to mining
		Outflows (-)	73L Pump 1, Pump 2, Pump 3, Pump 4 & Pump 5
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
Sub-shaft	Pump 1 & Pump 2	Power (kW)	500
		Flow rate supplied per pump (L/s)	16

Regarding the different flow rates as displayed in Table 7, the flow from the sub-shaft to 71L settlers and the chilled water flow from 58L chill dam to mining were used as constant inputs. This was done since the total daily volume of water supplied by these flows must remain constant for mine functionality, but can vary with production changes. The remainder of the volume flows was to be calculated by the simulation and compared with actual values. Table 9 displays a summary of the main results gathered from running the baseline simulation of Mine A's WRS compared with the actual recorded results pre-reconfiguration.

Table 9: Case Study A, baseline simulation and actual results comparison pre-reconfiguration

Flow	**Flow rate** (L/sec)	**Recorded average volumes** (ML/day)	**Simulated average volumes** (ML/day)	**Error margin** (%)
From 40L to surface	62	2.4	2.3	4.1
From 73L to 40L	66	3.3	3.4	2.9
From 73L to 58L	76	4.6	4.75	3.2
Sub shaft to 71L settlers	32	2.76	2.76	0
40L to 58L	16	0.9	0.866	3.8
To 58L fridge plants	107	7.6	7.4	2.6
58L chill dam to mining	59	5.1	5.1	0

The baseline model was simulated to represent the functionality of Mine A's WRS over a time period of three days. The attained average daily volume flow results, as displayed in Table 9, correlate to the actual measured values within a 5 % error margin. This was deemed to be accurate enough and the simulation of the proposed reconfiguration could commence.

B. Proposed reconfiguration initiatives simulation

With the baseline simulation completed and verified, the proposed reconfigurations could be simulated and validated. This would serve as justification that the proposed reconfiguration model would be sufficient in eliminating the identified problems within the WRS. Furthermore, it would have to prove that the excess water added to the mine would be removed from the mine as efficiently as possible without the compromise of any other of the WRS components.

Figure 39 displays the created simulation model of Mine A's WRS with the proposed reconfiguration changes included. As can be seen in Figure 39, the simulation was run with the two sub-shaft pumps permanently running as well as with the calculated average chilled flow supplied to mining permanently running. This simulated the actual workings of Mine A's WRS as closely as possible as chilled flow supplied to mining levels and the removal of sub-shaft fissure water are the main requirements of Mine A's WRS.

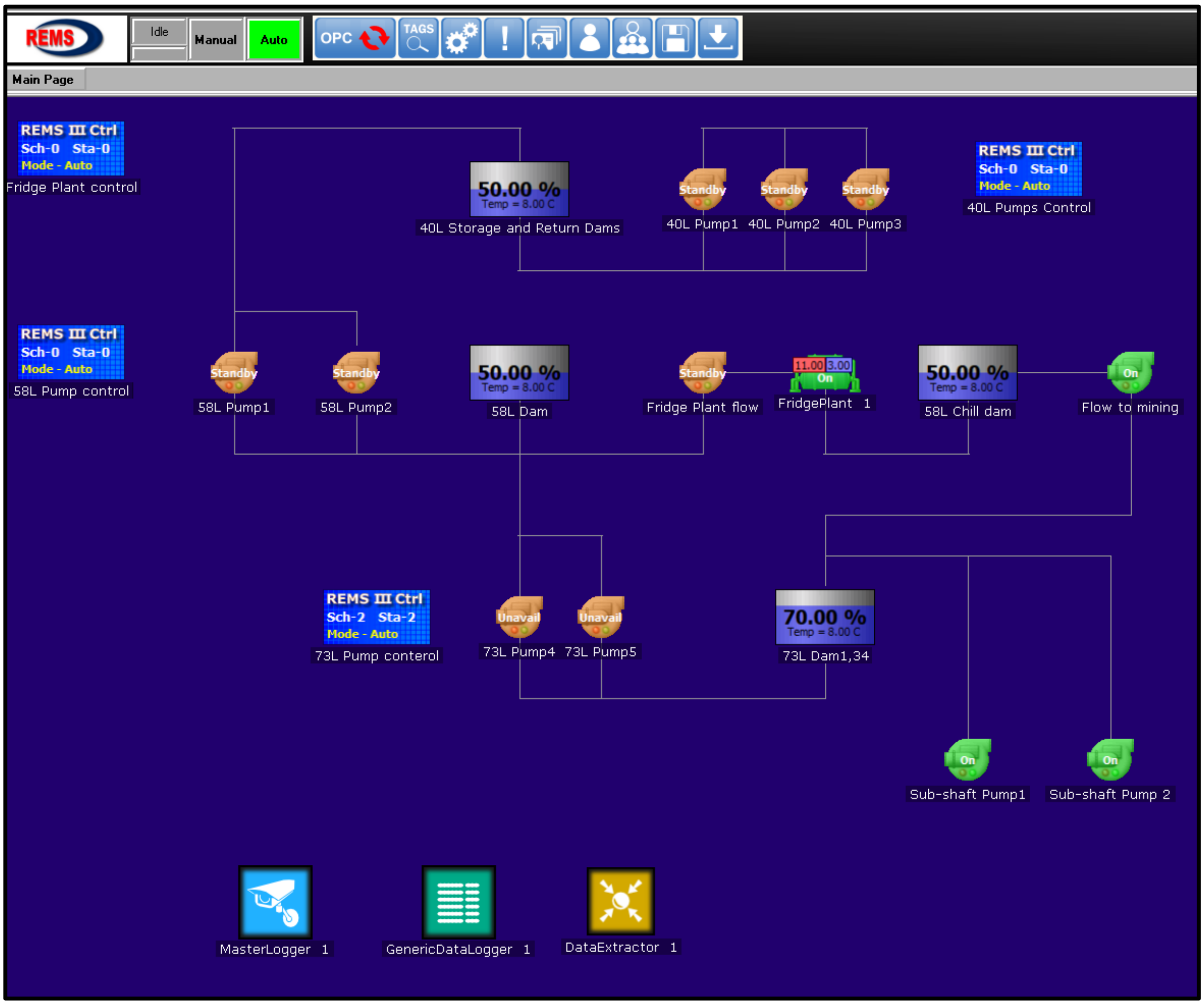


Figure 39: Case Study A proposed reconfiguration simulation model

From the simulation it would be made clear what volume flow would be required from 58L pumps 1 and 2 to sustain proper functionality of Mine A's WRS whilst removing the required amount of fissure water from Mine A. Table 10 is a summation of the inputs given for each component for the proposed reconfiguration simulation of Mine A's WRS, as displayed within Figure 39.

Table 10: Inputs of Case Study A proposed reconfiguration simulation

Level	**Component**	**Specification** (unit)	**Value/Result**
40	Storage and Return dam	Combined volume (m^3)	1,135
		Inflows (-)	58L Pump1 & Pump2
		Outflows (-)	40L Pump1, Pump2 & Pump3

		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
	Pump 1, Pump 2 & Pump 3	Power (kW)	1,440
		Flow rate supplied (L/s)	62
58	Pump 1 & Pump 2	Flow rate required (L/s)	Calculated with iterations
	Hot dam	Volume (m^3)	1,540
		Inflows (-)	73L Pump 4 & Pump 5
		Outflows (-)	58L Pump 1, Pump 2 & Fridge plants
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
	Chill dam	Combined volume (m^3)	2,543
		Inflows (-)	58L Fridge plant
		Outflows (-)	Chilled flow to mining
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
	Fridge plant	Instantaneous flow rate (L/s)	107
	Flow to mining	Average day flow rate (L/s)	59
73	Pump 4 & Pump 5	Power (kW)	1,200
		Flow rate supplied per pump (L/s)	76
	Dams 1, 3 & 4	Combined volume (m^3)	1,938
		Inflows (-)	Sub-shaft pump 1, sub-shaft Pump 2 & Chilled flow to mining
		Outflows (-)	73L Pump 4 & Pump 5
		Maximum level (%)	80
		Minimum level (%)	40
		Top/bottom offset before additional pump start/stop (%)	3
Sub-shaft	Pump 1 & Pump 2	Power (kW)	500
		Flow rate supplied per pump (L/s)	16

As can be seen in Table 10, pump efficiencies were not provided as simulation inputs because the actual supplied flow rates of each pump had been measured beforehand. The required flow rates for 58L Pump 1 and Pump 2 were attained through iterations within the simulation.

The proposed reconfiguration of Mine A's WRS was simulated successfully and the main results, regarding the water distribution within Mine A, are displayed within Table 11.

Table 11: Water distribution results of Case Study A's proposed reconfiguration simulation

Flow	**Flow rate** (L/sec)	**Average daily volume flow** (ML/day)
From 40L to surface	62	2.64
From 58L to 40L	144	2.5
From 73L to 58L	76	7.34
Sub shaft to 71L settlers	32	2.76
To 58L fridge plants	107	5.1
Chilled water from 58L chill dam to mining	59	4.82

As displayed within Table 11, the calculated flow rate needed for 58L Pumps 1 and 2 was 144 L/s. This flow rate would aid in WRS functionality and could be supplied by 1,200 kW pumps. Therefore, 73L Pumps 1, 2 and 3 could be used and relocated to 58L, or new pumps could be installed and the three unused pumps on 73L could be kept as spare.

3.2.4 Step 4 – Implementation and system improvement

Implementation of the proposed reconfigurations, as displayed in Figure 37, took place over a time period of more than 8 months. During this time multiple visits to Mine A took place, as well as constant communication and reporting to the relevant mine personnel. This was done to keep track of the project progress. During and after project implementation, daily water reticulation reports were sent to the relevant mining personnel. These reports enabled one to closely monitor the water reticulation flows and pump running hours for each day.

The first improvement made was the installation of the two 1,200 kW pumps on 58L. This change took the longest to complete. Once the pump station on 58L was commissioned and running, the flow between 73L and 40L was stopped and the pipe column sealed off. This could be done because water could now be pumped from 58L dams to 40L storage dam.

A month after the sealing of the pipe column between 73L and 40L, the flow from 40L down to 58L was stopped and the pipe column sealed. Finally, 73L dam 2 was decommissioned and all the proposed reconfigurations had been implemented.

The proposed improvements after reconfiguration could not be completed in time for the purpose of this study. The timely completion of the proposed improvements was the result of a shortage in work staff on Mine A, along with other unrelated problems that needed attention during this time. The SCADA on Mine A was fully functioning and the installed REMS program ready for full-automatic control, but mining personnel were reluctant to allow total automatic control of the WRS.

3.2.5 Step 5 – Results quantification

After the proposed reconfigurations were implemented on Mine A, the relevant data was captured over a period of five months after implementation. The average daily water volumes, as displayed in Table 11, fluctuated for the first two months after implementation as some needed adjustments had to be made within the WRS.

Mine personnel managing the equipment within the WRS had to gain familiarity with the new system. The pump attendants manning the 58L pumps had to learn the workings of the system and fluctuations within dam levels during the average day. Once familiarity and confidence were gained with the newly reconfigured system, the measured flow were more reliable. Table 12 displays a comparison of the recorded results and simulation results for Case Study A, Mine A, after the implementation of the proposed reconfigurations took place.

Table 12: Case Study A, proposed reconfiguration simulation and actual results comparison post-reconfiguration

Flow	**Flow rate** (L/sec)	**Recorded average volumes** (ML/day)	**Simulated average volumes** (ML/day)	**Error Margin** (%)
From 40L to surface	62	3.1	2.64	17
From 58L to 40L	144	2.3	2.5	8
From 73L to 58L	76	7.3	7.34	0.5
Sub shaft to 71L settlers	32	8.9	2.76	5
To 58L fridge plants	107	5	5.1	1.9
58L chill dam to mining	59	4.4	4.82	8.7

As displayed in Table 12, the results for simulated and recorded flow rates for Mine A, after implementation of proposed reconfigurations, differ with a variety of ranges, the largest difference being the volume flow to surface from 40L. The recorded volumes of water removed from Mine A exceeded what was estimated with the validation simulation. This was good news as the implemented changes outperformed what was expected.

Table 13 displays the measured daily volume flows of Mine A, pre-reconfiguration, versus the measured volume flows post-reconfiguration. A percentage difference is also calculated to display the improvements made by the implemented reconfigurations.

Table 13: Comparison of Case Study A results pre- and post-reconfiguration

Flow	**Average volume flows** (ML/day)		**Change**
	Pre-reconfiguration	**Post-reconfiguration**	
From 40L to surface	2.4	3.1	+ 29 %
From 73L to 40L	3.3	None	Removed
From 73L to 58L	4.6	7.3	+ 58 %
From 58L to 40L	None	2.3	Added
Sub shaft to 71L settlers	2.76	2.9	+ 5 %
40L to 58L	0.9	None	Removed
To 58L fridge plants	7.6	5	- 34 %
58L chill dam to mining	5.1	5	- 1.9 %

As displayed in Table 13, the average water volumes pumped from the sub-shaft and supplied to mining changed by 5 % and 1.9 %, respectively. The average daily volumes pumped from 73L to 58L increased by 58 % as water was not being pumped from 73L to 40L anymore. Volume flow through 58L fridge plants decreased by 34 % as water was no longer being recirculated through 58L hot dams from 40L.

Finally, the reconfiguration proved an additional 29 % of water removed from Mine A on an average day. These are significant results. The increased amount of water removed from Mine A on an average day meant that the system had been successfully reconfigured in terms of fissure water removal. The results of Case Study A proved successful as the identified problems were solved.

3.3 Case Study B

Case Study B took place on Mine B-1, B-2 and B-3, where these mines are large-sized gold mines within the Free State region of South Africa. Mines B-1, B-2 and B-3 are part of a large network of 6 interconnected mine shafts. Mine B-2 is located between Mines B-1 and B-3 and serves the purpose of a dewatering shaft as Mine B-2 is no longer active.

Mine B-1 is an active gold mine that received excess water from Mine B-2, which in turn receives water from Mine B-3. This large-scale dumping of water into Mine B-1 caused the dewatering system of Mine B-1 to become overwhelmed over time. Because Mine B-1 has a large inflow of internal fissure water, the risk of flooding the mine became prominent and action had to be taken.

Mine B-1 will serve as the centre point of Case Study B and Mine B-3 will play the second largest role. A detailed discussion of the WRS of Mines B-1, B-2 and B-3 along with the mine network surrounding these mines will follow in the data acquisition phase of Case Study B.

3.3.1 Step 1 – Data acquisition

The information gathered and researched for the complete familiarisation of Mines B-1, B-2 and B-3's WRS and surroundings along with the identified problems is discussed within Step 1 of Case Study B.

A. Data acquisition of Mine B-1, B-2 and B-3 WRS and surroundings

The first step within the data acquisition phase of Case Study B was to understand the surroundings of Mine B-1 as it is the focus of the case study. Mine B-1 forms part of a network of 6 mine shafts that are in close range of one another. These mine shafts are interconnected at certain levels, allowing for flood water to flow freely between the shafts. Some of the inactive shafts were dedicated as dewatering shafts that aid in removing excess water before reaching the active mine shafts.

Figure 40 is a schematic representation of the aforementioned mine shafts. The main shaft of Mine D extends to 58 L. The shaft is connected to Mine C, Mine E and Mine B-3 on 57L. Mine D 57L holds with Mine B-3 via a 2^{o} to 4^{o} stope holding. Mine D pumps 3 ML of water to surface per day [59]. Interconnecting tunnels are coloured yellow within Figure 40 and dewatering shafts coloured blue. Water flow directions are indicated with black arrows.

Water from Mine C and Mine E gravitates to Mine D on 57L haulage at 1.2 ML per day and 0.2 ML per day respectively. Mine D shaft is flooded from the shaft bottom (58L) up to 57L, where pumping occurs. If pumping at 57L ceases, water will then flow along with the 57L haulage network to Mine B-3 and Mine E shafts. With a steady state inflow of 3 ML per day, the impact to Mine E and Mine B-3 is likely to happen immediately after pumping is stopped. Dewatering at Mine D is thus essential for the existence of Mines E and B-3.

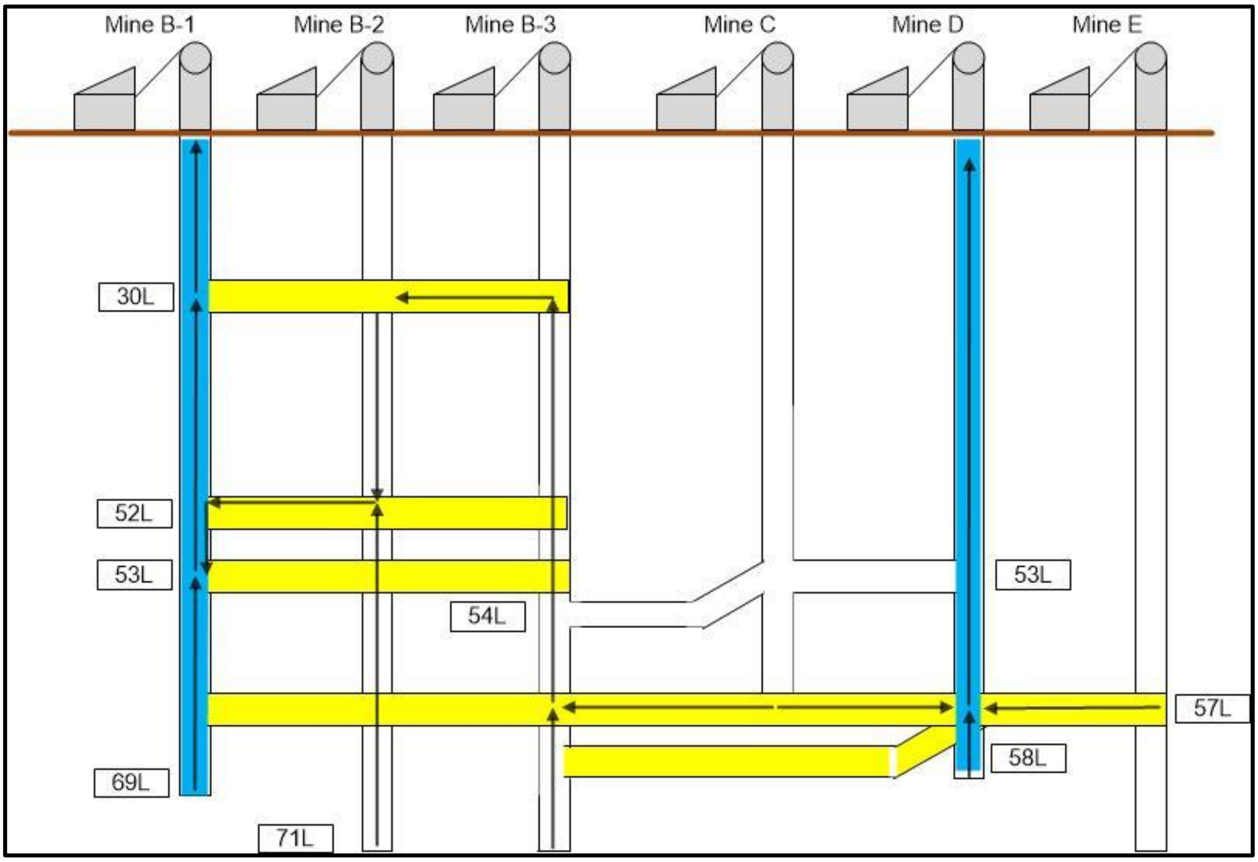


Figure 40: Case Study B interconnected mine shafts

Water is pumped from Mine C to Mine B-2, 52L via Mine B-3, 30L, at an average rate of 1 ML/day. This causes Mine B-2 to pump an average of 2.7 ML/day to Mine B-1, 53L. This causes Mine B-2 to pump an average of 2.7 ML of water per day to Mine B-1, 53L, per day. With the excess water contribution from Mine B-2 to Mine B-1, Mine B-1 pumps an average of 5.6 ML/day to surface. Mine B-2's pump station, on 52L, is run in series with Mine B-1 pump station on 67L to avoid flooding of Mine B-1 53L pump station.

Excess water from Mine B-1, 69L, is pumped to Mine B-1, 53L, from where the water is pumped to Mine B-1, 30L dams. Water is then pumped from 30L to the surface storage dams at Mine B-1's gold plant. Figure 41 displays the basic WRS layout on Mines B-1, B-2 and B-3 along with the interconnecting WRS equipment between these shafts.

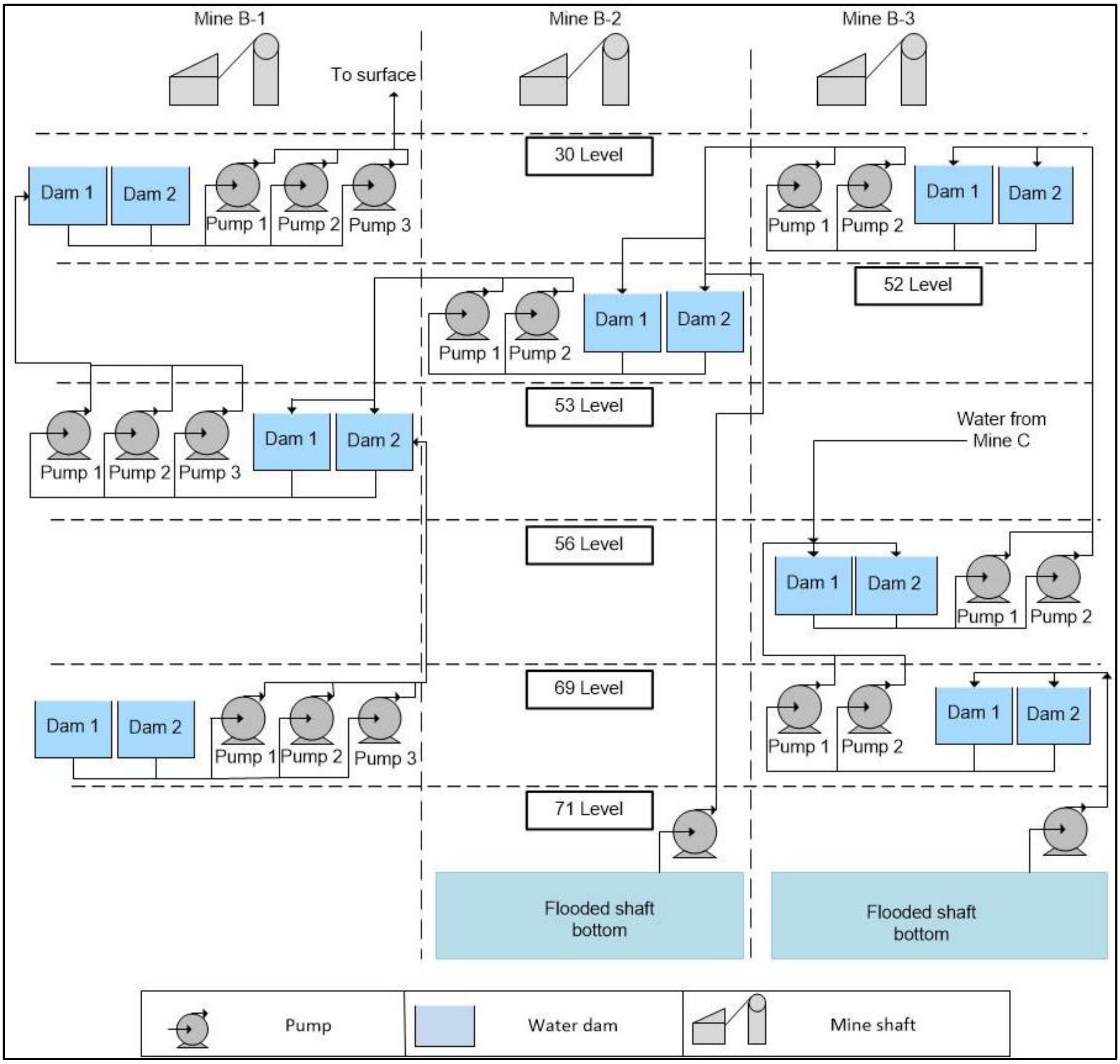


Figure 41: Mine B-1, B-2 and B-3 interconnections and WRS equipment allocation

It was found that no water is supplied from surface down Mine B-2 and that only drinking water is supplied from surface to Mine B-1. This meant that the only contributors of service water to Mine B-1 were the water received from Mine B-2 and internal fissure water from Mine B-1. The relevant WRS equipment and flow specifications of Mine B-1, B-2 and B-3 are summarised within Table 14. These values were attained through the SCADA, studying of log sheets, mine layouts, meetings with mine personnel and underground visits.

Table 14: Mine B-1, B-2 and B-3 flow rates, dam and pump specifications

Mine	**Level**	**Unit**	**Specification** (Unit)	**Value**
B-1	30	Pump 1, 2 & 3	Power output (MW)	3.2
			Flow rate supplied per pump (l/s)	85
			Volume pumped to surface (ML/day)	5.6
		Dam 1 & 2	Combined capacity (m^3)	3,014
	53	Pump 1, 2 & 3	Power output (MW)	3.2
			Flow rate supplied per pump (l/s)	120
			Volume pumped to 30L dam (ML/day)	5.6
		Dam 1 & 2	Combined capacity (m^3)	2,161
	69	Pump 1, 2 & 3	Power output (MW)	2.5
			Flow rate supplied per pump (l/s)	100
			Volume pumped to 53L dam (ML/day)	1.6
		Dam 1 & 2	Capacity (ML)	4,254
			Fissure water received (ML/day)	0.6
B-2	52	Pump 1 & 2	Power output (kW)	110
			Flow rate supplied per pump (l/s)	43
			Volume pumped to Mine B-1 53L dams (ML/day)	2.7
		Dam 1 & 2	Combined capacity (m^3)	2,161
			Fissure water received (ML/day)	1.1
B-3	30	Pump 1 & 2	Power output (MW)	1.6
			Flow rate supplied to Mine B-2 per pump (l/s)	44
			Volume pumped to Mine B-2 52L dams (ML/day)	1
		Dam 1 & 2	Combined capacity (m^3)	2,000
	56	Pump 1 & 2	Power output (MW)	1.6
			Flow rate supplied per pump (l/s)	90
			Volume pumped to 30L dam (ML/day)	1.6
		Dam 1 & 2	Combined capacity (m^3)	2,100
			Flow from Mine C (ML/day)	0.9
	69	Pump 1 & 2	Power output (kW)	1.6
			Flow rate supplied (l/s)	96
			Volume pumped to 52L dam (ML/day)	1.8
		Dam 1 & 2	Combined capacity (m^3)	2,000
			Fissure water received (ML/day)	0.7

B. Problem identification of Mine B-1, B-2 and B-3 WRS and surroundings

The main identified problem was that Mine B-1 received more water than could be removed from the mine effectively. This is due to an average amount of 1.6 ML/day of internal fissure water added to the system as well as 2.7 ML/day of water added to the mine from Mine B-2. The large quantities of water sent to Mine B-1 from Mine B-2 was because Mine B-1 and Mine D were the only mines that could pump water to surface. Hence all the excess water received from Mine C, B-3 and B-2 had to be removed from underground through Mine B-1.

Upon further investigation it was found that the 69L feed pipes on Mine B-1 had been corroded away. The corrosion was the result of very acidic water within Mine B-1 (pH level of 2.5). This corrosion led to large leakages of water on 67L and had a significant negative impact on the reliability of Mine B-1's de-watering system.

Although Mine B-1 was equipped with an operational SCADA, Mine B-2 and B-3 were not. This enabled the monitoring and data extraction of WRS equipment within Mine B-1 from surface. Furthermore, underground control valves and PLCs were also not present within Mines B-2 and B-3. This would make the control and monitoring of Mine B-2 and Mine B-3 WRS equipment impossible.

3.3.2 Step 2 – Solution development

Figure 42 is a basic layout of Mines B-1, B-2 and B-3 displaying the proposed reconfiguration solution to the problems identified within Step 1 of Case Study B. The major system changes made are circled in green and numbered 1 to 4. Proposed Change 1 was to repair the damaged pipe lines on Mine B-1, 69L, as mentioned in the data acquisition step of Case Study B.

Proposed Change 2 was that Mine B-3 must act as a de-watering shaft to remove water to surface. This would mean that Mine B-3 would pump water to the evaporative dams allocated on the surface of Mine D. The removal of water from Mine B-3 would mean less water being pumped to Mine B-1 via Mine B-2. For this to happen, an updated pump station would have to be implemented at Mine B-3, 30L to pump to surface along with surface pumps to pump water to Mine D.

Part of Proposed Change 2 was that the fibre connections and a SCADA system on both Mine B-2 and B-3 be installed to allow for full remote access to WRS equipment. With fibre connectivity underway at Mine B-3, completion of the project could be expected sooner.

As displayed in Figure 42, Proposed Change 2 for reconfiguration was the implementation of two pumps and a storage dam on Mine B-3 surface to pump water to Mine D evaporative dams. Proposed Change 3 was to disconnect the pipe column connecting Mine B-3, 30L pumps to Mine B-2, 52L dams. Proposed Change 4 was the implementation of larger pumps on Mine B-3 30L to pump water to surface. Other proposed changes, such as the implementation of SCADA and REMS implementation, are not displayed.

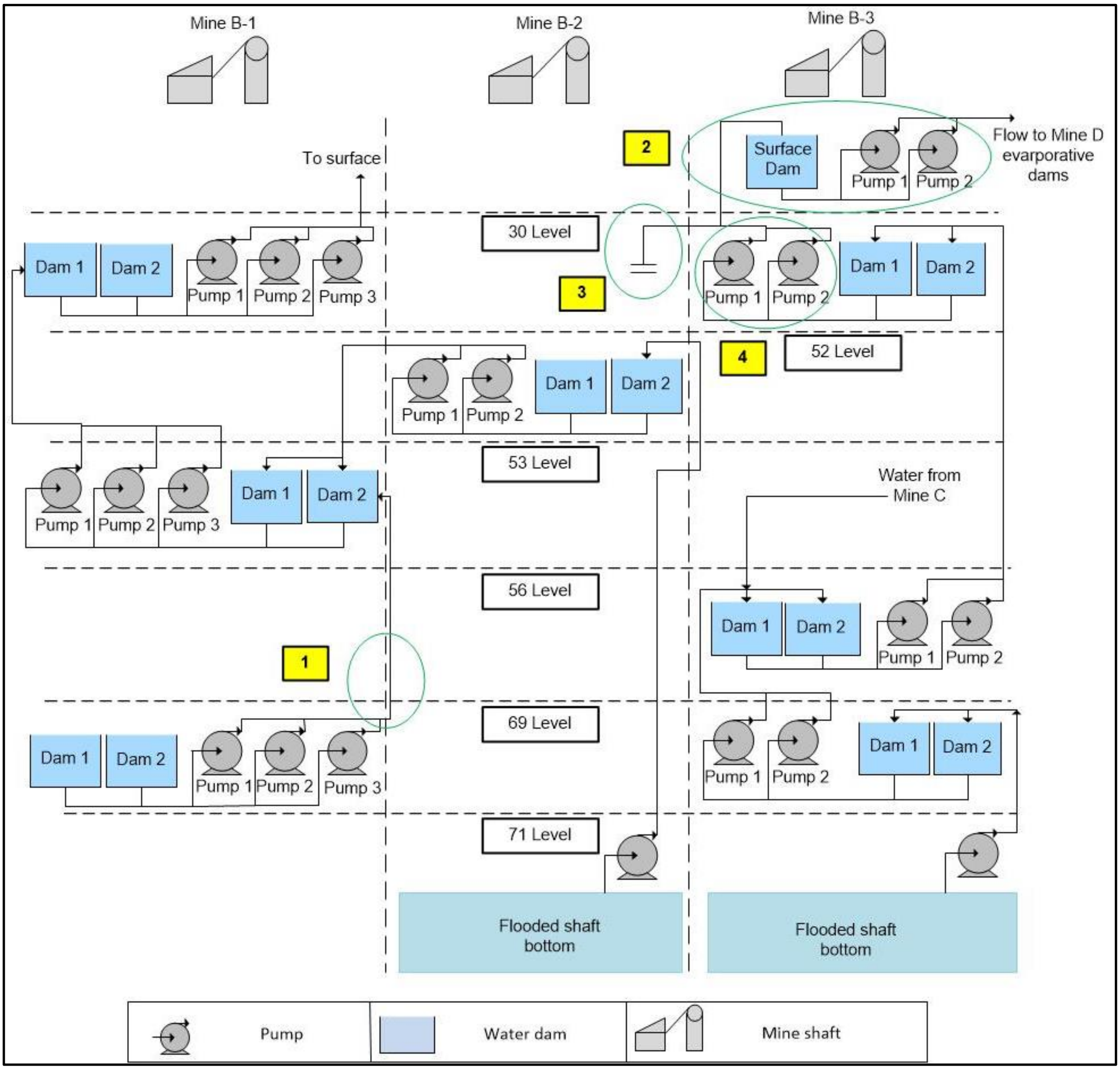


Figure 42: Proposed solution for the reconfiguration of Mines B-1, B-2 and B-3 WRSs

The proposed system improvements to the overall system after reconfiguration were to install a REMS system on Mines B-1, B-2 and B-3 to allow for fully automatic control and monitoring of WRS equipment. Once REMS was given access to the mine’s de-watering pumps, programming of REMS could be implemented to allow for load shift projects to take place on all three mines. Furthermore, it was suggested that stope isolation valves must be installed on Mine B-3 to reduce the inflow of water to mining levels each day from 17:00 to 21:00.

3.3.3 Step 3 – Validate proposed reconfiguration solution

Validation of the proposed solution suggested for Case Study B consisted of three main steps which are listed from A to C within this section of this study. The steps are (A) to develop the baseline simulation of Mines B-1, B-2 and B-3's WRSs before reconfiguration. Next (B) was a simulation of the Mine's WRSs with the proposed reconfigurations implemented. The final step (C) was to simulate the proposed reconfigurations with programming for a load shift project, on all three mines, included. All three simulations were created and refined successfully. The final versions of the simulations and their findings will, however, only be discussed later in Section 3.3.

A. Baseline simulation

The WRSs of mines B-1, B-2 and B-3, before reconfiguration changes took place, were simulated with a REMS model. Figure 43 displays the dashboard of the REMS model that served as baseline simulation for Case Study B. The inputs used within the baseline simulation had values equal to those measured on the actual system, as displayed in Table 14.

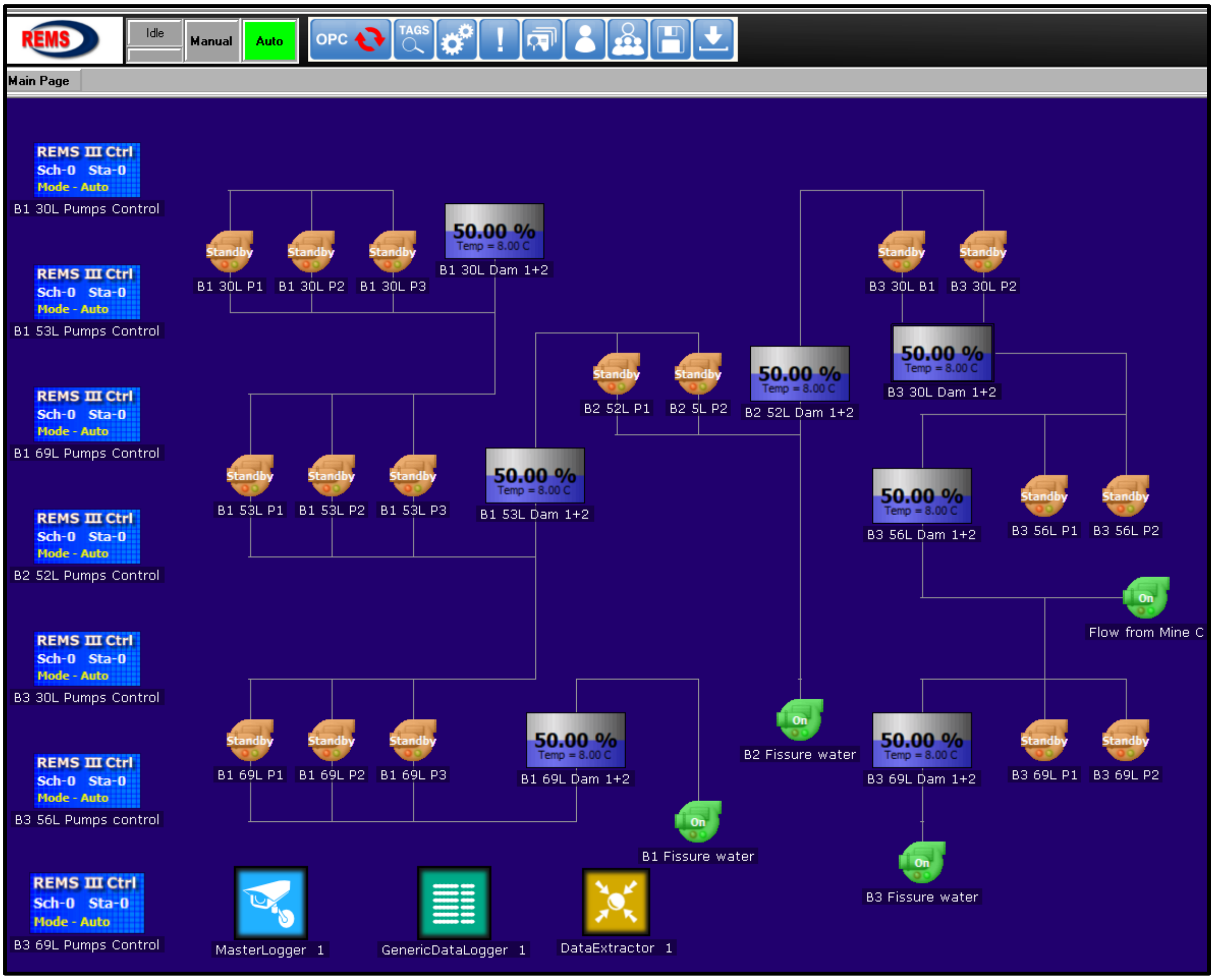


Figure 43: Case Study B baseline simulation REMS dashboard

Figure 43 displays adjacent dams on similar levels as one combined dam. This was once again done for the sake of simplicity as with Case Study A. The inflow of fissure water to 69L dams on Mine B-1 and B-2 along with Mine B-2 fissure water to 52L dam and flow from Mine C to Mine B-3 were chosen as constant input flows for simulation purposes. This is because these flows are the only water inflows to the overall system.

The maximum and minimum levels for all dams within the baseline simulation, as displayed in Figure 43, were specified as 85 % and 40 %, respectively. Pump control ranges were specified according to these maximum dam levels with a 3 % top/bottom offset margin before additional pumps start or stop. The fissure water inflows were calculated and applied as constant values that would amount to the average daily volumes measured. This would give accurate enough results for reliability.

The baseline simulation was refined and ran successfully. Table 15 displays a comparison of the attained results of Case Study B baseline simulation with the actual results, as displayed in Table 14. Results are shown in the form of average daily volume flows to certain areas of each of the three relevant mines (Mine B-1, B-1 and B-3).

Table 15: Case Study B baseline simulation results compared to actual results pre-reconfiguration

Flow	**Average daily volume flows** (ML/day)		**Difference** (%)
	Actual results	**Simulated results**	
Mine B-1: 30L to surface	5.6	5.54	1.07
Mine B-1: 53L to 30L	5.6	5.49	1.96
Mine B-1: 69L to 53L	1.6	1.52	5
Mine B-2: 52L to B-1 53L	2.7	2.81	4.1
Mine B-3: 30L to B-2 52L	1	0.96	4
Mine B-3: 56L to 30L	1.6	1.6	0
Mine B-3: 69L to 56L	1.8	1.76	2.2
Fissure water to Mine B-1 69L	0.6	0.6	0
Fissure water to Mine B-2 52L	1.1	1.1	0
From Mine C to Mine B-3 56L	0.9	0.9	0
Fissure water to Mine B-3 69L	0.7	0.7	0

As can be seen in Table 15, the largest percentage difference that occurred between simulated and actual results was 5 %. This proves that the baseline simulation is accurate to within a 5 % error margin and can thus be deemed accurate enough to continue with reconfiguration results.

B. Proposed reconfiguration initiatives simulation

For the proposed reconfiguration validation, two separate simulations were created. This was because the WRS of Mine B-3 would no longer be connected to that of Mine B-2. Therefore, Mine B-3 was considered as a separate system from Mines B-1 and B-2, which were simulated as one system.

The simulation of Mine B-3's proposed reconfiguration would have to calculate the flow rate and thus pumping capacity needed to effectively remove the water supplied from Mine C along with Mine B-3's fissure water. The second reconfiguration simulation of Mines B-1 and B-2 would serve the purpose of determining the impact caused by removing the inflow of water from Mine B-3 to Mine B-2. The two separate proposed reconfigured systems were simulated successfully with REMS models. Figure 44 displays the dashboard of the REMS model that served as the proposed reconfiguration simulation for Mine B-3.

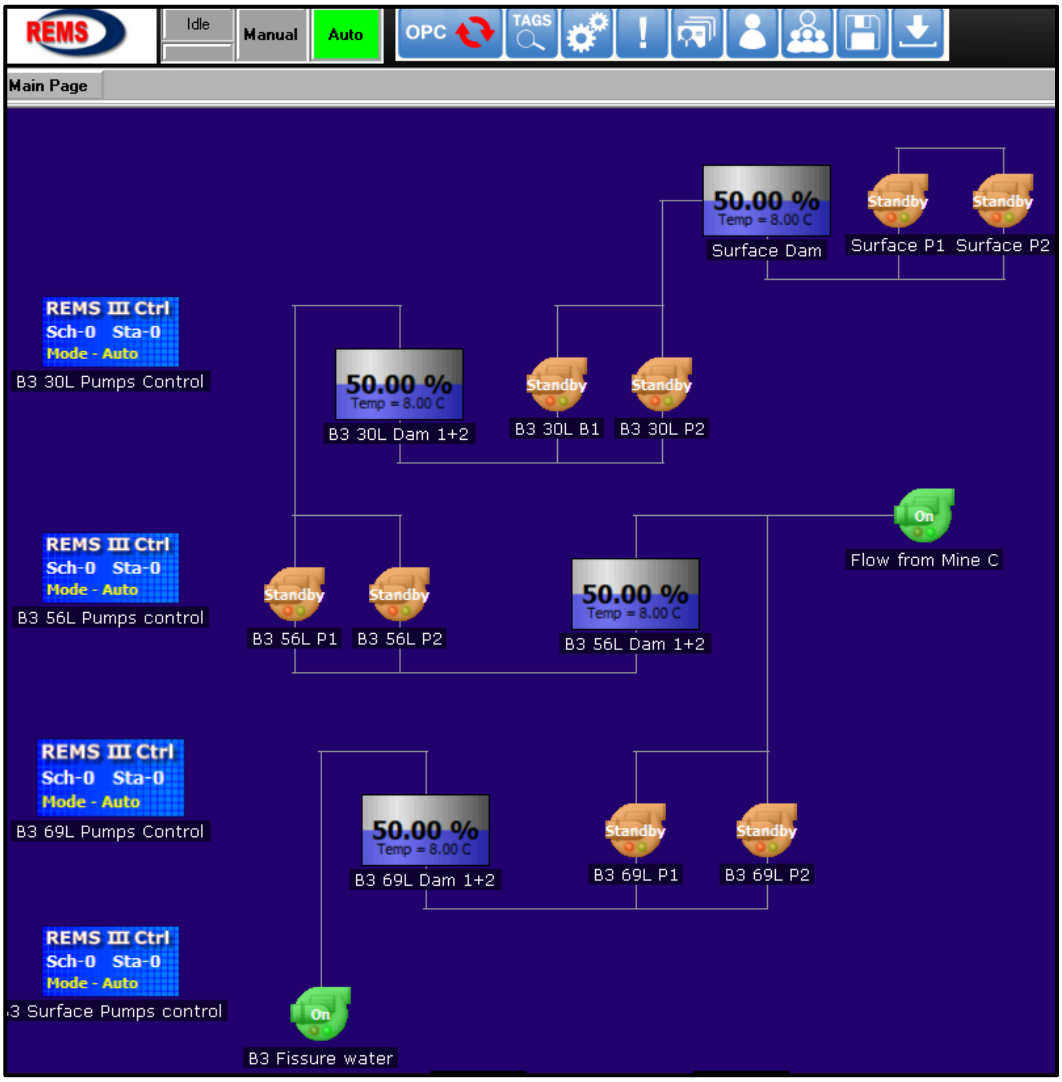


Figure 44: Case Study B, Mine B-3, proposed reconfiguration simulation model

Figure 45 displays the dashboard of the REMS model that served as the proposed reconfiguration simulation for combined Mines B-1 and B-2. The inputs given to both simulations were similar to those given to the baseline simulation. Simulation of the proposed reconfigurations, as displayed in Figure 44 and Figure 45, was refined and ran successfully. The final simulation results for the proposed reconfiguration initiatives for Case Study B can be seen in Table 16.

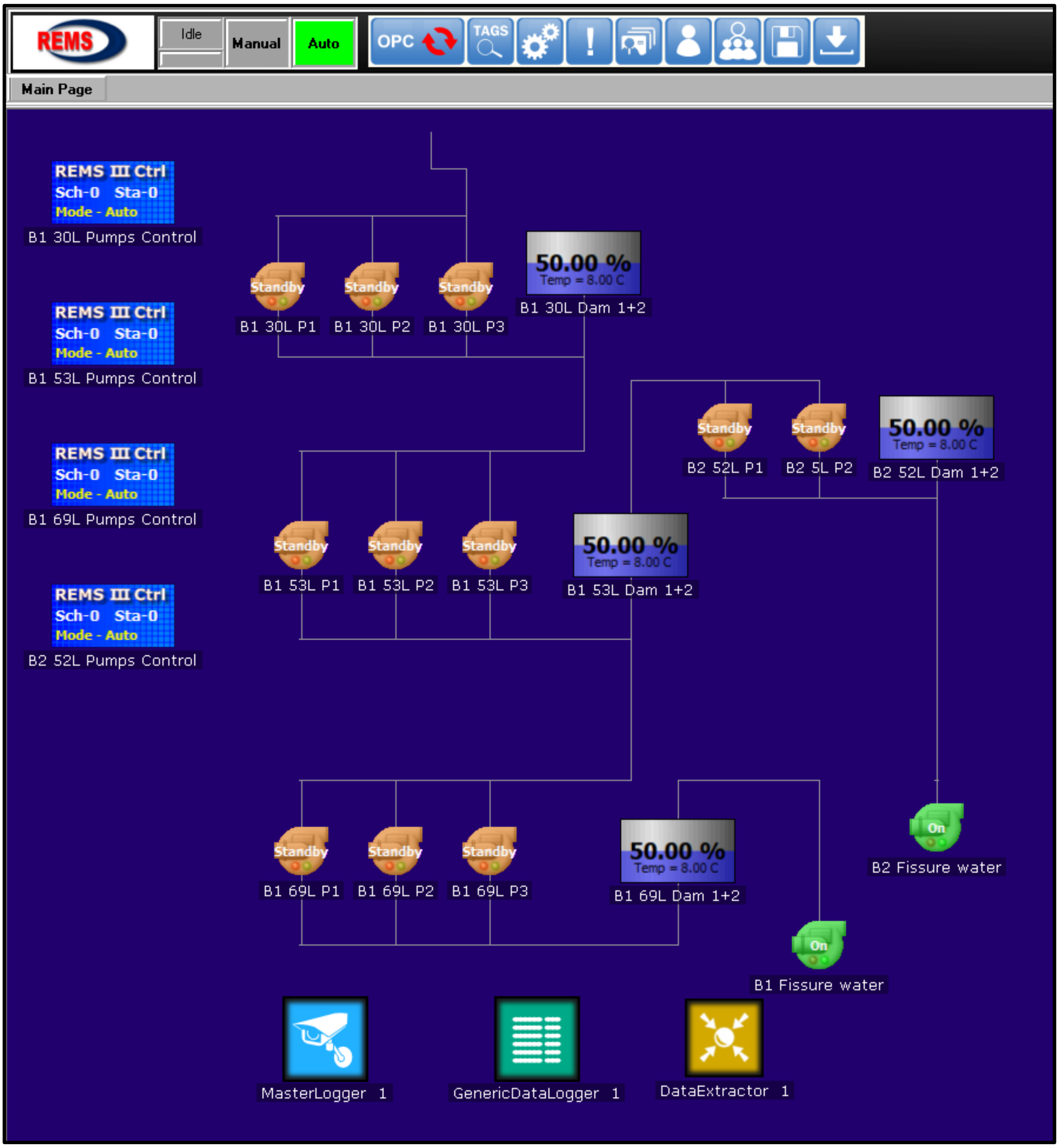


Figure 45: Case Study B, Mines B-1 and B-2, proposed reconfiguration simulation model

Table 16: Case Study B, simulation results for proposed reconfiguration initiatives on Mine B-3 and combined Mines B-1 and B-2

Flow	**Flow rate** (L/s)	**Average volumes distributed as simulated for post-reconfiguration** (ML/day)
Mine B-3 proposed reconfigurations simulation results:		
Mine B-3: 30L to surface	86	1
Mine B-3: 56L to 30L	90	1.61
Mine B-3: 69L to 56L	96	1.79
Mines B-1 and B-2 proposed reconfigurations simulation results:		
Mine B-1: 30L to surface	85	4
Mine B-1: 53L to 30L	120	3.9
Mine B-1: 69L to 53L	100	1.5
Mine B-2: 52L to B-1 53L	43	1.83

The outcome of the simulation proved that the proposed reconfiguration solutions would be viable in the sense that excess water would be effectively removed from the mines. Furthermore, no build-up of water formed to the point of dam floods occurring. After iterations it was found that the minimum flow rate needed to remove water from Mine B-3 30L to surface effectively was 85 L/s.

C. Proposed improvements after reconfiguration simulation

For the simulations of the proposed improvements after system reconfiguration, the same REMS models were used as displayed in Figure 44 and Figure 45. The only difference was that the systems were simulated with load shift initiatives implemented. This involved the implementation of control ranges, as displayed and explained in Figure 31 of Section 2.4 of this study.

The control ranges implemented into the two different simulations are displayed in Table 17. Control ranges must be specified per pump group and thus require that control ranges be specified for each pump station within each of the three mines. A total of 8 control ranges were investigated and specified for the two different simulations.

Automated load shift projects were implemented successfully on Mines B-1 and B-2; therefore the specified control ranges for these mines will only be displayed within Table 17. Control ranges for Mine B-3 were simulated, but not implemented. This will be discussed in Section 3.3.4 of this study. Please refer to Section 2.4 C for more information regarding control ranges on REMS.

Table 17: Control ranges within Case Study B proposed improvement validation simulation

Time	Mine B-1 control range			Mine B-2
	30L Pumps	**53L pumps**	**69L Pumps**	**52L Pumps**
00:00	15	15	25	25
01:00	15	15	25	25
02:00	20	20	25	25
03:00	15	25	25	20
04:00	15	15	25	10
05:00	10	10	20	5
06:00	10	10	10	10
07:00	5	8	5	10
08:00	5	8	5	10
09:00	5	8	5	15
10:00	20	35	25	25
11:00	20	30	15	25
12:00	20	25	15	25
13:00	20	25	20	25
14:00	20	20	20	20
15:00	10	20	20	20
16:00	10	15	22	20
17:00	10	15	22	20
18:00	5	8	5	5
19:00	5	8	5	5
20:00	25	28	30	25
21:00	25	28	30	25
22:00	25	25	30	25
23:00	20	10	30	25

The Megaflex peak hours, as discussed in Section 1.5.2, are highlighted in light grey in Table 17 and the control ranges are thus specified from the top for these hours (refer to Section 2.4 C). Mine B-1 30L dams had a maximum and minimum allowable dam level of 75 % and 40 % respectively. 53L and 69L dams had maximum and minimum dam levels of 85 %, 45 %, 90 % and 50 % respectively. Mine B-2, 52L had maximum and minimum dam levels of 65 % and 35 % respectively.

Two average day baselines were created, from the power profiles of Mine B-3 and Mine B-1 pumps, three months before implementation of the proposed load shift improvements. These baseline profiles would be used to determine the effect of implementing the load shift projects and to determine cost savings. Figure 46 and Figure 47 display the baseline power profiles as well as the proposed simulated power profiles for load shift implementation of Mines B-1 and B-3 respectively.

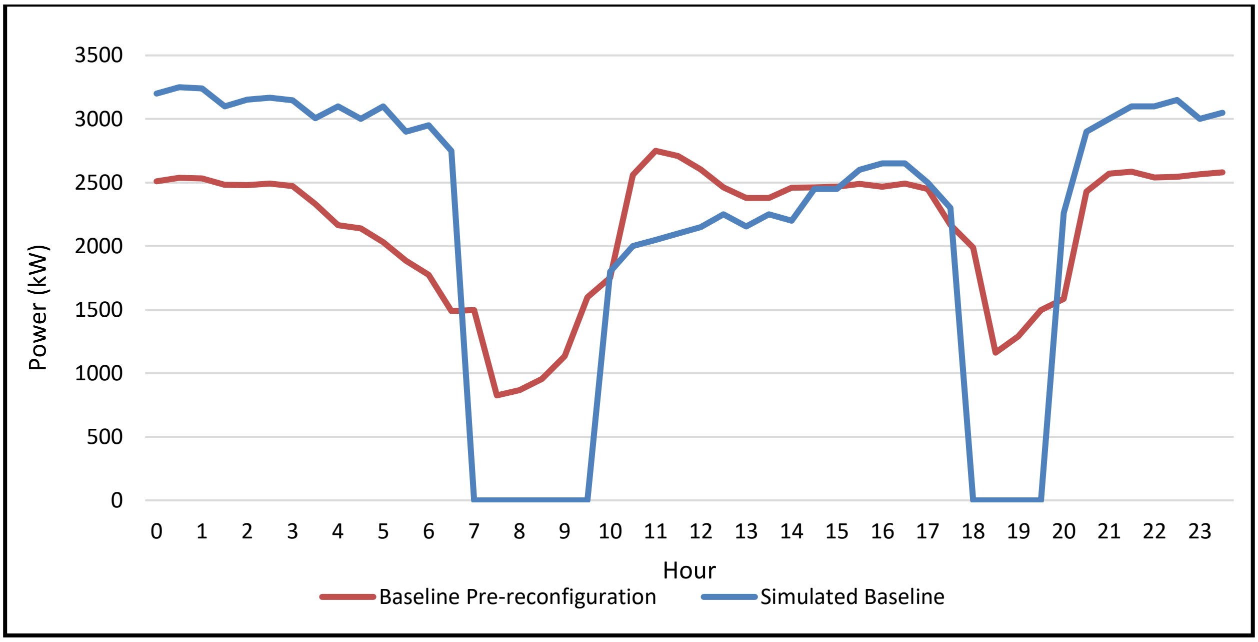


Figure 46: Mine B-1 simulated load shift vs actual baseline pre-reconfiguration

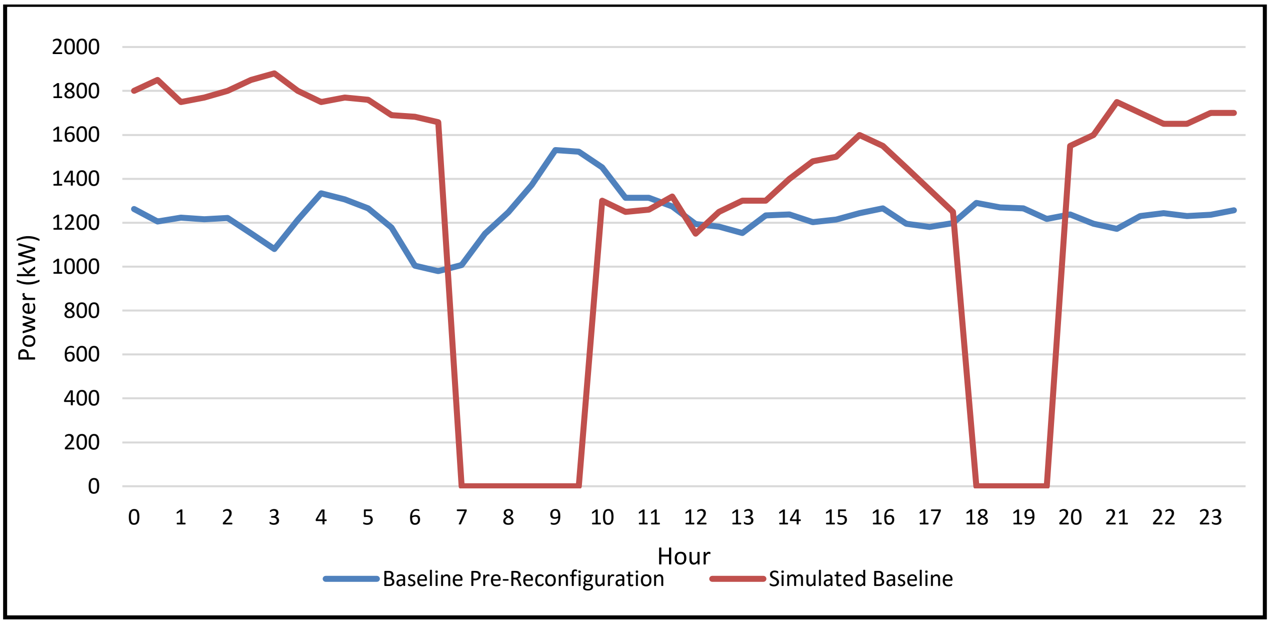


Figure 47: Mine B-3 simulated load shift vs actual baseline pre-reconfiguration

Feasible control ranges had been attained through refining the simulations and analysing the attained results. After simulation it was clear that the possibility of implementing load shift projects on all three mines existed. The simulation proved it possible to empty all dams without pumping during peak hours and whilst eliminating the possibility of flooding dams.

The estimated savings that could possibly be attained through the implementation of load shift projects on Mine B-1 and B-3 pumping systems were calculated using ESKOM 2018-2019 tariffs. The estimated savings were calculated as R 1.09-million and R 1.04-million per annum for Mine B-1 and B-3 respectively.

3.3.4 Step 4 – Implementation and system improvements

Complete implementation of Case Study B took place over a period of 10 months. This was due to the major system changes that had to occur for the project to realise. The first completed step within the reconfiguration process was the repair of the damaged pipe lines on Mine B-1, 67L.

The second completed step was the installation of a REMS server on Mine B-1 to monitor and control the de-watering sub-system of Mine B-1. REMS was given full-automatic control of all major de-watering pumps on Mine B-1 and an automatically controlled load shift project was implemented successfully. Several meetings were held with Mine B-1 personnel during the start of the REMS system implementation, as well as monthly feedback meetings. This was done to ensure smooth execution of the project.

The second step within the reconfiguration process was the completion of SCADA connectivity to Mines B-2 and B-3. With SCADA connectivity completed on Mine B-2, automation of Mine B-2 de-watering pumps on 52L followed along with full control by REMS. Mine B-2 pumps were implemented successfully into the automatic load shift project with Mine B-1 pumps.

Next to be implemented was the installation of Mine B-3 de-watering pumps on 30L to pump excess water to surface. A pipe column that connected Mine B-3, 30L dams to a surface dam at Mine B-1 was installed. A pipe column along with pumps to pump water from Mine B-1 to the surface evaporative dams on Mine D was installed. Mine B-3 could now pump water to surface and no longer sent water to Mine B-1 via Mine B-2.

A functioning REMS system was installed on Mine B-3, but automatic control was not allowed by mine personnel. A load shift project was, however, implemented manually on Mine B-3. The installation of stope isolation valves on Mine B-3 did not take place due to high volumes of fissure water within Mine B-3 and the fact that only drinking water was sent down Mine B-3.

3.3.5 Step 5 – Results quantification

During the implementation of the proposed reconfigurations to Mines B-1, B-2 and B-3, the progress was monitored, and the results recorded. The volume distributions and flow rates attained by each pump station on all three mines was recorded for several months after implementation. Table 18 displays a comparison of the recorded results and simulation results for Case Study B, Mines B-1, B-2 and B-3, after the implementation of the proposed reconfigurations took place.

Table 18: Results comparison of reconfiguration validation simulation to recorded values for Case Study A after implementation of proposed reconfiguration

Flow	**Flow rate** (L/s)	**Simulated average volumes** (ML/day)	**Recorded average volumes** (ML/day)	**Error margin** (%)
Mine B-3 proposed reconfigurations simulation results:				
Mine B-3: 30L to surface	86	1	1.2	20
Mine B-3: 56L to 30L	90	1.61	1.5	6.8
Mine B-3: 69L to 56L	96	1.79	1.69	5.5
Mines B-1 and B-2 proposed reconfigurations simulation results:				
Mine B-1: 30L to surface	85	4	3.8	5
Mine B-1: 53L to 30L	120	3.9	3.7	5.1
Mine B-1: 69L to 56L	100	1.5	1.4	6.7
Mine B-2: 52L to B-1 53L	43	1.83	1.6	12.5

As seen in Table 18, the simulated and actual results for flows post-reconfiguration implementation correspond within a close error margin with one exception, this being the flow from Mine B-3's 30L to surface. The actual volumes pumped to surface from Mine B-3's 30L outperformed the simulated results by 20 %. This was good news as additional water was removed from the mine system.

A comparison of the actual measured results for Case Study B, pre- and post-reconfiguration, is displayed within in Table 19. Here the percentage changes brought about by implementing the proposed reconfiguration changes, as discussed in Section 3.3.2, can be seen.

Table 19: Case Study B, comparison of actual results pre- and post-reconfiguration

Flow	**Average volumes distributed** (ML/day)		**Change**
	Pre-reconfiguration	**Post -reconfiguration**	
Mine B-3 proposed reconfigurations:			
Mine B-3: 30L to surface	None	1.2	Implemented
Mine B-3: 56L to 30L	1.6	1.5	+ 6.25 %
Mine B-3: 69L to 56L	1.76	1.69	- 3.78 %
Mines B-1 and B-2 proposed reconfigurations:			
Mine B-1: 30L to surface	5.54	3.8	- 31.4 %
Mine B-1: 53L to 30L	5.49	3.7	- 32.6 %
Mine B-1: 69L to 53L	1.52	1.4	- 7.9 %
Mine B-2: 52L to B-1 53L	2.81	1.6	- 43 %

As displayed in Table 19, implementation of the proposed reconfigurations on Mines B-1, B-2 and B-3 resulted in an additional 1.2 ML/day of water being pumped to surface from Mine B-3. The removal of water from Mine B-3, before flowing through Mine B-2 and B-1, resulted in a 43 % reduction in water volumes flowing through Mine B-2 52L. It also resulted in a 32.6 % reduction in water volumes pumped to Mine B-1 30L from 53L. Most important of all, the volumes of water that had to be pumped to surface from Mine B-1 30L were reduced by 31.4 %.

The proposed load shift projects were implemented successfully on Mines B-1 and B-3. Mine B-1 load shift was automatically controlled by REMS, whilst Mine B-3 had the load shift implemented manually. After the first year of project implementation Mine B-1 attained a saving of R 325,000. This underperformance in cost saving was the result of poor co-operation from the pump attendants at Mine B-1 as, they frequently locked pumps out of automatic control mode, along with technical difficulties. Mine B-3 saved a total of R 959,000 within the first year of load shift implementation. These were good results from Mine B-3's side.

Daily feedback reports are sent to the relevant mine personnel to display the complete water balances for the previous day along with performances and efficiencies of pumps and flow rates to certain areas. The implemented load shift projects on Mines B-1 and B-2 perform well when pumps are left in automatic control for REMS to operate. It was frequently found that pump attendants left pumps in lock-out. When this happens pumps cannot be controlled automatically, and the load shift projects must either be implemented manually or do not perform at all.

3.4 Conclusion

Implementation of the developed five-step-method can be relevant to most deep-level mines as the inflow of fissure and flood water into a deep-level mine is a very common occurrence within the mining industry. With increased mining depths comes an increase in water demand and fissure water inflows. A likely occurrence within older deep-level mines is that the initial design of the WRS becomes outdated due to increasing mining depths. Reconfiguration of the WRS can thus become a necessity.

CHAPTER 4 CONCLUSION

Chapter 4 is the final conclusion of the study along with recommendations of future work.

4.1 Summary and conclusions

The gold mining industry of South Africa consists of several gold mining groups that have various mine shafts sunk along the gold reef of the mined area. These shafts are frequently connected through a vast network of underground tunnels. Connecting tunnels bring about the risk of flooding as fissure and flood water can now freely flow from one shaft to another.

Along with the risk of flooding, fissure water can have a large negative impact on the refrigeration and ventilation systems of a mine due to humidification of refrigerated areas and heat transfer to the environment [39]. Additional fissure and flood water added to a mine can also have a negative impact on the WRS as additional water volume must permanently be removed from the mine.

The deepening of gold mines over time causes the original systems put in place for water reticulation, refrigeration and ventilation to become ineffective. Inevitably this can force mines to implement large-scale system reconfigurations on these systems to keep underground working conditions safe and bearable. Alternatively, flooding water must be kept from active mines through the implementation of secondary pumping systems.

The objective of this study was to focus on possible solutions for the reconfiguration of deep-level mine WRSs to compensate for excess water. The main objective was achieved through four steps. These four steps are listed below along with a description of how each was achieved.

1. **Problem area identification within the mine WRSs.**

   This was achieved firstly by gaining familiarity with the WRS of the relevant mine/s through extensive visits to the mine, performing underground audits, speaking with experienced mine personnel and by working from layouts and blueprints of the mine and WRS.

   Once familiarity was gained, all the problems within the mine WRS were identified. These problems involved improper water distribution, wastages of water, insufficient removal of water from the mine and additional water volumes added to the mine. The identified problems were then reported and discussed with the relevant mine personnel.

2. **Development and validation of a solution on how to reconfigure the mine WRS for excess water management.**

With the identified problems in mind, solutions were developed to firstly reconfigure the mine WRS to solve the identified problems. These reconfigurations could either be applied to the mine's WRS and/or the surroundings of the mine (i.e. neighbouring shafts and interconnecting tunnels). Developed reconfigurations depended on the source of the identified problems. The proposed reconfiguration solution was analysed and discussed with the relevant mine personnel to determine if it would be feasible.

Secondly, ways in which to improve the operation of the mine's WRS, after implementation of the reconfiguration solution, were developed. These were also analysed and discussed with the relevant mine personnel in order to determine feasibility.

The proposed system reconfigurations and improvements then had to be validated before implementation could commence. Validation of the proposed reconfigurations was done in the form of three simulations. Firstly, a baseline simulation was created to mimic the system before reconfigurations were implemented.

With the baseline simulation refined and proved accurate to the actual measurements taken on the mine, the proposed reconfiguration solution was simulated. Once the proposed reconfiguration simulation was refined, the proposed improvements to the reconfigured system were simulated. The estimated results were reported and presented to the relevant mine personnel. The simulations were performed using Real-time Energy Management System (REMS).

3. **Implement the reconfigured system solution.**
   The proposed reconfigurations were physically implemented on the mine/s. The progress of the implementation was monitored, and feedback meetings held with the relevant mine personnel. During and after implementation, the results attained from the implemented reconfigurations were quantified and compared with the estimated simulation results.

4. **Improve the reconfigured system in terms of demand optimisation, energy cost optimisation and pump automation.**
   The system improvements were identified and simulated with the proposed reconfigurations. These proposed improvements were implemented after system reconfiguration took place. Attained results were monitored and compared with the estimated results for quantification purposes.

This study made use of the findings of two case studies. The case studies can be summarised as follows:

Case Study A took place on Mine A and involved the reconfiguration of Mine A WRS to compensate for excess fissure water within Mine A.

Case Study B took place on Mines B-1, B-2 and B-3 that form part of a network of 6 interconnected mine shafts. The WRS of Mines B-2 and B-3 was reconfigured to prevent excess water from flowing to Mine B-1. The operations of Mine B-1 and B-2 WRSs were improved after reconfiguration.

In order to address the study objectives, a five-step method was developed that could be applied to most deep-level mines in order to manage excess water within the mine and possibly improve the WRS after implementation. The five steps developed were:

1. Data acquisition of mine WRS and problem identification
2. Development of solution
3. Validation of solution
4. Implementation of reconfiguration and system improvement
5. Results quantification

The developed five-step method for mine WRS reconfiguration was successfully implemented within the two case studies. Differences between the two case studies allowed for the implementation of the five-step method to take place on both an isolated mine and a large network of 6 interconnected mine shafts. After implementation of the five steps the projects were monitored for several months to quantify the results of the implemented reconfigurations.

Within Case Study A the proposed reconfigurations were implemented successfully onto Mine A. The result proved that Mine A could remove a significant volume of 0.7 ML, or 29 %, of additional excess water per day. Final recorded results of Mine A outperformed what was predicted with the validation simulation by an additional 0.46 ML of water removed per day. This meant that reconfigurations performed 17.4 % better than expected. The proposed system improvements after implementation of the reconfigurations included an automatically controlled load shift project of the de-watering pumps and fridge plants of Mine A. This was not implemented in time for the purpose of this study.

The implementation of the proposed reconfiguration solution for Case Study B was completed successfully. Mine B-3 was converted to a de-watering shaft that pumped water to surface. This eliminated the flow of excess water to Mine B-2 from Mine B-3 and reduced the amount of excess water pumped to surface by Mine B-1. After reconfiguration implementation, Mine B-1 pumped 5 % more water to surface per day than was initially estimated. The overall amount of water pumped to surface by Mine B-1 was reduced by a significant amount of 1.74 ML of water per day. This was equal to a daily flow reduction of 31.4 % and allowed better performance of Mine B-1 WRS.

The proposed improvements of Mines B-1, B-2 and B-3 after system reconfiguration were to install a REMS system to allow for fully automatic control and monitoring of WRS equipment. The automated system could then be used to implement an automatic load shift project. This realised for Mines B-1 and B-2 (53L pumps). A load shift project was implemented manually on Mine B-3 as fully automatic control was not given to the installed REMS system on Mine B-3. After the first year of load shift implementation, Mine B-1 attained a saving of R 325,000. Mine B-3 saved a total of R 959,000 within the first year of load shift implementation.

The developed five-step method is a generic solution for the management of excess water within deep-level mines and can be applied to any deep-level mine if needed. This could be of value to the mining industry as the occurrence of excessive fissure and flood water within deep-level mines is a common occurrence.

4.2 Recommendations for future work

As mentioned in Section 1.4 of this study, fissure water may have a negative impact on the temperatures of an underground working environment due to extensive moisture in refrigerated areas, humidification of ambient air temperatures and heat transfer from fissure water into the environment [39].

Fissure water temperatures, in South African mines, can increase by a temperature gradient of 1.7 ^{o}C / 100 m, reaching temperatures of 50 ^{o}C at depths of 2,685 m [39]. The refrigeration system is then negatively impacted because warmer water must be cooled, and cooling is negatively impacted as working areas are heated up.

Suggested future studies are thus the following:

- A study of the influence of excessive water or fissure water on the refrigeration systems of deep-level mines and possible solutions as to the improvement of found problems.

- A study of the influence of excessive water or fissure water on the ventilation system of deep-level mines and possible solutions as to the improvement of found problems.

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APPENDIX A: ESKOM PEAK PERIODS

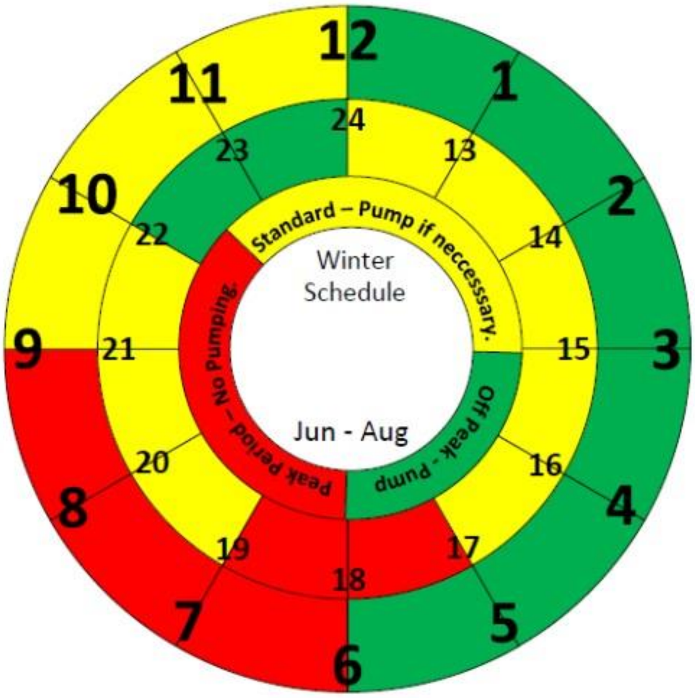

Figure 48: Eskom Winter Megaflex schedule

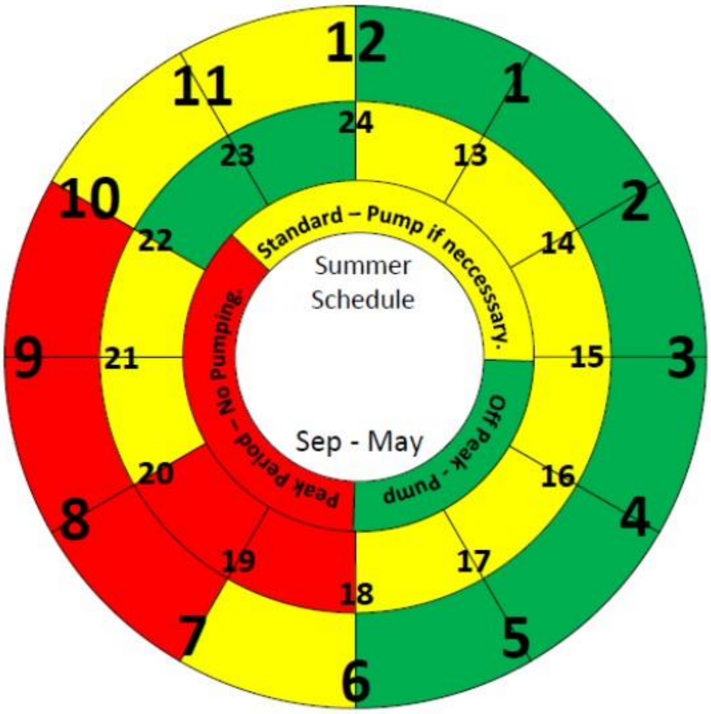

Figure 49: Eskom summer Megaflex schedule