

A simulation-based horizontal water transport management strategy in deep-level mines

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ABSTRACT

Title: A simulation-based horizontal water transport management strategy in deep-level mines

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Dewatering and water transfer pumping are two of the main consumers of electricity in the South African mining industry. In the ever-unstable electricity supply regime, it is important to consider **all** possible angles to a specific system to ensure maximum possible energy savings and efficiency (electrical, water consumption, etc.)

This thesis focuses on pumping systems which were previously excluded in improvement techniques. An opportunity was identified to allocate a scientifically derived water management strategy for horizontal water pumping (which are excluded in improvement strategy literature) in deep-level mines. Production level systems will be primarily analysed, and conclusions made accordingly. This will be achieved by obtaining improved process configuration through integrated simulation for current and future mining activities. Preliminary audits were done to ensure the system simulation reflected accurate actual values. It was found that no predetermined analysis regarding water demand was done upon installation of bullnose spindle pumps situated at cross-cut entrances. Normal procedure entailed the installation of one uniform pump size on every cross-cut's entrance (bullnose), regardless of the actual water demand in the section. System simulations were done for the currently installed systems based on updated return water flows on each level. Additional simulations were done to establish maximum demand limits for the currently installed system and new proposed pumps. Results revealed that the installed spindle pump system is over specified for the application. Scope, therefore, exists to exchange the majority of the bullnose spindle pumps with a smaller, better suited pump, based on current and future water demands. Implementation will result in an annual electrical cost reduction of 54% spent on horizontal water pumping.

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LIST OF UNITS

Unit	Name	Description
m^3	Cubic meter	Volume
m^3/s	Cubic meter per second	Volumetric flow rate
$^{\circ}C$	Celsius	Temperature
GWh	Gigawatt-hour	Energy
kg/m^3	Kilogram per cubic meter	Density
kg/s	Kilogram per second	Mass flow rate
kL	Kilo Litre	Volume
kL/tonne	Kilo Litre per tonne	Water intensity
kPa	Kilopascal	Pressure
kW	Kilowatt	Power
kWh	Kilowatt-hour	Energy
L	Litre	Volume
L/s	Litre per second	Flow rate
m	Meter	Head, depth, or length
m/s	Meters per second	Velocity
m/s^2	Meters per second squared	Acceleration
m^2	Meters squared	Area
ML	Mega Litre	Volume
mm	Millimeter	Length
MW	Megawatt	Power

MWh	Megawatt-hour	Energy
Pa	Pascal	Pressure
t	Tonne	Weight
Δh	Head difference	Pressure difference

LIST OF SYMBOLS

Symbol	Name	SI Unit
H_S	Static head	m (meter)
H_D	Dynamic head	m (meter)
P_{RT}	Pressure of receiving tank	m (meter, 1 st principle conversion)
P_{RES}	Pressure of surface reservoir	m (meter, 1 st principle conversion)
K	System loss coefficient	dimensionless
v	Fluid velocity	m/s (meters per second)
g	Gravitational acceleration	m/s ² (meters per second ²)
Q	Volumetric flow rate through pipes	m ³ /s (cubic meters per second)
A	Pipe cross-sectional area	m ² (meters ²)
$K_{Fittings}$	Pipe fittings loss coefficient	dimensionless
K_{pipe}	Pipe length loss coefficient	dimensionless
f	Pipe friction coefficient	dimensionless
L	Pipe length	m (meter)
D	Pipe diameter (outer)	m (meter)
k	Roughness factor	m (meter)
Re	Reynolds number	dimensionless
D_h	Hydraulic diameter	m (meter)
ν	Kinematic viscosity of water	m ² /s (meters ² /second)
ΔP	Differential pressure across pump	Pascal (Pa)

ρ	Fluid density	kg/m ³ (kilogram per cubic meter)
Δh	Vertical pumping distance	m (meter)
n	Similar size pumps sample size	dimensionless
N	Similar size pumps total quantity	dimensionless
t	Degree of probability	dimensionless
Δx	Sample mean	dimensionless
σ	Standard deviation from sample mean	Dimensionless

ABBREVIATIONS

Abbreviation	Description
BAC	Bulk Air Cooler
3CPFS	Three-Pipe Water Pumping System
BAU	Business-As-Usual
BEP	Best Operating Point
CAPEX	Capital Expenditure
CT	Current Transmitter
DSM	Demand Side Management
DXF	Digital Exchange Format
FTHX	Finned Tube Heat Exchangers
FY	Financial Year
LOM	Life-Of-Mine
MTB	Management Toolbox
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
POET	Pumping Operation Equipment Technology
PRV	Pressure Reducing Valve
PT	Potential Transformer
PTB	Process Toolbox
REMS	Real-time Energy Management System
S&M	Simulation and Model

SCADA	Supervisory Control and Data Acquisition
TBD	To Be Determined
TOU	Time-Of-Use
UG	Underground
UPVC	Unplasticized Polyvinyl Chloride
VT	Voltage Transmitter
XC	Cross-cut

GLOSSARY

Terminology	Description
<i>Annex holes</i>	A centralised water drainage hole where all service water on a level converges
<i>Booster pumps</i>	Pumps used within a water distribution network to add pressure to the water system
<i>Bullnose spindle pumps</i>	Submersible pumps situated at the entrance of a XC
<i>Chilled water dam</i>	A dam specifically constructed for the sole purpose of storing refrigerated water and ice until distribution
<i>Cooling cars</i>	Spot coolers placed in sections to cool down areas where temperatures are high
<i>Cross-cut</i>	Horizontal mine workings built parallel to the main working or haulage and are used for the disposal of rock resulting from cutting or drilling and for ventilation purposes
<i>Dynamic adaptability</i>	The ability to autonomously assess system criteria and propose corresponding remedial actions
<i>Fissure water</i>	Groundwater originating as seepage through sedimentary rock
<i>Footwalls</i>	Water drains constructed on the cross-cut or haulage floors
<i>Gravity feed</i>	Services or entities distributed to sections using height rather than pumps
<i>Haulage</i>	Mining tunnel used for locomotive travel, equipment and human transport
<i>Horizontal water transport systems</i>	Pumps used to distribute water on a single level rather than vertically between levels
<i>Multistage pump</i>	A pump containing two or more impellers of the same or different size

<i>Ore</i>	A naturally occurring mineral or rock from which a valuable or useful substance, especially a metal, can be extracted at a reasonable cost
<i>Pre-cooling</i>	Removal of field heat from water prior to entering the refrigeration system
<i>Pressure reducing valves</i>	A normally open valve limiting the pressure of a system to less than maximum limits
<i>Production level</i>	A numerically determined section below surface where mining activities take place
<i>Spindle pump</i>	Semi-submerged arrangement pumps used for liquid transfer
<i>Stope</i>	Narrow working mine area accessible through cross-cuts
<i>Sump</i>	A low dam-like space collecting undesirable liquids
<i>Temperature gradient</i>	Rate of change of temperature relating to a given measurement (height)
<i>Three-pipe water pumping system</i>	An energy recovery water system using incoming chilled water to displace outgoing warm water
<i>U-tube water system</i>	A water distribution and return system operating solely on pressure within the system
<i>Water reticulation systems</i>	A distribution system used on deep-level mines to distribute water to required sections

STUDY OUTLINE

Chapter 1: Introduction to water reticulation systems and improvement strategies in deep-level mines

Chapter 1 provides an insight into the operation of water reticulation systems on deep-level mines. Previous research conducted on water systems management and improvement is documented and explained in a critical literature review. From the gaps identified within the literature, a clear problem is formulated and addressed through the novel contributions of this study.

Chapter 2: Development of strategy

In Chapter 2, a new detailed simulation and model approach methodology to horizontal water transport management is developed, with the main objective of addressing the shortcomings listed in Chapter 1. The strategy will be developed in steps which aims to ensure sustainability and future replication is possible. The simulation-based methodology is explained comprehensively in this chapter to ensure all bases are covered should the method be adapted to various scenarios.

Chapter 3: Results and verification

In Chapter 3, a method is applied on selected case studies. The results from the applied methodology are thoroughly discussed, evaluated and compared to the derived simulation results. A conclusion will be drawn from the comparison to determine whether the implemented suggestions provide solutions to the existing problems that were identified in Chapter 1.

Chapter 4: Conclusion

The final Chapter concludes the findings and outcomes of the study. The final conclusion on the success of the applied method is discussed, evaluated and concludes whether the novel contributions of the study are met through the derived objectives. Finally, recommendations for further studies are provided.

1

CHAPTER 1

INTRODUCTION TO WATER RETICULATION SYSTEMS AND IMPROVEMENT STRATEGIES IN DEEP-LEVEL MINES

“There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.”

~ Niccolo Machiavelli

1 INTRODUCTION TO WATER RETICULATION SYSTEMS AND IMPROVEMENT STRATEGIES IN DEEP-LEVEL MINES

1.1 Preamble

Electricity tariffs in South Africa have increased significantly in the past two decades. This has resulted in more focus being placed on system consumption improvement [1]. Figure 1 shows the increase in electricity tariffs since 1994 [1].

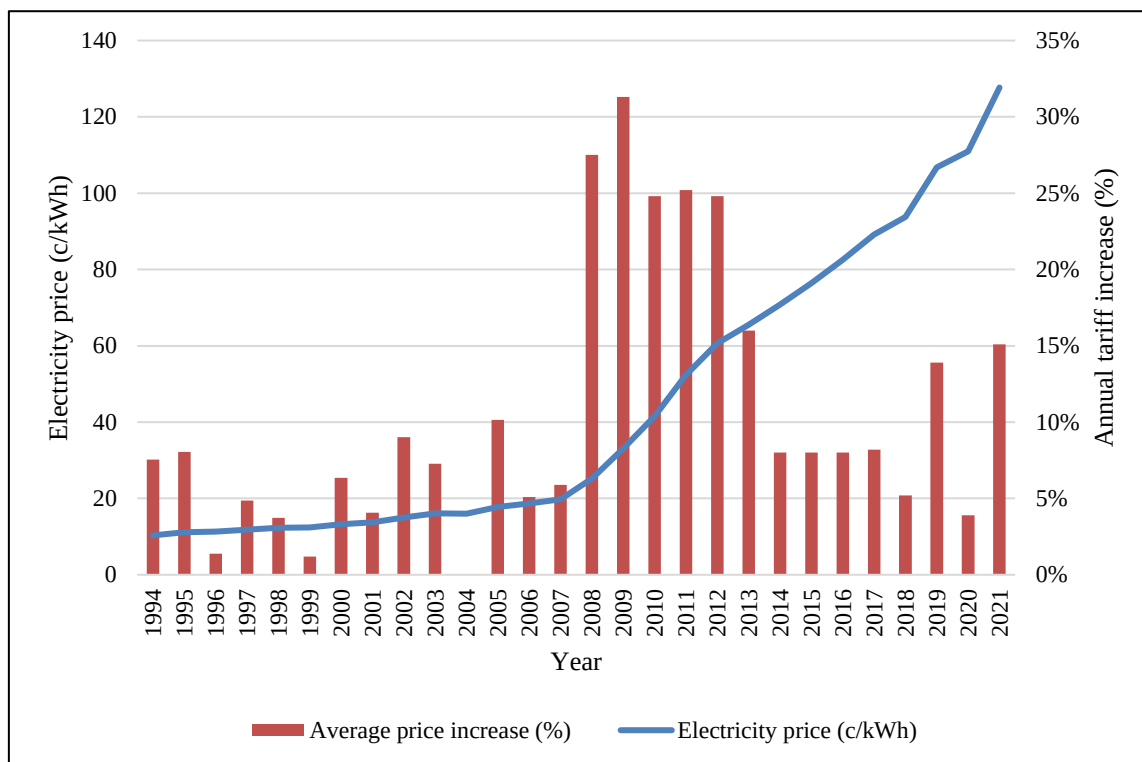


Figure 1: Annual Eskom tariff increase (1994 - 2021)

Tariffs have increased significantly since 2008 which earmarked the start of a major economic crisis at the state-owned entity. The industrial sector is a major contributor to South Africa's total energy consumption, contributing to 51% of the total energy demand [2]. The volatile electricity price provided motivation to establish methods to minimise electricity consumption and achieve increased process efficiency to the furthest extent. The notable increase also highlights the importance of proper energy management techniques across **all** energy-consuming systems on industrial operations to assist with South Africa's ailing electrical grid stability.

1.2 Deep-level mine water reticulation systems

Deep-level mines in South Africa use process water in large quantities for various applications on surface and underground [3]. Underground applications mainly include [3], [4]:

- Cooling and dust suppression,
- drilling and mining activities (ore and haulage cleaning, sweeping of ore etc.),
- energy recovery,
- backfilling, and
- water jet cleaning.

The large underground water demand (>40ML daily) in deep-level mines adds significant complexity to the construction and operation of the distribution systems [5]. End-users are located on different mining levels which adds to distribution challenges throughout the underground mining complex. Figure 2 is a visual representation of an underground process water reticulation network used in large deep-level mines.

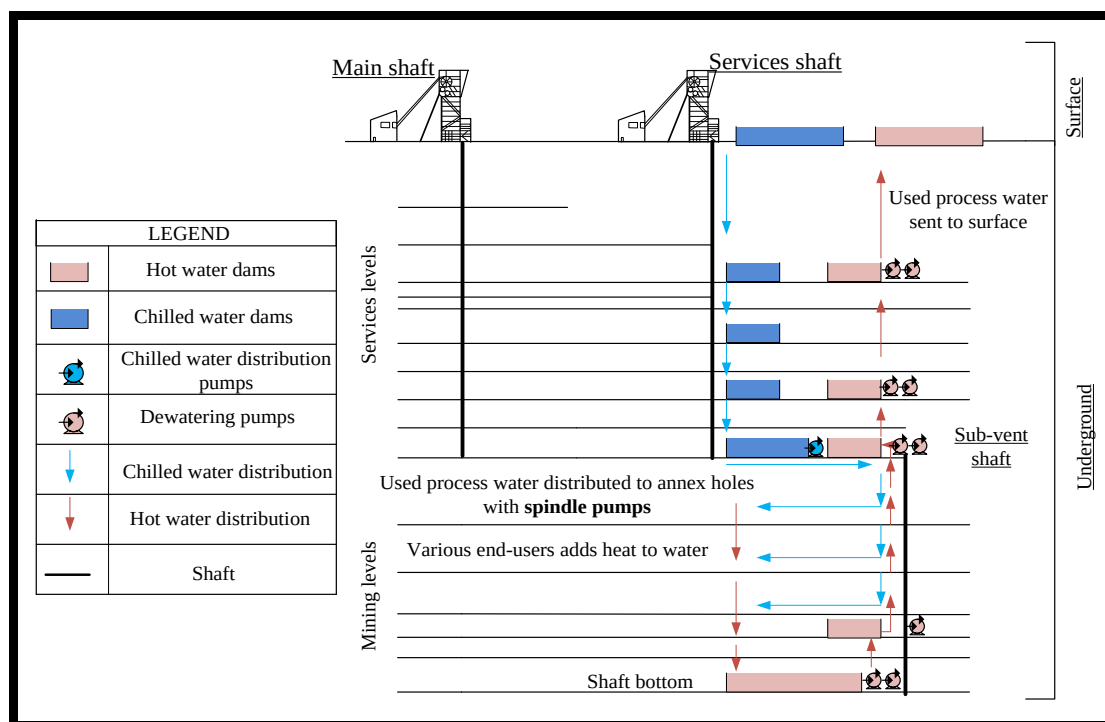


Figure 2: Water reticulation representation of deep-level mines

Surface water holding dams distribute water to pre-cooling systems before it enters the refrigeration cycle. Water is distributed from surface after it exits the refrigeration system [6]. For deeper mines, there are dams strategically situated on descending levels as it moves through the shaft column [6]. This ensures there is enough storage capacity for water being sent underground and reduces water pressure. As the water moves down from one chilled water dam to the next on the various levels, it usually accumulates at a central location with a larger dam capacity and is distributed to the various mining levels. Figure 3 shows a simplified flow diagram of deep-level mines' water reticulation and highlights the areas of focus for this thesis.

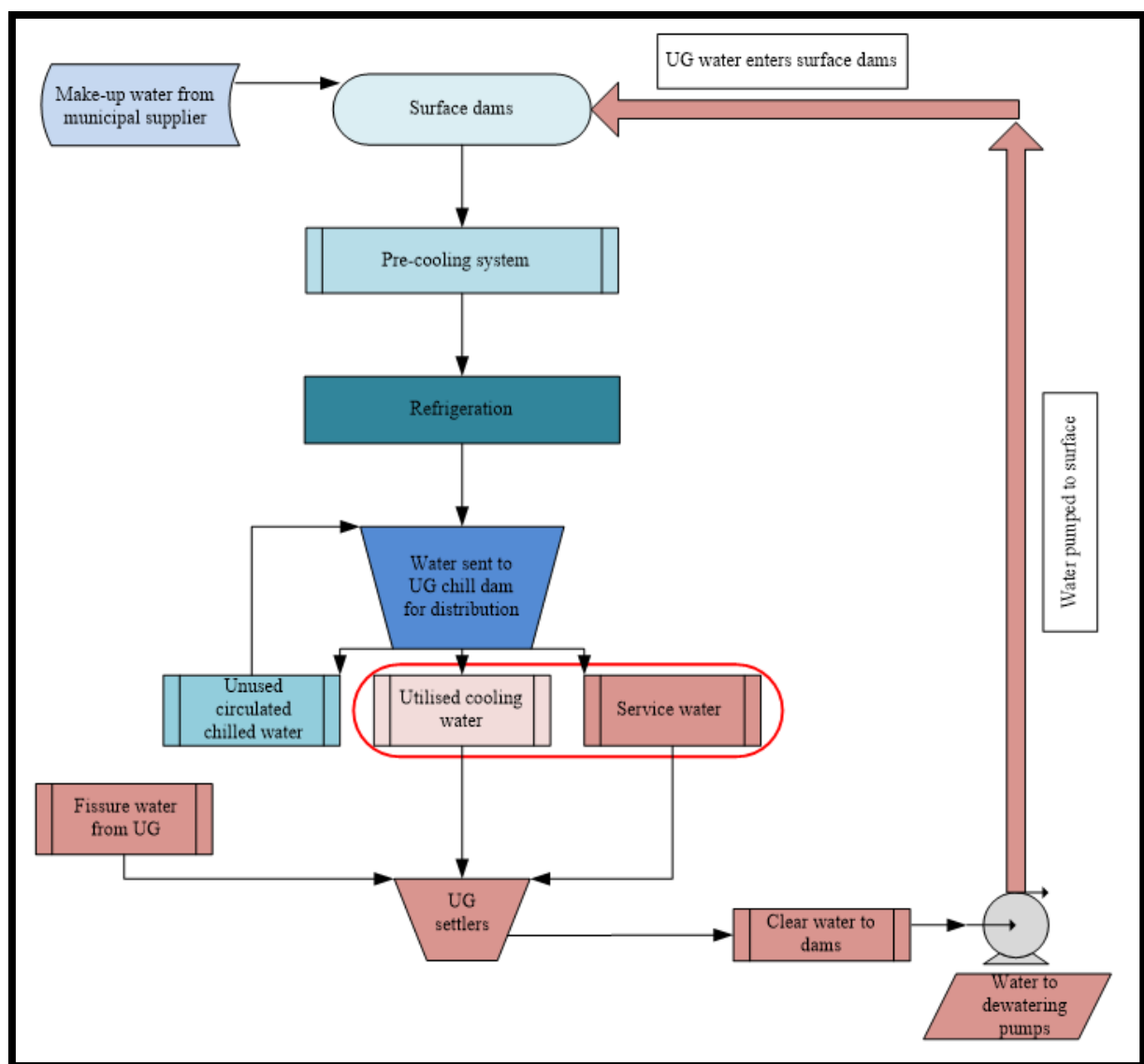


Figure 3: Simplified flow diagram of deep-level mine water reticulation

Most mines feed the production levels through gravity feed and make use of booster pumps situated on the production levels to ensure the chilled water reaches the various end-users at a sufficient pressure [6] [7]. The most common underground chilled water end-users include [4], [6]:

- Cooling cars,
- Bulk Air Coolers (BACs),
- winders,
- drills,
- face cleaning, and
- fridge plants.

Chilled water return systems are used in deep-level mines to minimise the pumping cost to surface. This principle comprises returning chilled water which retained low enough temperatures (unused by mining activities) to a central accumulation point, underground or on surface, without re-entering the refrigeration cycle [8], [9], [10]. Unused chilled water is transported from the various production levels, the predominant users of chilled water, either through a U-tube water transport system or centrifugal pumps [8]. A representation of an underground chilled water return system is shown in Figure 4.

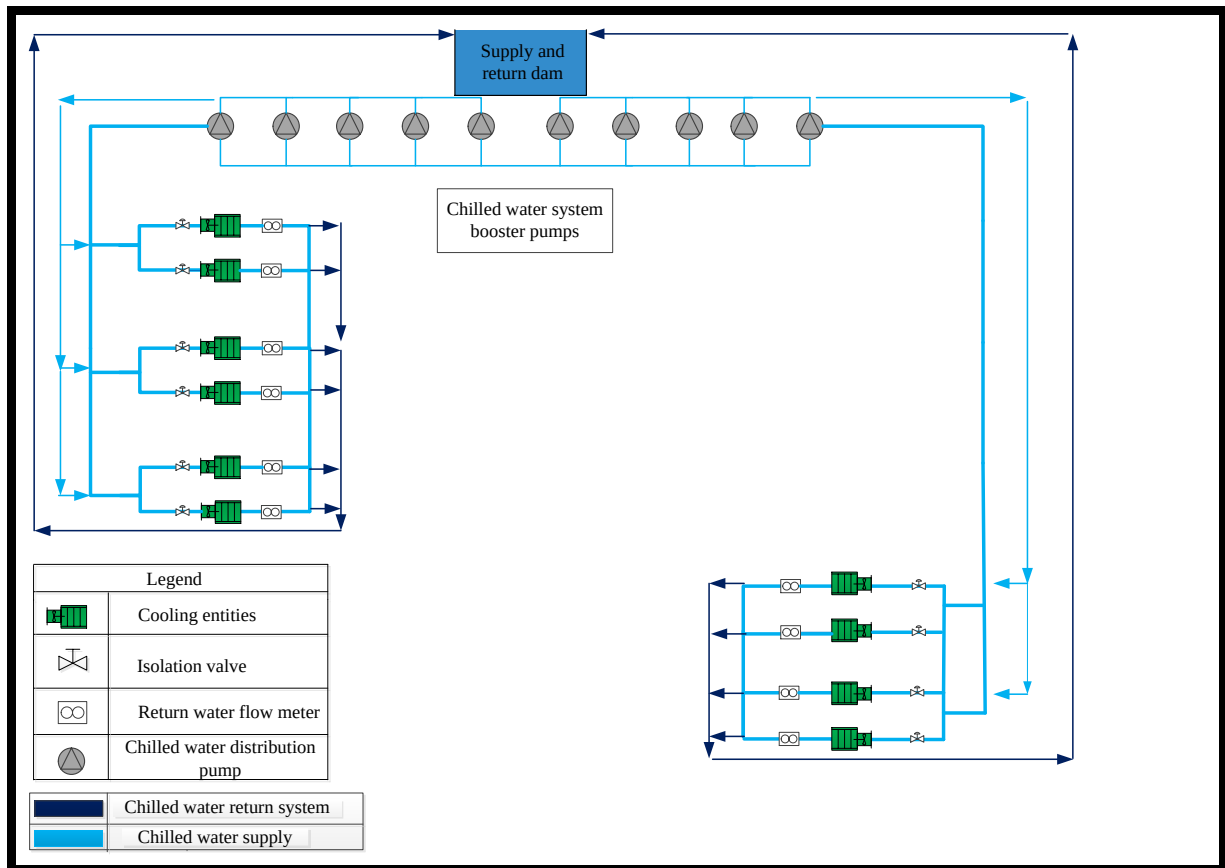


Figure 4: Return water distribution and return principle representation in deep-level mines

Chilled water is distributed from an accumulation dam towards the production levels' mining blocks. Chilled water is first used for cooling entities after which a portion of water in each cross-cut (XC) is sent to the stopes according to demand required at specific hours of the day. The portion of water not sent to the stopes returns via the chilled water return pipe which takes strain off the fridge plants due to the return water not needing to circulate through the refrigeration system repeatedly. Large quantities of returning chilled water mitigates unnecessary pumping of water back to surface to re-enter the refrigeration system.

Water sent to the stopes (used for mining activities as mentioned on Page 3 line 5) does not remain in the chilled water system. The water used for the various specified mentioned mining activities adds significant heat to the water and would render a large temperature gradient should it return via the chilled water system.

Used mining water drains from the stopes through means of footwalls and service water return pipes.

Water accumulated along the footwall drive of a XC is transported through a series of submersible spindle pumps towards the front of the section where the return service water is dumped into a sump. Each XC section contains a sump at the entrance where the service water accumulates and is pumped into the main service water return line suspended in the main haulage of the level [11]. The entrance spindle pump is referred to as the bullnose pump. Figure 5 is a visual top-view representation of the spindle pump return water system currently in use at the active XCs on deep-level gold mines [11].

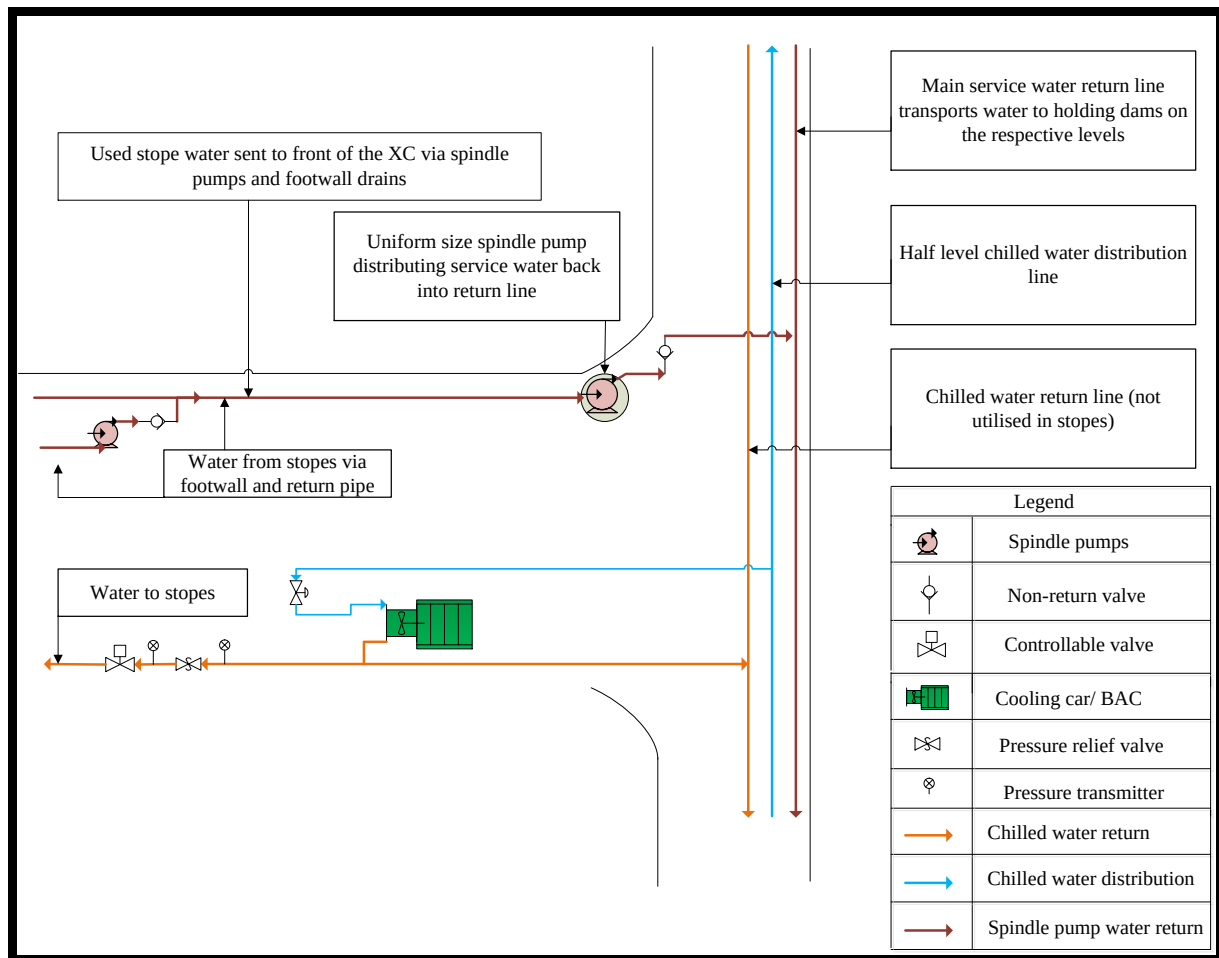


Figure 5: Bullnose spindle pump top view XC configuration

After the water is syphoned through an intricate system of annex holes or conventional level holding dams, it enters an underground settler system to ensure all debris and mud particles are filtered before it enters the dewatering system [12]. Figure 6 is a visual representation of an underground settler system [13].

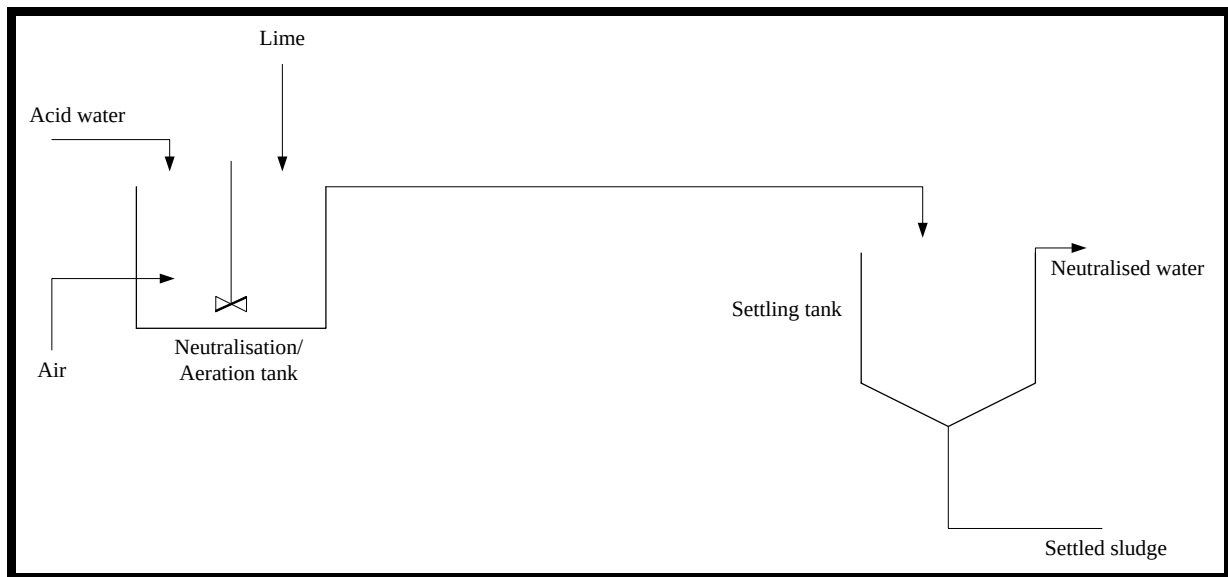


Figure 6: Simplified diagram of underground settler operation

The overflow of the settlers is channelled to the clear water underground dams where the water accumulates before entering a complex underground dewatering system [14]. The underground dewatering system is an essential part of the mining operation due to its function of flooding prevention and shaft water balance regulation [12]. Process water sent down the shaft is re-used for the refrigeration process on surface once it exits the dewatering system. The dewatering system works on a cascading principle where water is transferred from one reservoir to the next until it ultimately reaches the surface holding area [15]. Each reservoir consists of a set of dewatering multistage pumps varying in size. Some dewatering systems are especially complex and need to be constantly monitored to prevent flooding or pump failure. Figure 7 indicates a representation of a **complex** dewatering system following a cascading principle monitored by a Real-time Energy Management System (REMS) [16].

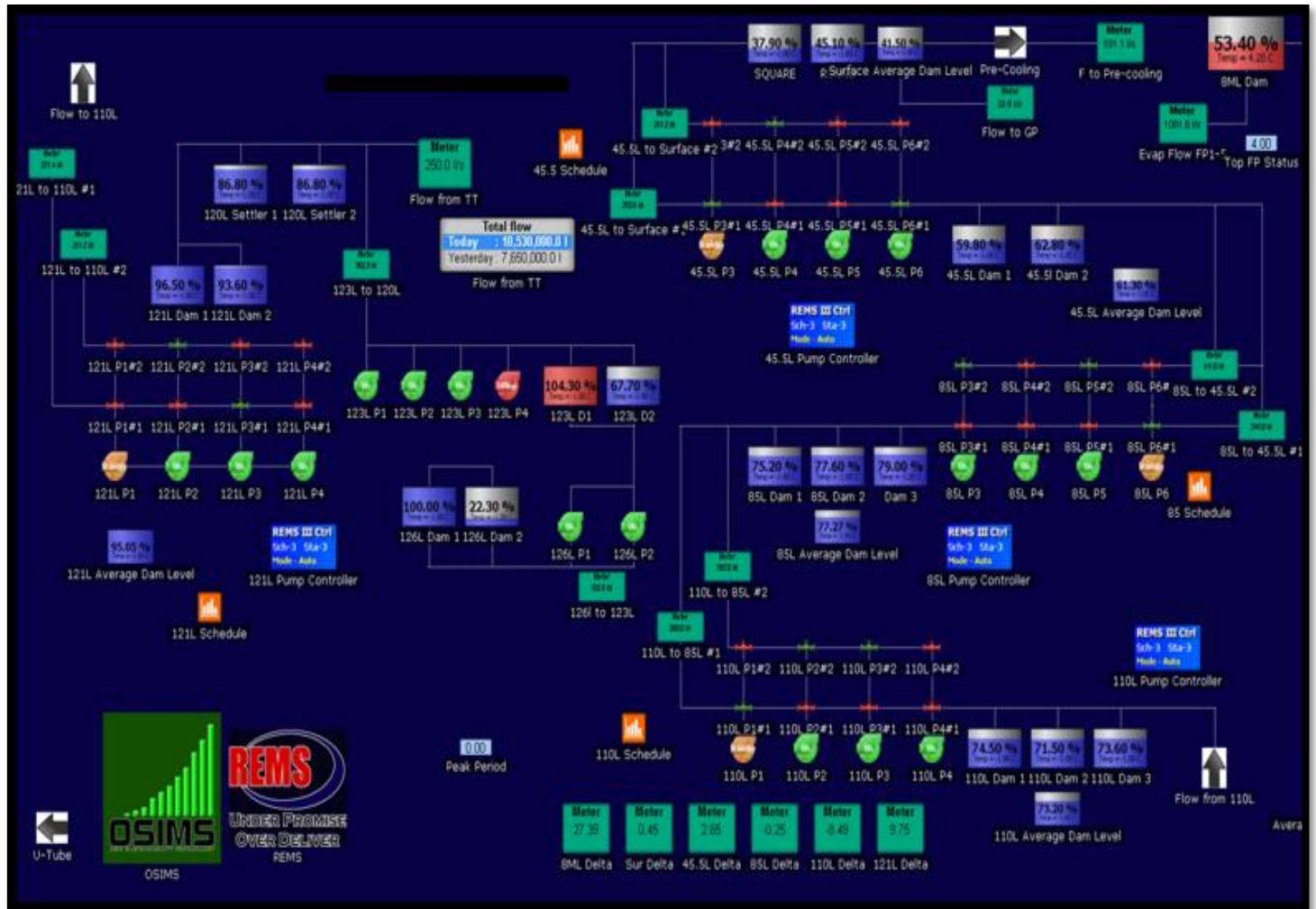


Figure 7: Real-time Energy management System for water distribution networks

Deep-level mines strive to re-use as much water as possible, attempt to mostly operate as a closed loop system, and only replenish water from a municipal supplier if a notable water decrease within the system is noted [12], [17]. Water shifted from the underground environment exits the dewatering system into a surface chill or holding dam before entering an intermediate pre-cooling process prior to re-entering the refrigeration system [18]. Demand Side Management (DSM) and system modelling are some of the methodologies developed for electrical cost savings for larger deep-level mine dewatering systems [6], [14], [15], [19]. This study will focus on **the horizontal transport management of water** i.e., focusing on the improvement of the current system transporting service- and utilised chilled water toward the annex holes/holding dams on the various mining levels of a deep-level mine. To accurately determine the electrical cost saving of a proposed improvement strategy, it is important to establish the main contributors toward the average pumping electrical load.

1.3 Water reticulation infrastructure and energy consumption

It is important to be aware of the existing infrastructure's operational expenditure (OPEX) to pinpoint exactly where improvements are needed. Water reticulation infrastructure mainly consists of pumps for dewatering and distribution purposes.

Dewatering pumps

The dewatering pumps on a mine are usually the largest pumps within the system due to the pump impeller shaft work exerted to pump water extensive vertical distances upward out of the shaft (>1000m vertically) [7], [20]. System consumption monitoring is widely used on deep-level mines to properly allocate electricity consumption to all the various end-users. The dewatering system contributes an average of 15 - 25% of a deep-level mines' total electrical load and is, therefore, one of the most monitored systems on mines [7], [21].

Figure 8 is a visual representation of a typical multistage pump used primarily for dewatering purposes from underground towards surface [22] Multistage pumps vary in size according to the level of mining operations and vertical distance between accumulation dams.



Figure 8: Multistage pump used for industrial dewatering

As seen in Figure 7, the multistage pumps are strategically placed on ascending levels where chilled and hot water dams are present. The installed pumps are **specified** and **designed** according to the head they need to overcome and the volumetric flow rate required to pump. Equation 1 is used to determine the operating pressure of a pumping system, which in turn forms part of the fundamentals of pump design [23].

Equation 1: Operating pressure of a pumping system

$$H_{total} = H_s + H_D + ((P_{RT} \times 0.102) - (P_{RES} \times 0.102))$$

Where:

H_s = Static head (m). Physical elevation change between the surface of the reservoir and point of discharge in the receiving tank [23].

H_D = Dynamic head (m). This is generated as a result of friction within the system [23].

P_{RT} = Pressure on the surface of the water in the receiving tank (m). **Note: 1 kPa = 0.102 m.**
For first principles to apply, all units used must be the same.

P_{RES} = Pressure on the surface of the water in the reservoir (m).

Dewatering pumps situated on ascending levels in large deep-level mines are the primary focus of improved techniques due to the large size of the pumps required to pump water out of the mines [12], [20], [24]. Due to the dynamic nature of a gold mining operation, energy costs and consumption vary throughout the year. Various factors can influence an increased or decreased pumping consumption such as fissure water ingress, water leaks, misuse of service and potable water, cooling demand increase, and increased mining activity [4], [6], [25]. Figure 9 shows the average pumping energy cost contribution of dewatering and distribution pumps in deep-level mines [5], [26], [27].

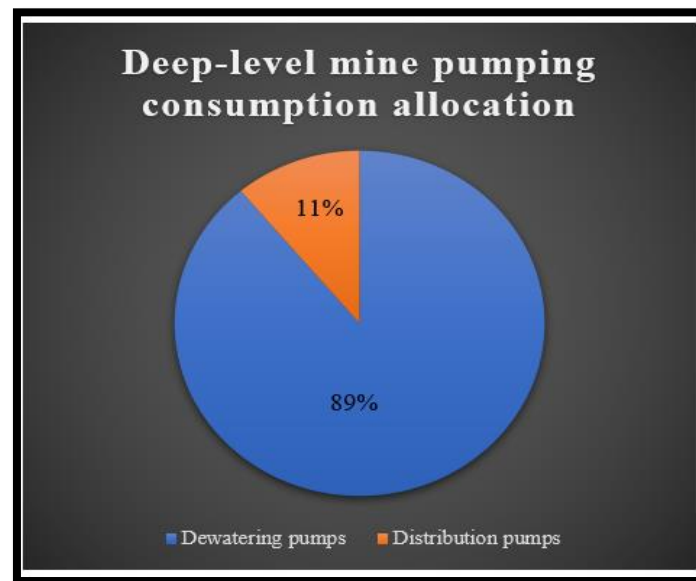


Figure 9: Deep-level mine pumping energy consumption cost

Dewatering is an essential part of the total mining operation because shaft flooding and decreased cooling water availability would halt the mining activities due to safety concerns [28], [29]. Distribution pumps, although a significantly smaller contributor to the overall pumping consumption, can reduce energy consumption on deep-level mines if proper management strategies are applied.

Distribution pumps

Distribution pumps can be classified into two categories [30]:

- Interlevel distribution pumps: Distribution of water between two levels of different depths below collar (vertical water transport).
- Intralevel distribution pumps: Distribution of water on the same level or depth below collar (horizontal water transport).

Interlevel distribution pumps are pumps used to distribute the chilled/service water to the different mining blocks after being sent from surface for accumulation in a central holding dam or storage facility. These pumps are smaller than dewatering pumps because the water is distributed by means of gravity [31]. These pumps are still used to deliver the water to the various sections at usable pressures [12] [32]. Before the water enters the specific working sections, it flows through a series of Pressure Reducing Valves (PRVs) to ensure the smaller pipes in the sections do not burst and the equipment does not get damaged [32]. Chilled water return systems in deep-level mines form part of the distribution pump system. The unused chilled water is returned via the return line back to a centralised dam.

Intralevel distribution pumps are pumps used to transfer used service, cooling, and fissure water towards annex holes or holding dams situated on the same level or depth below collar. These pumps are significantly smaller than dewatering or interlevel distribution pumps due to the principle of a horizontal pumping direction (will be thoroughly discussed in the proceeding chapters). Referring to Equation 1, the static head (H_s) of intralevel pumps would be significantly smaller than the dewatering and interlevel distribution pumps. Due to little to no elevation change, the pressures on the surface of the reservoir (P_{RES}) and receiving tank pressure (P_{RT}) will also not undergo significant changes. The majority head of the total system is determined by the dynamic head (H_D). Equation 2 is used to determine the dynamic head of a pumping system (Darcy Weisbach equation) [23].

Equation 2: Darcy Weisbach equation

$$H_D = \frac{K v^2}{2g}$$

Where:

K = Loss coefficient

v = Velocity in the pipe (m/s)

g = Acceleration due to gravity (m/s²)

Velocity is calculated using Equation 3 [23].

Equation 3: Water velocity calculation

$$v = \frac{Q}{A}$$

Where:

Q = Flow rate through the pipe (m³/s)

A = Pipe cross sectional area (m²)

The loss coefficient consists of two elements as seen in Equation 4 [23].

Equation 4: Loss coefficients of water within a pipe

$$K = K_{Fittings} + K_{pipe}$$

$K_{Fittings}$ is associated with the fitting type and quantity used within a specific pipe network of a given system [23]. The full list of resistance coefficient values and head loss conversions can be found in Appendix A [33]. K_{pipe} is associated with the straight-line lengths of pipes used within the system and is seen in Equation 5.

Equation 5: Straight line length loss coefficient

$$K_{pipe} = \frac{fL}{D}$$

Where:

f = Friction coefficient

L = Pipe length (m)

D = Pipe diameter (m)

The friction coefficient is calculated using Equation 6 (Colebrook white) [23].

Equation 6: Colebrook white friction coefficient equation

$$f = \frac{0.25}{[\log \left\{ \frac{k}{3.7 \times D} + \frac{5.74}{Re^{0.9}} \right\}]^2}$$

Where:

k = Roughness factor (m)

Re = Reynolds number

Pipe roughness for each material can be found in Appendix A [34]. The Reynolds number is a dimensionless quantity related to liquid flow smoothness and to energy absorbed within the fluid as it moves through the pipe [23]. For any pipe flow, the Reynolds number can be calculated using Equation 7 [23].

Equation 7: Reynolds number calculation

$$Re = \frac{vD_h}{\nu}$$

Where:

D_h = Hydraulic pipe diameter (m)

v = Water velocity (m/s)

ν = Kinematic viscosity of water (m^2/s , 1.31×10^{-6}) [35].

1.4 Intralevel water distribution

After following the described steps above, the dynamic head of a pumping system can be accurately determined through manual calculations if required. The intralevel distribution pumps will be the focus of this study and are described as submersible spindle pumps (these focus areas will be discussed in detail in the following chapters). These pumps are placed within a sump where water accumulates and is pumped from the sump into a pipe, usually suspended approximately two meters above the sump [11]. Figure 10 is a visual example of the pumps used for inter- and intralevel pumping in deep-level mines [36], [37].

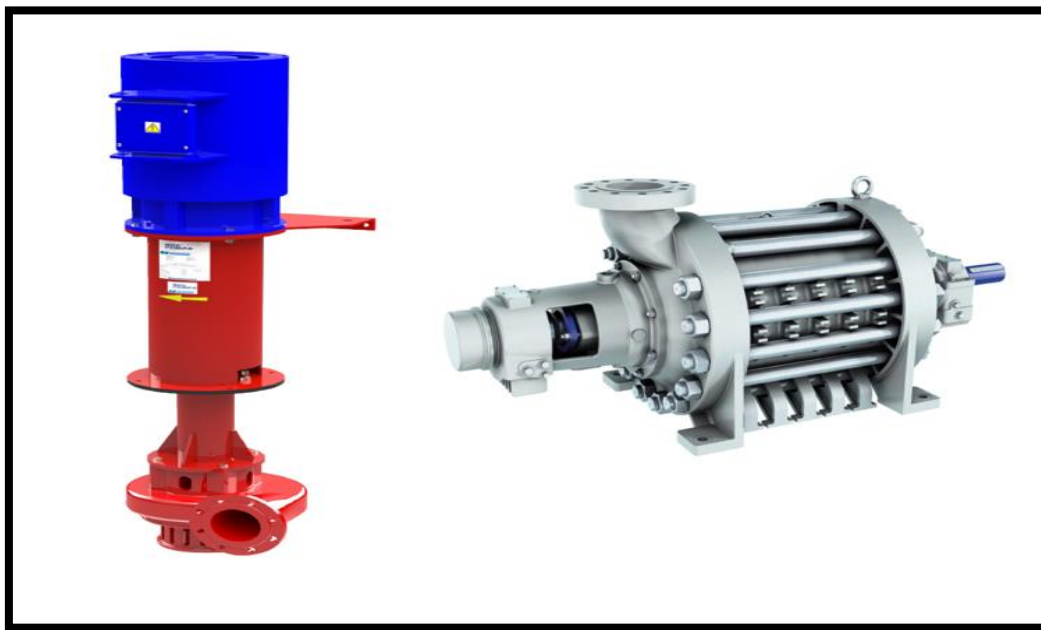


Figure 10: Inter- and intralevel pumps infrastructure used in deep-level mines

The intralevel pumps are smaller in size and capacity compared to the interlevel pumps. On the production levels, each XC consists of multiple spindle pumps to transfer the service water used in the stopes and excess water accumulating along the footwall drive and the XC. For the purpose of this thesis, focus will be placed on the main production levels' **bullnose** spindle pumps, which are located at the entrance of each XC and at the East/West split of the active mining sections. These pumps are ultimately responsible for the transport of **all** the service water from the production sections and are essential to keep haulages clear of water. Figure 11 provides a visual indication of where these pumps are located.

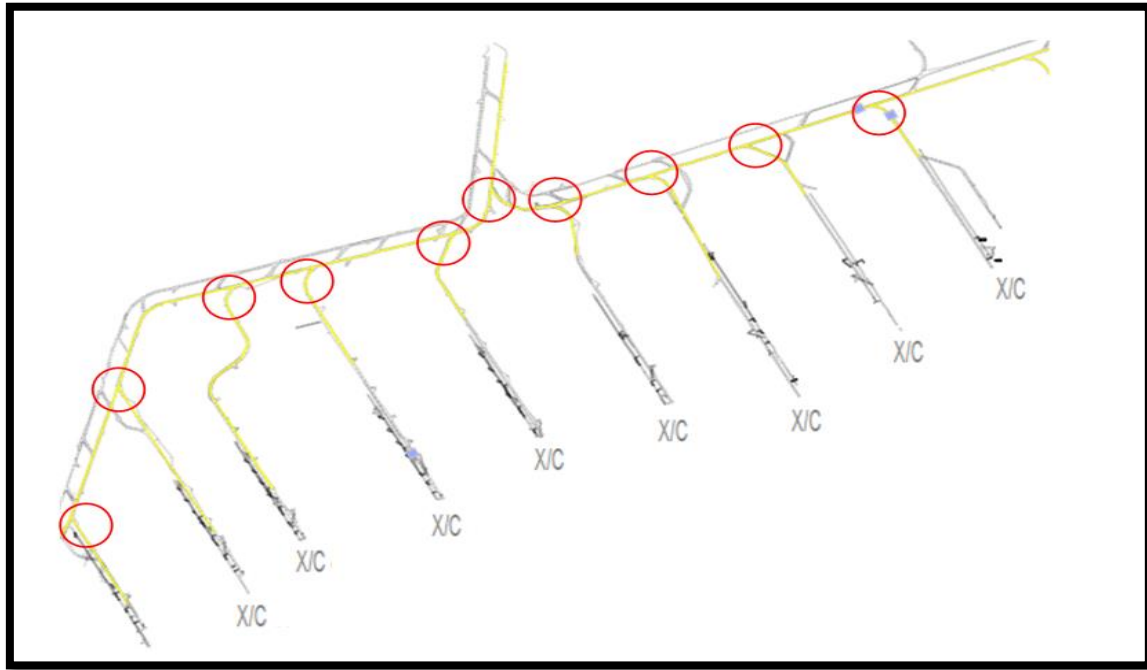


Figure 11: Typical XC bullnose spindle pump locations

The ore-producing levels are classified as the main production levels due to development and deepening still actively taking place.

Research was conducted on the operation of the horizontal water transport system in deep-level mines. It was found that **according to mining standards and procedures set out for deep-level mining, the bullnose spindle pumps are of a pre-set standardised uniform size for each operation regardless of the water demands present on the various levels where the pumps are situated** [11]. The application of standardised **uniform** pump sizes without **thoroughly investigating** the water demands may result in inefficient operation. This is particularly applicable if the standardised pump sizes are not adapted to suit water demands. The standardised pump sizes were confirmed through preliminary audits of spindle pump operations conducted in deep-level mines.

The pumping operations of bullnose spindle pumps require that the pumps run throughout the day to ensure all excess service water is moved towards holding dams on corresponding levels. Flow switches have been considered for this application, but pose challenges related to sump depth and flow switch malfunction due to varying sump levels. This ultimately leads to the flow switch getting stuck in the pump suction [38], [39].

Despite the distribution pumps being substantially smaller than the dewatering pumps, it is important to be aware of the OPEX costs and manner of operation (particularly considering the quantity of pumps installed on operations). Figure 12 illustrates the average contribution of the inter- and intralevel pumps on the distribution pumps' consumption [5], [26], [27].

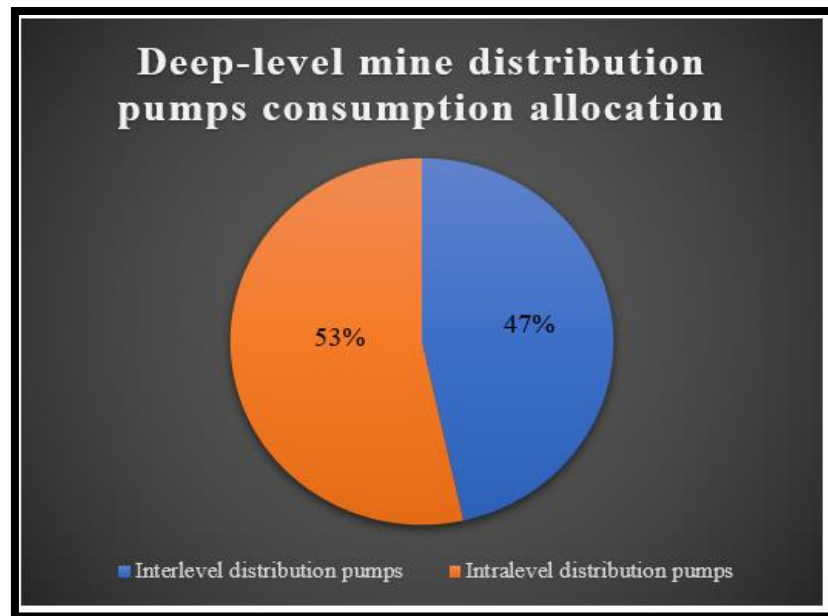


Figure 12: Deep-level mine distribution pumps' consumption allocation

The cost of both types of distribution pumps is 87% less than the large dewatering pumps [26], [27]. It is, therefore, valid to primarily focus on the improvement of the larger pumps present at the mine. However, the OPEX costs for the distribution pumps remain a large portion of the electrical costs on deep-level mines. It would, therefore, be beneficial to improve the distribution pump network where feasibly possible. Due to the lack of monitoring on the lower consuming pumping systems, benchmarking has not yet been determined [7]. It is important to obtain a baseline of performance to establish where scope exists to improve a certain system [7].

Improvement focus has not yet been directed at the bullnose spindle pump system at deep-level mines. **The purpose of this study** is to extend water management strategies to the horizontal water transport system to improve the water reticulation system. **Scope, therefore, exists to properly research, evaluate, and improve the system in question.**

1.5 Literature review – Current mine water management strategies

Preamble

Water management in the mining industry is a widely researched subject. Various strategies have been trialled, tested and implemented to obtain electrical cost savings on deep-level mines. This section focuses on previous studies conducted related to types of water management strategies and identifies the similarities and shortfalls when compared to the objective of including horizontal water transport system improvement as a prerequisite to holistic water management. The studies were chosen to include all **types** of water reticulation improvements relating to design, water control, electricity cost savings, load shifting and DSM projects, storage capacities, failure analysis, service delivery and pump specifications.

Systematic review of water management and improvement strategies

The relevant studies included to **illustrate a gap in the literature** relating to horizontal water transport system are discussed below.

Science Direct, Ebsco Host, SpringerLink, Scopus, Web of Science and Google Scholar were searched for publications with “water management strategies in deep-level mines”, “horizontal water transport management strategies in deep-level mines” as **keywords and combinations** with “electrical cost savings”, “energy efficiency”, “simulation-based”, “water demands”, “horizontal dewatering”, “submersible/spindle pumps”, “system improvement”, “sustainable” and “dynamic” in the title of the study.

All major **relevant specialty journals** in the areas of water management, water system improvement, deep-level mining water systems and energy efficiency were also searched. These included Journal of Energy in Southern Africa, International Journal of Mine Water, Sustainable Energy Technologies and Assessments, Electric Power System Research, The South African Journal for Industrial Engineering, Mine Water and the Environment and South African Institute of mining and metallurgy.

No relevant studies focusing on horizontal water transport in deep-level mining could be found. All types of water management strategies previously researched on deep-level mines were examined and considered to assist with the identification of a gap within literature.

Articles referenced in primary sources and their relevant citations were also checked. An array of articles and studies were included to illustrate which methods were prevalent in the years leading up to this study.

Only **articles using the following parameters were included**: Electrical load management, water demand control, system improvement (electrical and volume), pump specification, water distribution control and energy-efficient pump operation. Each of these were analysed and it was concluded whether any form of horizontal water transport systems inclusion was present. Focus points of strategies outlined in the literature study **can further be applied** to horizontal water transport systems as a potential improvement strategy.

- **Vosloo, 2008** [12]

Summary: In 2008, Vosloo investigated novel techniques to optimise, simulate and control all the elements involved within a mining water reticulation system [12]. Analysis of individual components can be done quicker, and changes can be made more efficiently if needed. Integrating all the elements of a water reticulation system enables control while reducing the effects on other connected parts of the reticulation system [12].

Key findings: Various simulation control packages such as Wonderware, REMS and Adroit were analysed and compared. New techniques were developed and applied to two case study mines. A significant reduction in electricity consumption was seen upon implementation of the novel control techniques (reduction of 2.3MW on average) [12].

Shortcomings: Although the techniques developed were considered a holistic approach, horizontal water transport infrastructure was not included in the study. Accordingly, the results obtained were for control strategies implemented on large energy-consuming pumping systems only.

- **Botha, 2010** [40]

Summary: Botha conducted a study in 2010 investigating the reduction of mine water demands for electricity cost savings. The study bypassed traditional strategies such as load shifting and DSM projects and focused primarily on water wastage [40]. The main objectives of the study were leak management, stope isolation control and water pressure management towards mining blocks [40].

Key findings: The application of all three techniques were trialled at a deep-level gold mine after which the reduction in water consumption and subsequently the reduction in pumping costs were analysed. Successful implementation led to additional testing and implementation at various other deep-level gold mines [40].

Shortcomings: This study primarily included water management strategies to decrease the quantity of water being pumped out from underground by 1.4 ML. Daily savings of 9.16 MWh were, therefore, seen on the large energy-consuming dewatering pumps and did not include improvement of any horizontal transport water systems.

- **Rautenbach et.al, 2005** [41]

Summary: A study by Rautenbach *et.al* was done in 2005 relating to the operation of a Three-Pipe Water Pumping System (3CPFS). Changes suggested for water distribution systems are not easily quantifiable due to it being a new concept. Simulation software is used as a method of cost savings prediction to accurately determine the effects of the changes before actual implementation [41].

Key findings: Models of the system were built using the simulation software and simulation results were verified with actual measured data from the mining water system [41]. The results yielded by the simulation showed a potential reduction in the pumping costs and electrical load within an Eskom peak period [41].

Shortcomings: U-tube systems operate on a similar basis to the 3CPFS. In this case, however, the 3CPFS is used for dewatering purposes only and does not form part of any horizontal water transport distribution pump system.

- **Stephenson, 1983** [3]

Summary: A study conducted in 1983 by Stephenson focused on older improvement techniques and various challenges encountered in deep-level mine water reticulation [3]. Techniques such as separate level water returns, pipe size improvement, water hammer elimination and pump sizes were discussed in the study [3].

Key findings: Methods to reduce pipe wear and water distribution control were utilised as control improvement within this study. This provides a parameter baseline to consider when

analysing water distribution systems (pipe sizes, type and length etc). Simulation software was also integrated to establish the limits of operation to reduce infrastructure costs upon design.

Shortcomings: The study outlines the main challenges when designing a water reticulation system but neglects to include the distribution system to and from the active mining blocks (which consumes the largest quantity of water going underground).

- **Bridgwood *et.al* 1983** [42]

Summary: The paper written by Bridgwood *et.al* in 1983 discusses the various contributing factors to consider when designing a mining pumping layout. Pumping duties allocated to mine dewatering systems were specified in terms of delivery rate, total head required and quality of mine water [42]. The identified parameters led to various inter-related design factors such as standage capacity (the time which the pump is off-load), the cost of minimising friction losses and the comparison of different pump dewatering configurations [42].

Key findings: The pumping characteristics of submersible pumps were discussed and the flow regimes of operations established. Impeller designs at the flow regimes were outlined in unison with protective operational measures [42]. Conclusions comprised the importance of considering the calculated pumping duty of the mine pumping system to establish whether the design justifies the application [42].

Shortcomings: The importance of duty calculation and mathematically corrective design was clearly stated within this study, but only focuses on the main dewatering system of the water reticulation system.

- **Murray, 2000** [6]

Summary: The study conducted by Murray in 2000 was among the first to optimise the water reticulation of a mine using simulations and mathematical modelling to obtain the best configuration at different energy tariffs. Conceptual model understanding was used to develop formal, equation-based models to be trialled.

Key findings: The objective of the study was to create accurate models which can simulate the cost of electricity associated with normal operation of a water reticulation system [6].

Models were integrated to allow experimentation with scheduling, pumping configuration and load shifting strategies [6]. The effects of correct pipe sizing and pumping efficiency on electricity costs were also discussed. The models were verified, and improvement techniques were suggested on the case study mines included in the study [6].

Shortcomings: The study highlights the efficacy of system modelling and the ability to pre-determine actual savings before implementation [6]. Models were built for the **main** energy consuming water systems where savings can be maximised as quickly as possible.

- **Venter, 2020** [25]

Summary: Venter conducted a study in 2020 focusing on the reconfiguration of mine dewatering systems for increased volumes of water. The study objective was to establish cost effective methods to ensure existing mine water reticulation infrastructure could tolerate an excess influx of water either through fissure water, a sudden increase in mining activity or the mismanagement of water [25]. Secondary objectives include optimised control of the reconfigured system [25].

Key findings: A method was developed and tested on two case studies involving four different mine shafts [25]. The case study implementation revealed that 29% of excess water could be removed, while the second case study revealed a reduction of 31.4% in water pumped to surface. Decreasing the water consumption through the optimised reconfiguration enabled simpler control of the dewatering system and resulted in electrical cost savings of R1.28 million in the first year through a reduced pumping demand [25].

Shortcomings: This study considered the possibility of excess water through either development or sudden influx and compared it to the ability of the current infrastructure to remove the excess water.

Optimised configuration established that the additional quantities of water (up to certain limits) can be removed without major Capital Expenditure (CAPEX). Worst case scenarios and future requirements should be considered when attempting water management improvement to ensure that all the bases of the strategy are addressed. The study did **not**, however, extend the system reconfiguration to the smaller energy-consuming pumps.

- **van Niekerk, 2017** [43]

Summary: A study by van Niekerk was done in 2017 which focused on a marginal mine's (low ore grade and high production costs) pump scheduling. These mines are extremely cost sensitive due to profit only being viable when commodity prices are high [43].

Key findings: Scope, therefore, existed to critically analyse the water reticulation system to ensure all unnecessary pumping of water is avoided. Water is required underground only when mining is active and, therefore, reduces the necessity for immediate dewatering [43]. The dewatering system also included sets of manually operated pumps with minimal monitoring infrastructure [43]. A simulation model was developed using the available information and it was concluded that the mine schedule can be adjusted in such a way to completely avoid the Eskom standard- and peak-tariff times [43]. The new developed pumping schedule was implemented, and cost savings of R935 000 per year were realised on the dewatering pumps [43].

Shortcomings: Due to the high commodity prices in recent years, the simulation model can be used to predetermine potential optimal configurations due to the increased mining activity with the current monitoring infrastructure on the mine [43]. Monitoring techniques, on a widely unmonitored system, were applied to the **main** reticulation system using simulation and excluded horizontal water transport systems.

- **du Plessis *et.al*, 2015** [44]

Summary: du Plessis *et.al* conducted a study in 2015 that entailed a variable water flow strategy to match the unique demands of the cooling system. The strategy included matching the thermal requirements of the evaporator to the chilled water demand, adapting the corresponding condensers to the specific heat load and matching the BAC with the ventilation air requirements [44]. This variable flow strategy can be effectively used during periods of low demands or when cooling requirements have reduced due to certain mining areas no longer being utilised.

Key findings: A simulation integrated with the mine cooling system was developed and accuracy was verified with actual results [44]. The potential savings prediction revealed a 33% reduction in electricity consumption should implementation occur [44].

Shortcomings: The cooling requirements throughout different periods of a working week and adjusting the supply with the demand would yield cost savings on the main water reticulation and refrigeration systems. Demand would also inevitably change within the mining blocks due to reduced water distribution and accumulation of water in footwalls through losses. The effects of the demand adjustments should also be analysed through quantification of the water volumes to be moved by the horizontal water transport pumps and required changes to the system should be made accordingly.

- **Conradie, 2018** [24]

Summary: A study conducted by Conradie in 2018 focused on reducing the chilled water demand within a mine water reticulation system. This was done by focusing on the replacement of spot coolers or cooling cars with centralised BAC units [24]. The location of the newly suggested BAC units was strategically determined to maximise cooling efficiency and electricity cost reduction [24].

Key findings: A methodology was developed to accurately determine energy and cost savings of the reconfigured water reticulation system. Simulations and actual manual measurements were used to verify the obtained data and evaluate potential electricity cost savings. The methodology was applied on a reconfigured reticulation system of a South African gold mine. The predicted energy efficiency and electrical cost savings, should implementation occur, were 49.1 GWh and R 31.8 million per annum (p.a.), respectively [24].

Shortcomings: The reduction in water demand reduced the strain on refrigeration and dewatering systems underground. The effects of the demand reduction due to the reconfiguration on the intralevel distribution pumps were not included in the study.

- **van Staden, 2018** [45]

Summary: van Staden conducted a study in 2018 and developed a methodology that aimed at improving the use of cooling cars in underground environments [45]. Preliminary audits were conducted and it was seen that the installed cooling units lacked regular maintenance and were utilised in areas where mining activities decreased significantly [45]. A methodology was developed to assist with the identification of inefficient cooling cars and corresponding actions thereafter.

Key findings: The devised methodology was implemented on a gold mine situated in the Gauteng province of South Africa. Extensive audits were conducted using the developed methodology and the findings thereof were documented and handed to the mine. The results of the implemented project yielded pumping water reduction totals of 47- and 150 ML, respectively, within the two months monitored [45]. The water reduction resulted in an electrical cost saving of R580 000 and R1.8 million, respectively, within the monitored two-month time frame [45].

Shortcomings: The study focused on the reduction of chilled water demand going towards the spot coolers in the end-user sections. The effect of water reduction was analysed on the main dewatering and refrigeration system, but the effect of demand reduction on the intralevel pumps was excluded.

- **van Rooyen, 2019** [46]

Summary: The study conducted by van Rooyen in 2019 focused on the development of a model to predict fouling within Finned-Tube Heat Exchangers (FTHX) [46]. Fouling within FTHX occurs while in operation underground on deep-level mines. The study provides a prediction model which includes optimum and actual air-cooling duty, performance loss due to fouling (without additionally installed instrumentation) and ideal maintenance intervals [46]. Application of the model assists in minimising excess water needed to obtain sufficient cooling at off-design conditions due to fouling within the FTHX.

Key findings: Nine case studies were used to verify the model predictions. The results revealed actual performance deviating by 29% from optimal performance due to internal and external fouling (11% external and 18% internal) [46]. The fouling contributed to a BAC outlet temperature rise of 0.7°C (due to internal fouling) and 1.3°C (due to external fouling). The external foulants were removed with high pressure water through a strategically devised cleaning method. This resulted in an air temperature decrease of 0.7°C. Specifically formulated thermal and production related labour relations incorporated into the maintenance model revealed substantial annual revenue increase of R58 million [46]. Water quantities needed to obtain optimal air temperatures, therefore, decreased by 41% as a result of the foulant removal [46].

Shortcomings: The study focused more on improving the BAC outlet air temperature within underground environments than a reduction in water quantity or electrical cost savings.

Cost savings were realised as a secondary objective through the reduction in water quantity needed to reach optimum air temperatures as a result of the removed foulants. Improvements on the mine dewatering system were seen through quick evaluation but were not analysed extensively within the results. Horizontal water transfer system improvements were not included.

- **Ashmead, 2019** [47]

Summary: In 2019, Ashmead conducted a study focused on the feasibility of implementing ice thermal storage on deep-level mines. Load management strategies on refrigeration systems were analysed and used to devise new techniques to maximise the cost savings potential of refrigeration systems. Ice thermal storage on deep-level mines was identified as a possible cost saving strategy [47]. The utilisation entailed thermal ice storage release during periods where electricity is cheapest and releasing the ice mass quantity during high electricity demand periods [47]. A feasibility analysis was conducted using a simulation and analytical approach [47].

Key findings: Implemented results revealed significant load reduction and cost-saving potential at the expense of a reduction in cooling system performance [47]. Morning and evening Eskom peak period load-shifting results revealed a R4.5 million saving p.a. if maintained throughout the year [47]. A further reduction of R502 per ML of water cooled was seen which contributed to the decrease in service delivery performance [47]. Ice thermal storage can be implemented as a cost saving solution. This is, however, only suggested as a viable solution on mines with a life of mine of greater than 10 years [47].

Shortcomings: The study focused on the utilisation of thermal ice storage and consequently chilled water reduction on refrigeration systems during certain periods of the day.

The water reduction would be seen during the prescribed periods of thermal ice storage but only on the surface refrigeration (with the exception of underground fridge plants) and ice plant machines. The study did not include the effect thermal ice storage utilisation would have on intralevel water distribution.

- **Taljaard, 2012** [32]

Summary: Taljaard conducted a study in 2012 which focused on the control of chilled water distribution through means of a control valve selection [32]. The investigation conducted on a deep-level mine in South Africa revealed a substantial lack of chilled water control throughout the day. An analytical control valve selection method was developed by considering constraints such as water hammering, cavitation, flashing, safety ratings and control ranges [32].

Key findings: A simulation model was developed to illustrate the behaviour of the water reticulation system and project the effects of the control changes [32]. After the valve solution was implemented, a daily water reduction of 3.1 ML was seen. The electrical cost savings contribution, through means of the dewatering pumps, amounted to a daily saving of 3.55 MW [32].

Shortcomings: The developed methods did address the water demand to be distributed by the interlevel distribution pumps but neglected to extend the investigation to the return side of the utilised chilled water system.

- **Zhang, 2011** [19]

Summary: Zhang conducted a study in 2011 focusing on the optimal sizing of large centrifugal pumps to achieve energy efficiency and load shifting [19]. Optimal pump-sizing models are suggested for new system design and existing infrastructure [19]. These models aim to minimise energy consumption costs and improve the actual energy efficiency of the pumping system. Pumping system performance, running operation, equipment and technology (POET) are the key performance parameters on which the study is based [19].

Key findings: A pump capacity selection algorithm was developed and tested based on the POET framework mentioned. The algorithm demonstrates the reduction in energy cost by balancing energy efficiency and load shifting contributions during the operation [19]. The model was designed such that it can be altered to adapt to various operational configurations and conditions [19]. The study concluded that energy efficiency as well as load-shifting strategies are simultaneously attainable using model predictive techniques [19].

Shortcomings: The predictive model developed for dewatering systems by Zhang is an effective way to predict pumping behaviour and adjust configurations to find the best suitability

for the application. The dynamic adaptability of the model adds a significant contribution to effectively establish a best mode of operation in a fluctuating demand system. These practices should be extended to **all** pumping systems to obtain maximum efficiency.

- **Cilliers, 2014** [20]

Summary: In 2014, Cilliers concluded a study focusing on the reduction of preparation- and comeback loads on mine dewatering pumps. Cilliers developed a dynamic controller which used a step-by-step control technique to alter the control ranges of underground dam levels [20]. This enabled effective Time-Of-Use (TOU) load shifting to obtain electrical cost savings on dewatering pumps [20].

Key findings: The technique was tested on two case studies at South African gold mines. When comparing the analysed results to conventional control methods, it was seen that financial cost savings of R1.096 million and R579 394 p.a. were obtained for each respective case study [20].

Shortcomings: The implementation of dynamic control methods for dewatering systems have proven to be more effective than conventional, outdated strategies. Dynamic controls were not tested on intralevel distribution pumps during the study.

- **Jacobs, 2021** [48]

Summary: Jacobs' research published in 2021 focused on the failure prediction of mine dewatering systems. A prediction model was designed, tested and successfully verified through case studies conducted on four pumps at different underground depths [48].

Key findings: The results revealed a 90% confidence lower bound on the minimum failure time of a pump [48]. Correlations between pump operating depth were analysed and it was found that pump life decreases with an increase in pump operating depth, most likely due to more extreme operating conditions being characterised by an increase in depth underground [48]. Through the use of the prediction model, optimal pump replacement times can be determined long before actual replacement and consequent downtime can thus be avoided [48].

Shortcomings: The study is of importance due to the monitoring focus placed on dewatering pumps. More than sufficient condition monitoring equipment is installed on large dewatering systems but is rarely installed on smaller pumps such as the intralevel distribution pumps.

This is due to the monitoring equipment price usually surpassing the actual pump acquisition price. The study highlights the enhanced monitoring of large mine dewatering systems and illustrates the significant need for pump monitoring to avoid costly breakdowns.

This thesis aims to increase the monitoring of an otherwise largely unmonitored system with minimum installed instrumentation. Jacobs' study focused **solely** on larger pumping systems and was not extended towards horizontal transfer pumping systems.

- **Jerling, 2019** [49]

Summary: In the study conducted by Jerling in 2019, an indirect approach was taken to optimise the water reticulation system for electrical cost savings. Focus was placed on refurbishing pre-cooling towers on deep-level mines and the consequence thereof was analysed [49]. The end goal was to lower the inlet water temperature of the refrigeration system by using a refurbishing strategy for the pre-cooling towers. A five-step methodology was developed to evaluate the impact of pre-cooling tower refurbishment and the results thereof were analysed [49].

Key findings: A case study was used for validation at a deep-level mine located in South Africa. Implementation resulted in a 29% efficiency increase for the pre-cooling towers which led to an annual cost saving of R6.86 million [49]. Due to increased efficiency of the pre-cooling towers, heat absorption decreases for the same amount of cooling was noted on the evaporator side of the refrigeration system [49]. Water quantities needed for the same cooling requirements were also noted but not reported on extensively.

Shortcomings: The study focused primarily on the improvement of the refrigeration system and had corresponding benefits for the water reticulation system. The benefit analysis was not extended to the water distribution systems on the case study mine.

- **Peach *et.al*, 2018** [50]

Summary: An article written by Peach *et.al* in 2018 highlights the importance of control integration with water reticulation sub-systems on deep-level mines [50]. The focus was placed on 3CPFs installed on South African gold mines. Investigations revealed that 3CPFs are directly responsible for the performance decreases of conventional dewatering and refrigeration load management strategies, primarily through a lack of control integration [50].

The study addressed the problem through the development of an integrated control strategy between the dewatering, refrigeration and 3CPF systems [50].

Key findings: A solution was developed and tested with a real-time energy management system, which optimally utilised the 3CPFs and improved the performance of the implemented load management initiatives [50]. This resulted in an electrical load shift improvement of approximately 400% compared to previous values.

Shortcomings: Although some sub-systems were included in the study, an overall holistic approach to dewatering sub-systems was not used. Distribution systems such as the intralevel distribution pumps were not included in integration.

- **Mare', 2016** [51]

Summary: The study conducted by Mare' in 2016 brought to light novel contributions for energy management on mine cooling systems through simulation [51]. Integrated transient response simulations were used to highlight possibilities for new energy cost savings and successful energy management [51]. Procedures for new applications were also developed from the newly derived transient approach simulations [51].

Key findings: The developed models and approaches were verified by comparing actual operational data from a deep-level gold mine with simulated results [51]. A combined accuracy of 97% was achieved [51]. Applications of the models yielded potential daily energy savings of 145.5MWh and translates to R31 million p.a. [51].

Shortcomings: Mare's study is significant due to new simulations constructed for new applications, and new procedures developed for the applications.

Summary

From the studies listed above, insight was provided on the various water improvement strategies formulated over the years. A criteria setlist was constructed **to highlight the main aspects included in this study** and emphasize the shortcomings of each of the summarised studies to clearly indicate a need for the study at hand. See Table 1 for a summary of the developed criteria.

Table 1: Study criteria development summary

Criteria	Description
Underground horizontal water management	This criterion was selected to established if research has been conducted on horizontal water management strategies.
Pump specification improvement	Pump specifications are critical to improved operation and should be considered in the majority of water improvement studies.
Simulation	Research conducted on pumping system improvement using simulation software provides a solid foundation on the parameters to focus on upon development.
Energy efficiency	Energy efficiency on pumps is closely connected to correct pump specifications and improved control operation.
Electrical cost savings	The main objective of management strategies is to obtain cost savings on water systems, primarily on electricity consumption.
System monitoring tool with minimum infrastructure	System monitoring is an important aspect to the success of any major industrial improvement strategy.
Sustainability	Pumping configurations and changes should be able to operate under variable scenarios to be classified as successful.
Water demand management and forecast	Managing and forecasting water demand is needed to maintain continuous sustainability or predict when change is necessary.
Dynamic adaptability	Dynamic adaptability is required to react swiftly should unexpected problems occur.

**Based on the literature review studies' methodologies, criteria indicated in green were used for novel contributions; orange entails important relevance.*

From Table 1, a state of art matrix was constructed to illustrate the shortcomings and inclusions of the research within the critical literature review. Only criteria indicated in orange and green were included to substantiate the most important criteria to consider for the study at hand. The state of art matrix compares the focus of the different water management strategies and **assessed whether any of the studies extended research to the horizontal water transport system**. This illustrates the **gap** found within the literature research and emphasizes the areas where focus can be placed when applied to horizontal water systems. Furthermore, the fundamentals of strategies implemented on the larger dewatering systems can be used to formulate a system improvement strategy for the horizontal water transport systems.

Table 2 contains the state of art matrix.

Table 2: State of art matrix

			A simulation-based horizontal water transport management strategy in deep-level mines							
Study	Year	Ref	Underground horizontal water management inclusion	Pump specification optimisation	Simulation	Electrical cost savings	System monitoring tool with minimum infrastructure	Sustainable	Water demand management and forecast	Dynamic adaptability
Vosloo	2008	[12]		X	X	X		X		X
Botha	2010	[40]				X			X	
Rautenbach et.al	2008	[52]			X	X		X		
Stephenson	1983	[3]		X						
Bridgwood et.al	1983	[42]		X						
Murray	2000	[6]		X	X	X		X		X
Venter	2020	[25]				X		X	X	
van Niekerk	2017	[43]			X	X	X		X	
du Plessis et.al	2015	[44]			X	X		X	X	X
Conradie	2018	[24]			X	X			X	
van Staden	2018	[45]				X			X	
van Rooyen	2019	[46]					X	X		
Ashmead	2019	[47]				X				X
Taljaard	2012	[32]			X	X		X		X
Zhang	2011	[19]		X		X		X		X
Cilliers	2014	[20]			X	X		X		X
Jacobs	2021	[48]					X	X		
Jerling	2019	[49]				X	X		X	
Peach et.al	2018	[50]				X		X	X	X
Mare'	2016	[51]			X	X		X	X	X

*Criteria highlighted will be used to formulate the novelties of the study.

Table 2 indicates, as far as can be determined, that **focus has not yet been placed on horizontal water transport management** in the underground environment. Focus is primarily placed on the main dewatering systems, which consist of vast installed electrical capacities, to realise large-scale electrical cost savings.

Monitoring infrastructure on the horizontal transport systems is also minimal due to instrumentation cost in relation to pump cost. It is, therefore, a largely unmonitored system after pump installation. A management strategy which also comprises monitoring aspects, particularly with minimal infrastructure available, can enhance project sustainability.

The application of simulation software (discussed in Chapter 2) to model the currently installed system can assist in determining current and future water demands as the development of the mine progresses. Supplementary CAPEX projects, which influence the return water management, can be incorporated into the simulation and adjustments made accordingly.

Dynamic adaptability plays an essential role in prolonged project management success. Real-time monitoring of the horizontal water transport systems assists with water demand control and necessary configuration changes. Constant monitoring of systems adds an additional fault-finding mechanism which can assist in identifying faulty equipment or supplementary instrumentation.

The improvement strategies implemented on the larger dewatering systems provides a guideline on the focus areas previously investigated. This provides a good indication of the requirements to replicate the strategies and **apply them correctly** to the previously excluded horizontal water transport system.

1.6 Problem statement

The shortcomings of previous studies are used to derive the problem statement. The exclusion of horizontal water transport systems in improvement techniques was used as the **main motivation for the study**.

Water and system management strategies for main dewatering systems have been widely researched throughout industry. Upon investigation, it was seen that the **intralevel** distribution pumps on deep-level gold mines contribute approximately 94% less to the pumping electrical load compared to the large dewatering pumps [27]. Considering the quantity of installed intralevel distribution pumps on various mining levels throughout the mine, it is worthwhile to include the sub-system in improvement strategies. Through comprehensive preliminary investigations, the problem statement is identified.

The lack of evaluation and monitoring procedures for deep-level mines' horizontal water transport systems affects the system efficiency contributing to unnecessary operational expenditure.

1.7 Research aim and objectives

Water management in deep-level mining can be improved by implementing modern Simulation and Model (S&M) derived approaches to both forecasting methods and overall system operation. Existing outdated forecasting or system application design methods can prove costly in a dynamic environment such as deep-level mining.

Process operation can be improved by analysing the scientific process principles and water demand requirements of the entire horizontal water transfer system through the integration with S&M developed approaches.

A need exists to develop, implement and validate a simulation-based water management strategy to improve operation of horizontal water transport systems in deep-level mines.

The study objectives identified for a successful simulation-based water management strategy are:

- Integrate current and future water demands through simulations to reduce OPEX costs.
- Increase water demands forecasting accuracy for better capital allocation.
- Test scenarios of horizontal water management improvement and the effects on water demand prior to implementation.
- Add a system monitoring aspect to previously unmonitored and under-equipped systems.

1.8 Original contributions of the study

This study aims at delivering various novel contributions to the field. This section will outline these contributions in more detail and clarifies how the shortcomings of previous literature works will be addressed.

Novelty 1 - Main contributing novelty

S&M of horizontal water transport systems in a deep-level gold mine to obtain improved operation leading to electrical cost savings.

What needs to be done?

Horizontal water transport systems in deep-level mining are crucial for operational efficiency of the larger energy-consuming vertical dewatering pumps. In order to fully grasp the requirements of the horizontal water transfer system, comprehensive simulation regarding this system is required. The availability of a digitally replicated horizontal water transport system, built in a simulation environment for a previously unmodelled system, will assist to establish the most efficient system operation attainable [12], [26]. It should be noted that the spindle pump dewatering system contains minimal quantities of instrumentation; therefore, selected measurements/audits need to be conducted manually. An S&M approach will be developed using software and validated system operation models. The newly developed approach will be compared to actual data obtained after implementation to validate the procedure.

How is the comparison currently done?

Requirements for spindle pump operations on deep-level mines are currently not being investigated prior to installation due to it being a smaller contributor to electrical load. Previously set standards of operation are still being followed which does not take the dynamic nature of the system into account.

Forecasting system operational requirements are also not considered with the current method. This method does not have any scientific integration involved.

By using a dedicated system simulation of the horizontal water transport system, more accurate demand predictions can be forecasted through analysis and current system operation can be improved.

Why are the current methods insufficient?

The current management method operates according to a principle of outdated operational acceptability. Little to no investigation is done into system requirements before spindle pump installation. There are various factors that can influence system performance over time and these must be considered when planning ahead. Current incorrect system operation causes increased operational expenditure, potential equipment damage, unnecessary additional infrastructure upgrades and increased capital expenditure costs.

How does this study solve the problem?

Optimal equipment procurement, designation, installation and operation assist to identify where capital can be allocated to more urgent improvements. By determining the correct operation configuration, electrical cost savings can be obtained through decreased pump quantity requirements and decreased electricity consumption due to the correct sizing of the pumps. The potential for additional benefits is possible by way of simulating the best operating point (BEP) of the installed spindle pumps and adjusting accordingly. Better financial management enhances scope to potentially allocate previously misaligned capital to improve system performance throughout the mine.

Novelty 2 – Secondary novelty

Continuous horizontal water system simulation integration used as a means of mine development planning (without additionally installed condition monitoring infrastructure).

What needs to be done?

The developed S&M approach is initially done with the current demand of the return water quantity on production levels.

In order to achieve sustainable solutions for the dynamic underground environment, the simulation needs to be updated according to the development plan of the mine. Possible future scenarios are to be simulated to establish future OPEX and accurate budgeting of certain isolated systems. All the additional water end-users (that contribute to return water) need to be identified to calculate accurate future values. System limits need to be identified and changes implemented where needed.

How is process improvement currently done?

There are currently no procedures in place to determine the future water quantities needed to be moved by the horizontal water transfer system. Standard size spindle pumps are installed as development takes place without considering the actual required pumping specification. This leads to inefficient pumping operation (mostly due to incorrect standardized pump sizes) and unnecessary higher electricity costs. The ability to simulate different development demands and obtain simulated results before any change is implemented on the actual system adds reliability to the study.

Why are the current methods insufficient?

The horizontal water transfer system operates according to set instructions of what is considered to be the correct operation of the system. Water management is a dynamic process which can be improved by analysing each system individually according to the current and predicted future water demand in the system. Seasonal demands also need to be considered as return water quantities may differ in each season. This can be done by altering certain parameters or events (projects etc.) which can lead to an increase in water demand. Using modern, dynamically adaptable simulation methods to determine improved operation for each system can achieve lower future OPEX costs. Various unexpected events can be simulated to determine an action plan should the events occur within the actual water system. The current methods are not scientifically integrated and adaptable which can lead to higher OPEX costs and incorrect pump sizing for certain water transfer applications.

How does this solve the problem?

Through integrated simulation methods, scenarios where water demand has increased or decreased significantly can be identified and tested. This method assists with the correct pumping application scenario. This, in turn, contributes to electrical cost savings compared to incorrectly sized pumps being used for the application. Budgets can be allocated more accurately due to all scenarios and actual future developments being considered and simulated to obtain the improved operation. Unexpected scenarios can be simulated to establish an action plan should these scenarios occur within the actual water transfer system.

Novelty 3- Secondary novelty

Integrated horizontal water management strategy using simulation techniques to establish resulting water demands.

What needs to be done?

The management of system water needs to be improved by considering the effects of unrelated projects influencing the return water system together with simulation analysis to assist with horizontal water transfer management.

How is process improvement currently done?

Projects implemented for systems process improvement may have certain effects on the demands of services distributed to sections of the mine. Projects' influence on the return water system are not considered as one uniform spindle pump size is utilised regardless of any potential fluctuations that may occur due to the influence of new projects. Problems arise when the effects of the projects on the return water system, regardless of increasing or decreasing water demand, are not being considered as a basis for system re-evaluation of the installed spindle pump configuration. It is beneficial to analyse the effect of any system changes to ensure the optimal running configuration of a system.

Why are the current methods insufficient?

By **not** considering spindle pump system re-evaluation, if changes to another influential system occur, the current configuration might be under-equipped to transfer an increased cumulative quantity of water. In contradiction, the omission of system re-evaluation leads to missed energy savings opportunities due to a reduced quantity of return water in the system. Nevertheless, the effect of the implemented changes will remain unanalysed and further system improvement potential unexplored.

How does this solve the problem?

Through an integrated S&M approach with isolation control implementation, the reduction or increase in utilised chilled water return in certain areas can be simulated. After simulation results are analysed, conclusions can be made to either adjust the current horizontal water

transfer configuration or keep it unchanged. OPEX costs can be reduced and system performance increased if changes are correctly analysed and adjusted.

Novelty 4 – Secondary novelty

Integrated monitoring technique for low priority water transfer systems.

What needs to be done?

The spindle pump system is a largely unmonitored water transfer system in deep-level mines. This is mostly due to the individual size and cost of the pumps, rendering it not feasible to equip the systems with instrumentation. Monitoring is important for all systems to avoid significant downtime, and in this case, warm used water build-up within cross cuts. Warm water build-up leads to environmental and safety complications (temperature from the water gets transferred to the air). Continuous simulation of the system adds a monitoring aspect to a previously unmonitored system. Simulation integration with the SCADA can be done to ensure real-time monitoring of the system performance to ensure system limits are not surpassed.

How is process improvement currently done?

Spindle pumps are not equipped with any monitoring instrumentation due to the aforementioned cost implications. This can influence production output and lead to temperature increases due to the build-up of water in certain areas of the mine. Manual communication channels are used to communicate complications through a series of management departments. This significantly delays any rectification actions and has a notable influence on production.

Why are the current methods insufficient?

The current lack of system monitoring is regarded as insufficient due to the absence of focus on a system which is indirectly responsible for production level ore transport efficiency (due to water build-up prevention).

If cross-cut return water quantities decrease, it can cause damage to the pump as it is continuously running and is not submerged in water for prolonged periods of time. If cross-cut return water quantities increase, bullnose sumps can regularly overflow causing cross-cut temperatures to rise and introduce locomotive travel complications due to water build-up.

Previous methods used did not have any monitoring techniques in place and solutions had to be derived after complications arose and extended the timeframe on which rectification actions took place.

How does this solve the problem?

By continuously monitoring the cross-cut return water quantities, a monitoring aspect to the previously unmonitored system is introduced (SCADA integration). Regular system checks can identify potential future pump failure which would otherwise lead to a downtime in production. In addition, using the system simulation as a monitoring technique can act as real-time observation measure to the system without procuring costly additional monitoring infrastructure which exceeds actual pump costs.

Objectives for the study were identified after which novel contributions to the field were determined. The novel contributions identified with the corresponding linked objectives is shown in Table 3.

Table 3: Novel contributions and corresponding objectives

#	Novel Contribution	Corresponding Objective(s)
1	Simulation & modelling of horizontal water transport systems in a deep-level gold mine to obtain improved operation leading to electrical cost savings.	1 & 3
2	Continuous horizontal water system simulation integration used as a means of mine development planning (without additionally installed condition monitoring infrastructure).	2
3	Integrated horizontal water management strategy using simulation techniques to establish resulting water demands.	3
4	Integrated monitoring technique for low priority water transfer systems.	4

1.9 Thesis layout

Chapter 1 - Introduction to water distribution systems and improvement strategies in deep-level mines

This chapter provides insights into water reticulation operation and management in deep-level mines. Operational expenditure awareness is discussed and highlights the importance of including all sub-systems within improvement strategies. Previous literature is analysed and used to derive problem statements which will be addressed by novel contributions formulated from the gaps identified within literature.

Chapter 2 – Horizontal water transport management strategy development

A strategy for improved horizontal water transport system configurations in deep-level mines is developed in this chapter. The strategy will be developed in numerous devised steps including identification, detailed investigation, simulation and model development, savings potential verification, specific solutions development, dynamic adaptability, sustainable improvement, implementation approval and results analysis. Emphasis was placed on obtaining a sustainable and dynamically adaptable improved system configuration by using integrated simulation software (comparison and identification of software also done in this chapter).

Chapter 3 – Results and verification

The strategy developed in Chapter 2 is applied to an actual case study in this chapter. A deep-level gold mine was identified in the Gauteng province of South Africa (Mine A). Results obtained post-implementation of the newly developed horizontal water transport management strategy will be thoroughly discussed. Focus is placed on the detailed validation of the management strategy and serves as the verification of the study. The chapter is concluded by summarising the information discussed throughout the chapter.

Chapter 4 - Conclusion

The thesis is concluded by summarising the key findings of the research process followed to develop a scientifically derived horizontal water management strategy in deep-level mines. Outcomes of the study are discussed based on the achieved objectives and novel contributions to the research field. Recommendations for future studies are outlined and shortcomings of the developed strategy are discussed.

CHAPTER 2

DEVELOPMENT OF METHODOLOGY

“Nothing is right and wrong in research; research is an addiction with an endless search for its drug.”

— P.S. Jagadeesh Kumar

2 HORIZONTAL WATER TRANSPORT MANAGEMENT STRATEGY DEVELOPMENT

2.1 Preamble

This chapter focuses on methodology development to establish sustainable horizontal water transport management strategies through simulation software. The developed methodology aims to address the shortcomings listed in Chapter 1, while fulfilling the outlined requirements.

2.2 Research methodology

The research methodology will involve following the Case Study Methodology as seen in Figure 13. This type of research methodology is mostly used in design research when [53]:

- Certain phenomena or data due to changes implemented needs to be analysed,
- hypotheses need to be generated, and
- validation of a developed method is required.

Figure 13 shows a high-level flowchart of the Case Study Methodology [43].

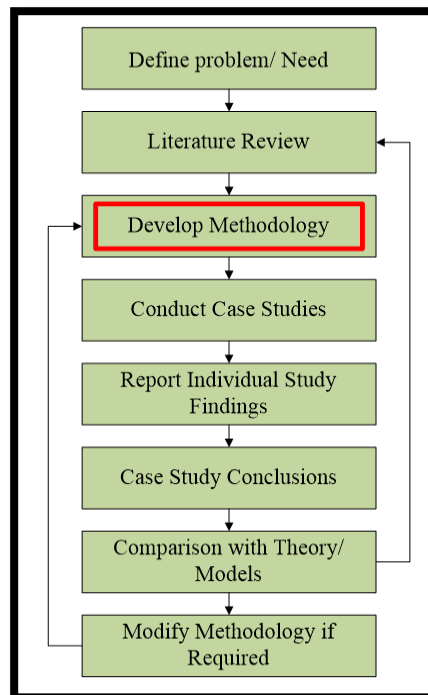


Figure 13: High-level flowchart of the Case Study Methodology

The inclusion of horizontal water transport management has not yet been properly integrated when assessing mine dewatering and distribution systems. It is, therefore, essential to follow a well-structured methodology plan to accurately identify the problem areas and devise alternate dynamically adaptable solutions to the identified problems (if solutions are deemed feasible according to operations' standards). A combination of self-designed and industry approved guidelines were used to formulate the strategy in this chapter [54]. A visual representation of the developed methodology is shown in Figure 14.

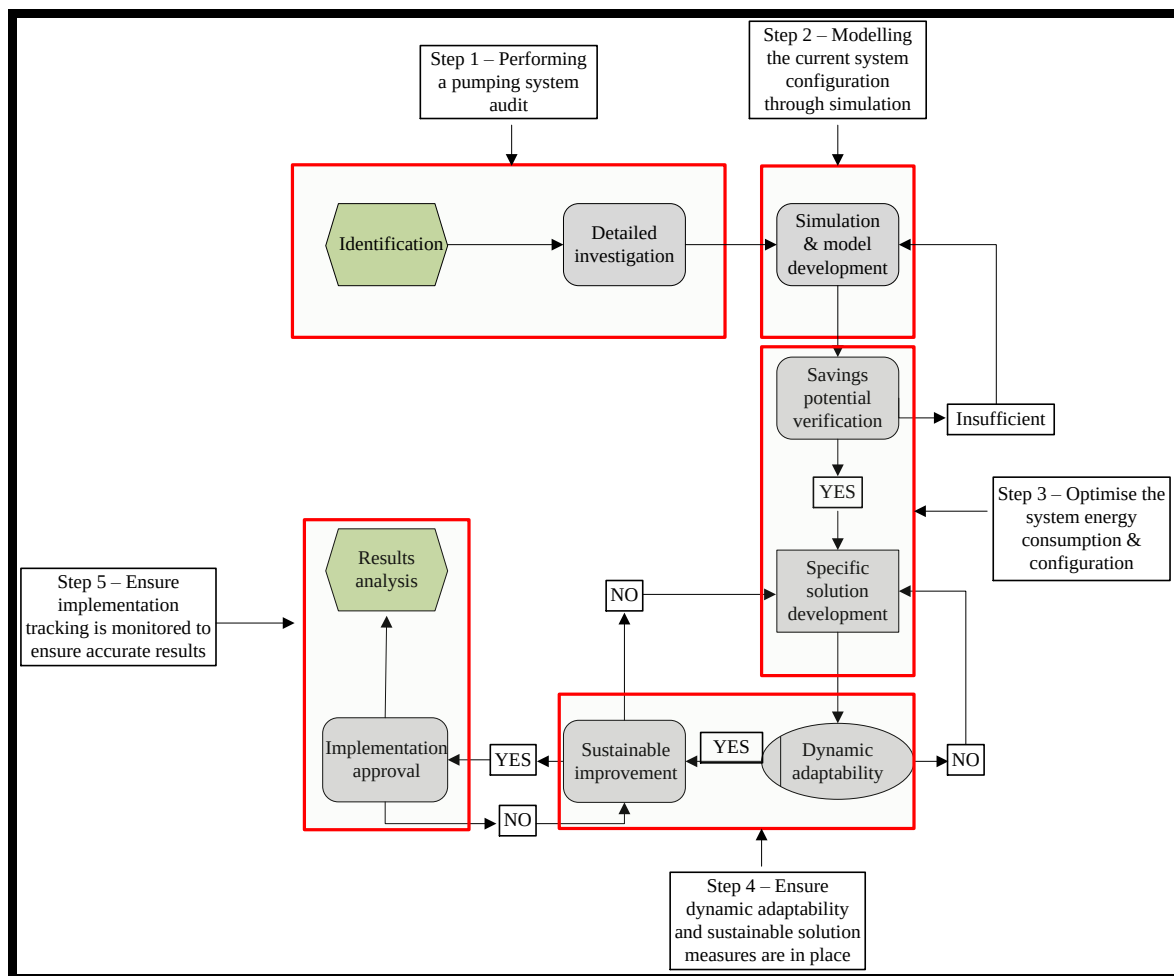


Figure 14: Strategy overview

Figure 14 shows all the steps that need to be taken to conduct preliminary investigations and develop an integrated horizontal water transport management strategy. Each step will be further analysed as a five-step method which includes industrially accepted methods ([54], [55], [56], [57]) and new approaches in order to assess the horizontal transfer pumping network.

2.3 Step 1 – Performing a pumping system audit

The first process step entails a preliminary pumping system audit from which certain conclusions, limitations and design specifications can be determined. Secondly, a detailed investigation regarding the pumping system must be conducted to establish usable operational parameters and the most efficient operating configurations [56]. Figure 15 is a visual summary of **Step 1** in the methodology.

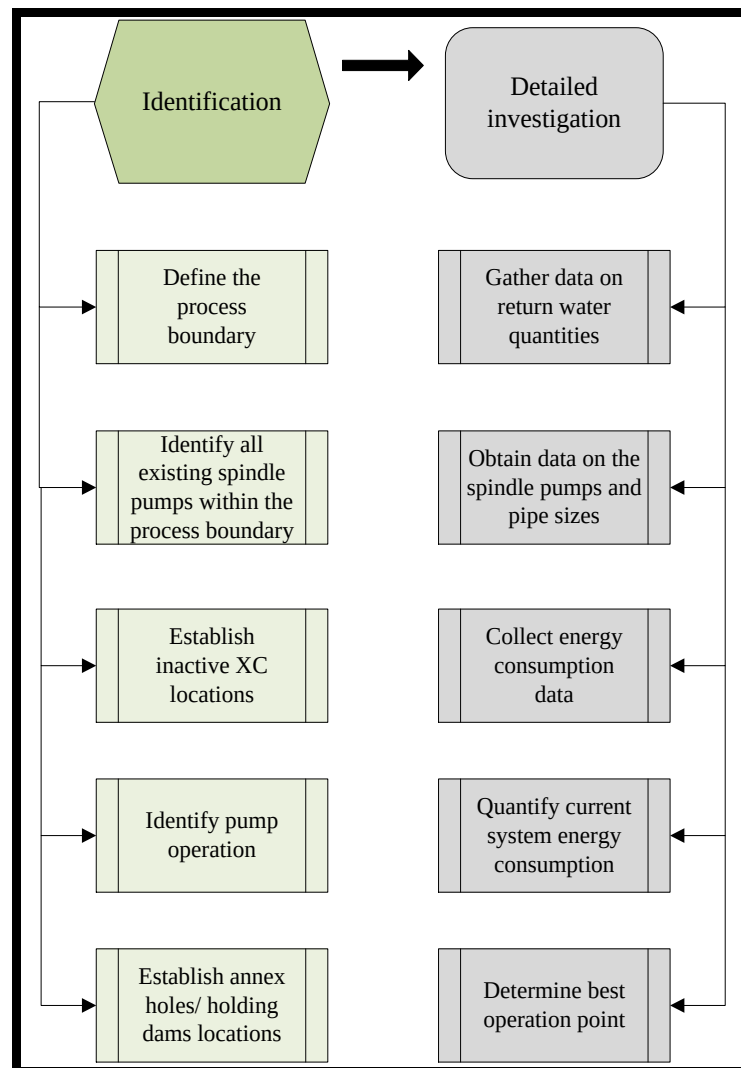


Figure 15: Step 1 methodology summary

Identification

Identification of the system to be comprehensively audited needs to occur before the audit process can commence. The information can either be obtained from sources at the surface operations or be attained underground if not readily available.

Define the process boundary

A boundary for the study at hand is essential to determine the start and ending point of the audits to be conducted and simulation model development. The boundary selection should be chosen to ensure that most/all areas of concern are included and that irrelevant areas which can complicate calculations are excluded. Most water management strategies include the reticulation network up and until the interlevel distribution pumps, but the boundary in this thesis will be focused on the spindle pumps distribution system. Figure 16 represents the typical boundary conditions for isolated spindle pump system inclusion.

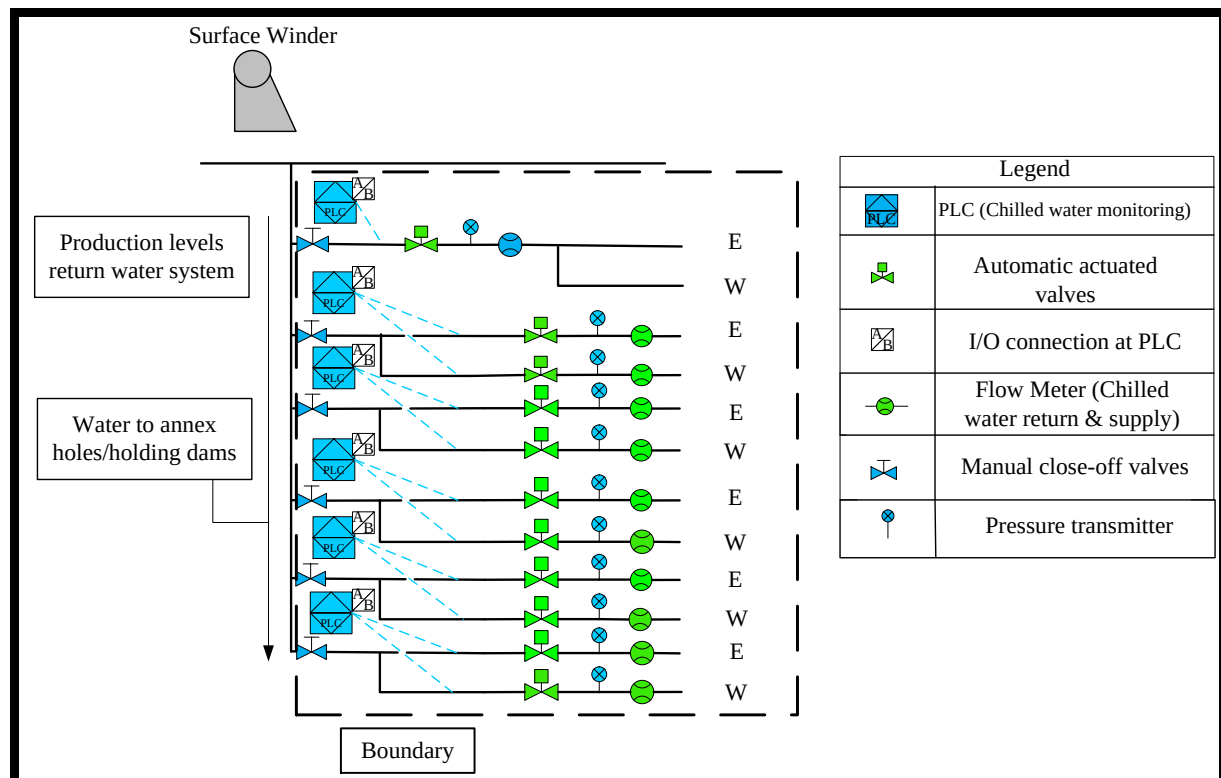


Figure 16: Process boundary summary

The study will focus on the bullnose spindle pumps installation and configuration on the production levels. The production levels are chosen due to the majority of mining activities taking place on these levels. Consequently, these are the levels which contribute most to utilised chilled water in the hot water return system. If required, the study can be expanded to areas where reduced mining activities take place, or areas re-opened for mining purposes.

Identify all existing spindle pumps within the process boundary

Spindle pumps are classified as specially designed pumps which are partially submerged in the fluid it is selected to pump [58]. The pumps are designed with all the electrical components at the top of the pumping shaft where it is marked as safe from any harmful liquids [58]. As mentioned, the study will **only** focus on the spindle pumps installed on the bullnoses of the XCs on the main production levels of a deep-level mine.

The spindle pump locations included on each production level can be found in Figure 11. From the initial audit conducted, the size of each spindle pump should be noted. The size establishment is necessary to correctly quantify the overall energy consumption of the spindle pumps on each production level after various sample power measurements are taken underground. This is due to **individual** spindle pump consumption being too small to register on main level electrical feeders.

Identify inactive XC locations

Inactive mining areas are locations underground where no stoping, development or reclamation activities are taking place [59]. These sites can essentially be cordoned off from the haulages as there is no longer any significant use for the areas. These areas should theoretically no longer contribute to any used return water and, therefore, do not require spindle pumps in the XC or at the bullnose (depending on the distance towards the half-level split).

Inactive XCs should, therefore, be investigated during the preliminary audits to suggest immediate remedial actions. These actions include the removal of the installed pumps if no excess fissure water and groundwater circulating in fissures of hard erupted or sedimentary rocks is detected flowing from the XC [60]. The identification of inactive XCs will be essential to simulation development later in the methodology.

Identify pump operation

Pump operation for any installed pump is essential to determine the energy consumption and the corresponding savings potential should any changes be recommended to the current operation. Spindle pumps usually do not consist of monitoring or operational controls. Some installations do, however, have equipment installed such as level flow switches. These switches are defined as control mechanisms used to open or close the pump supply circuit based on the low and high level of the sump compared to the ballast [61], [62], [63].

The spindle pump operation can further be broken down into the operational method of the identified pump. The flow diagram in Figure 17 can be used to determine the operation of the identified spindle pumps.

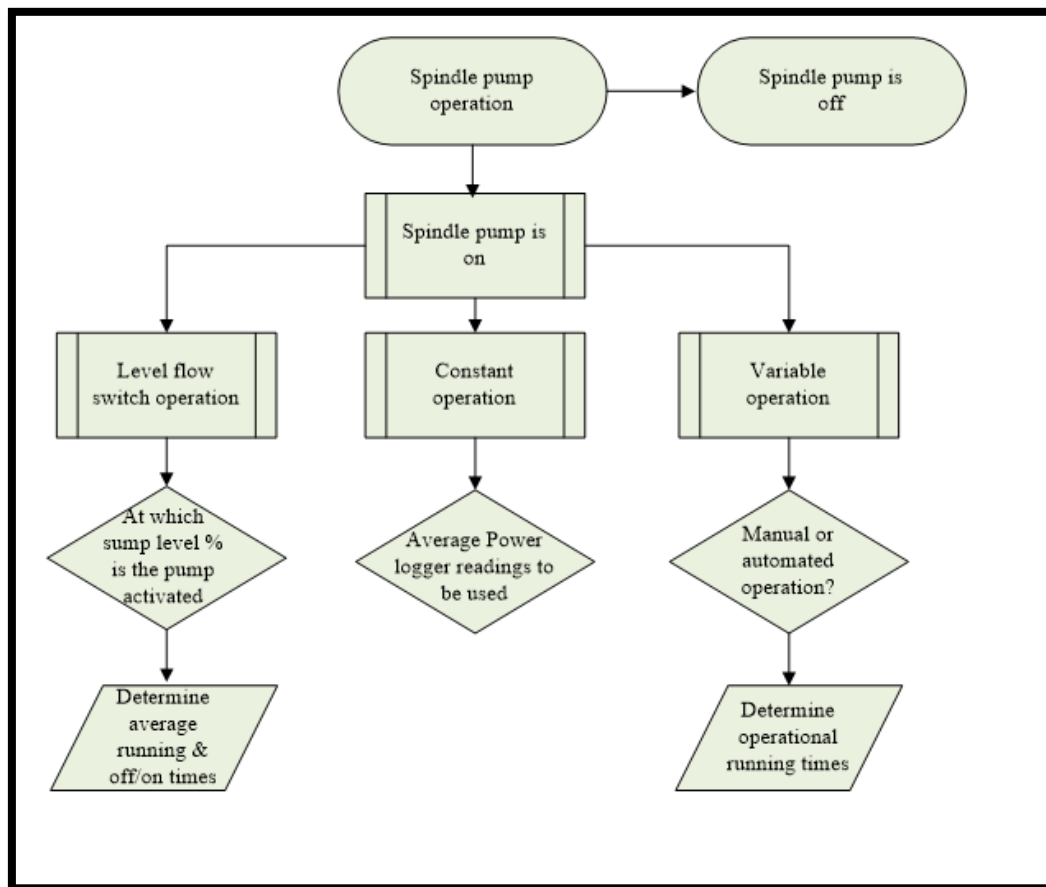


Figure 17: Spindle pumps operation determination diagram

After the operation of the identified spindle pumps is determined, the running hours of the pumps can be calculated. This will be used to correctly quantify the energy consumption of the pumps (calculation steps to be done in quantification step of Chapter 2).

Establish annex holes/ holding dams' locations

Annex holes are drainage holes which are used to drain excess water from certain areas of a production section towards dewatering pumps. These holes usually converge at the bottom of a mine shaft, forming a sump, to pump the water to surface [64]. Utilised water from the XCs on the production sections are transported to the annex holes/holding dams through the spindle pump system. Annex holes are located on each production level to ensure each individual level's excess water is thoroughly drained to the water basin near the shaft bottom. Figure 18 provides a representation of an underground mine's layout and ore pass locations [65].

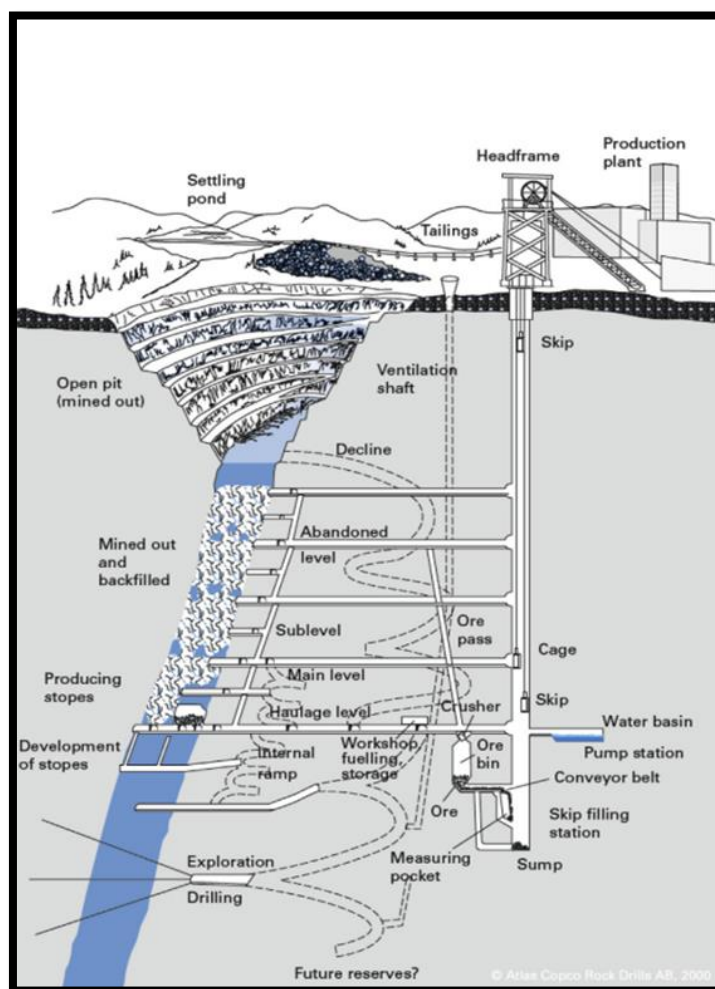


Figure 18: Deep-level mine ore pass locations

The locations of the annex holes/holding dams are important to this study due to the distance from the last available spindle pump. After identification of the annex holes/holding dams' location, the following questions need to be answered:

- What is the distance from the level-specific annex hole/holding dam to the nearest spindle pump in the system?
- What is the size of the nearest spindle pump in the system in proximity to the annex hole/holding dam?
- Are there any holding dams situated near the annex holes?

The information obtained above will be essential to the calibration of the simulation model of the spindle pump system.

Detailed investigation

The detailed investigation can either be done in unison with the initial audit identification step or be done separately to ensure all-inclusivity. All the information readily available without conducting physical audits underground should be done first, but still sequentially in order to streamline **Step 1** of the methodology.

Gather data on return water quantities

Return water quantities will be crucial to the potential system configuration changes obtained from the developed simulation model. The water volumes measured on each level will ultimately determine whether the current system is the best suited configuration or if changes can be made to obtain cost savings.

Most mines monitor the difference between the chilled water delivered and returned to and from the production sections. Deep-level mines that monitor these flows simplify the data collection for this step. If the data is monitored, it can usually be obtained from the mine's SCADA or archived measured values to quantify the monthly water usage. Installation of a permanent flow meter is an effective way to enable constant monitoring of the return water system, while obtaining accurate data measurements. These flow meters are usually installed strategically at the split on production levels. A typical water flow meter installed on deep-level mines is shown in Appendix A in Figure 60 [66].

If the return flow quantities are not measured in any way, manual measurements need to be conducted. There are portable measuring devices available on the market to measure water in a pipe without altering the infrastructure of the pipe or pumps.

The use of ultrasonic water flow meters is a suitable alternative to determine the return water quantities of each production level or half level. Figure 61, shown in Appendix A, is a visual representation of a typical ultrasonic water flow meter [67]. It is important to obtain accurate measurements for each production level's separate production sections. Hourly measurement values, which can be converted into a daily flow profile, are most beneficial. This will establish a more accurate level-specific solution when calibrating the simulation model.

Data acquisition of spindle pump designs and haulage return pipe sizes

Performance curves

All pumps are designed to fit a uniquely developed pumping curve. Pumping curves provide crucial information on the variation of the differential pumping head across the pump as the flow through the pump changes [68], [69]. Differential head (Δh) is related to differential pressure (ΔP) by Equation 8 [68].

Equation 8: Differential pressure formula

$$\Delta P = \rho g \Delta h$$

Where:

ΔP = Differential pressure across pump (Pa)

ρ = Fluid density through pump (kg/m^3)

g = Gravitational acceleration (m/s^2)

Δh = Vertical distance to be pumped (m)

A typical pumping performance curve is shown in Figure 19 [68].

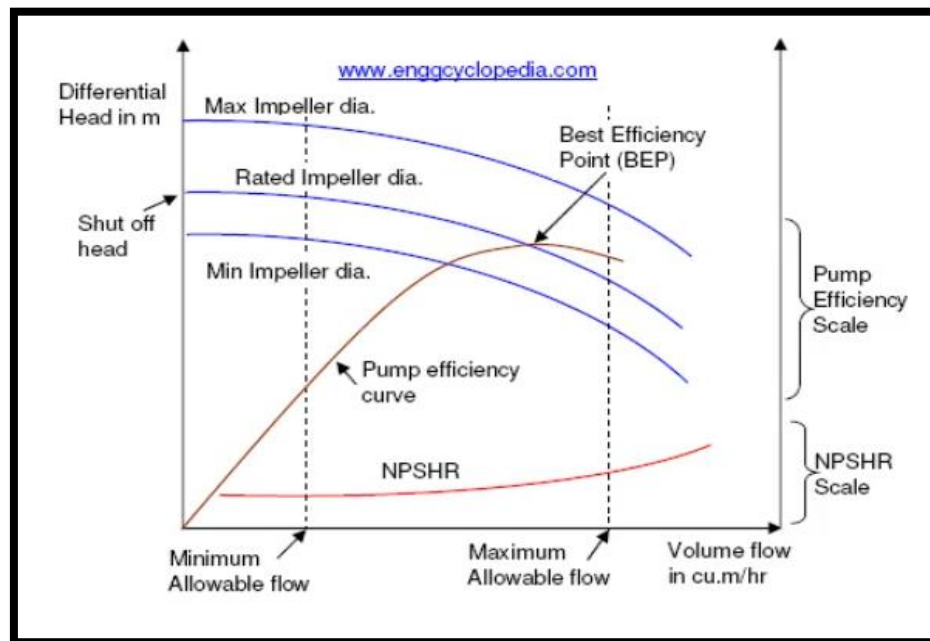


Figure 19: Pumping performance curve description

As shown in the sample performance curve in Figure 19, there are usually three curves plotted relating to differential head versus volumetric flow [68]. These are described as:

1. Performance curve of differential head for rated impeller diameter: This represents the variation of differential head with volumetric flow for the impeller with rated diameter [68].
2. Performance curve of differential head with volumetric flow for maximum impeller diameter: This curve is plotted with the maximum diameter that the installed pump can accommodate [68]. This impeller can be used as an alternative if increased flow requirements or differential head is required with the same pump [68].
3. Performance curve of differential head with volumetric flow for minimum impeller diameter: This curve is plotted for the impeller with the minimum diameter that the impeller can accommodate [68]. This impeller can be used if flow or differential head requirements are reduced in the future and would result in lower electrical consumption [68].

Although the curves are plotted for a wide range of flow rates, the actual operation should be limited **between** the minimum and maximum flow ranges as indicated on the curves [68].

Another factor to consider when encountering underground spindle pump operation is the water quality. Suspended solids will be more prevalent in return water applications compared to other underground applications. Pump curves for Δh and variable flow are thus calculated for specific liquid densities. For slurries containing up to 15% solids, mass may be considered to behave as clear water [68] [70]. For higher concentrations, friction losses should be adjusted according to a factor determined by using Figure 62 in Appendix A [68].

Pumping efficiency is also indicated on the performance curves. It is an important factor to consider upon installation as operation should occur closest to Best Efficiency Point at minimum power requirements (usually between 80-85% of shutoff head) [68] [71]. Figure 20 illustrates the relationship between head and flow. Curve design is based on the Nelson Barringer pump reliability curve [71], [72].

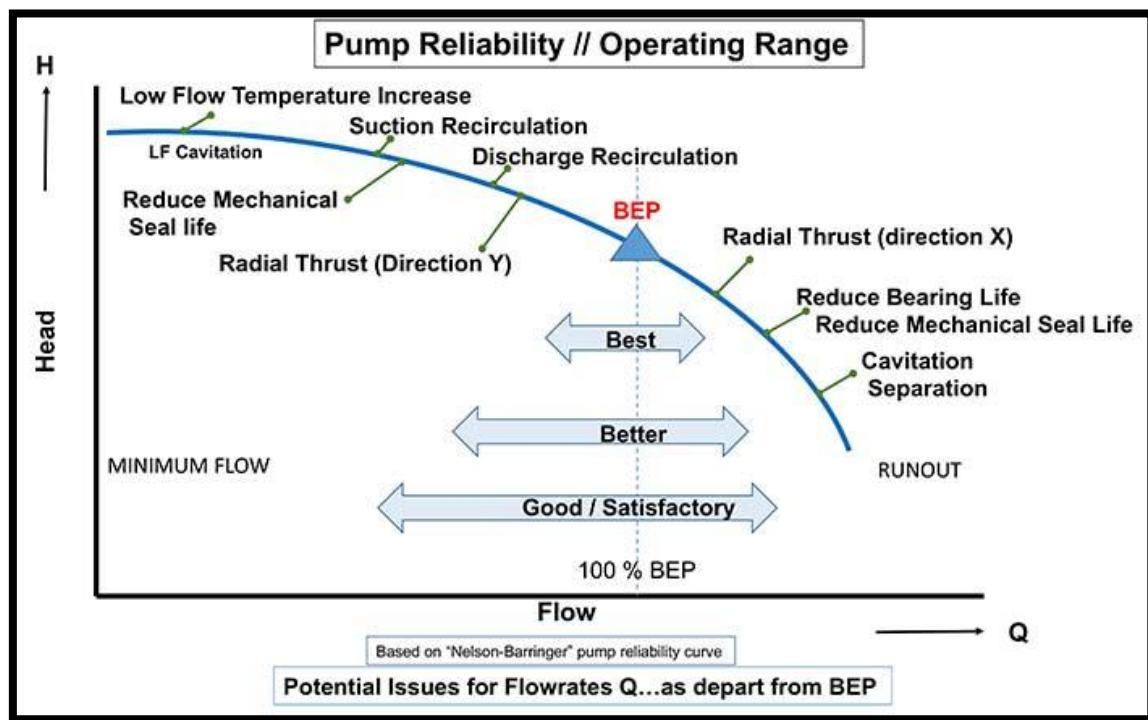


Figure 20: Best efficiency point head and flow relation

From the curve above it can clearly be seen that pumps operating too close to the minimum or maximum differential head are not beneficial in terms of pump life and power consumption. Pump efficiency is described as the ratio of energy delivered by the pump to the energy supplied by the pump shaft [73]. Operating at an adequate efficiency will assist in minimising pumping

costs as systems may often run off their performance curve. Figure 63 in Appendix A is an example of how efficiency influences pump power consumption [73].

Composite performance curves are another form of pumping performance establishment and contain parameters such as efficiency, power factor, current, and rotational motor speeds [69]. These curves are used less often than performance curves, but still provide valuable information regarding the pumps in question if **the more common** pumping curves cannot be obtained. Figure 64 in Appendix A is an example of a composite performance curve [69].

Comprehensive information regarding a pumping system is essential in a simulation-based approach. More accurate results can be obtained through correct calibration leading to more effective improvement solutions.

Haulage return pipe sizes

Pipe sizes have significant influence on the efficiency of a pumping system [74]. Energy is lost through friction, leakage and excess pressure [74]. Pipe sizes are usually designed for a specific flow rate to compensate for the roughness factor in a pipe in order to maximise the energy efficiency of the water distribution. The spindle pump return system operates as part of the mine's drainage system. The drainage system does not form part of the immediate intensive water demand system such as the distribution system and, therefore, pipe sizing procedures are often overlooked due to water pressure and flow not being significant. Proper piping material selection and system design can control the flow rates and velocity in a manner that reduces energy costs [74], [75].

According to [76] and [77], increased velocity in water pipes leads to an increase in corrosion within the pipes. High velocities within pipelines, therefore, promote corrosion/pitting and may require pipe replacement earlier than anticipated [75], [76]. It should also be noted that when increasing the pipe diameter, the pipe cost increases. In return, the pressure drop in the pipes decreases, resulting in less power required to pump the water [75]. A well-maintained balance should, therefore, be obtained between pipe diameter and pump energy costs.

In the study conducted by [76], experiments were done to determine when corrosion rates will start increasing exponentially (for certain pipe materials) when considering velocities within pipes. The limit before the corrosion rates increase was determined and was established as the

critical flow limit of the evaluated pipe materials [76]. The spindle pump system transports used mine water and contains corrosive metals and various other chemicals related to underground mining. It is, therefore, critical to ensure the spindle pump system uses appropriate piping materials to ensure minimal damage to installed pipes due to corrosion. Unplasticized Polyvinyl Chloride (UPVC) pipes are used for applications where corrosive materials are dominant and may damage steel piping [78], [79].

When auditing the initial spindle pump system, all the sizes of the return drain column in the XCs as well as haulages should be noted. Instances where incorrect piping is used, such as pipes made from easily corrodible material, should also be reported to ensure swift action is taken to correct this. Line sizes are important to the system simulation calibration due to them directly affecting the fluid dynamics within the pipe.

In summary, the information required for this step within the method is as follows:

1. Obtain all available performance curves for the spindle pumps installed in the return system. The pumping curves will be used to correctly calibrate each pump indicated on the simulation.
2. Indicate all pipeline sizes and pipe materials used within the return system. Line sizes need to be accurately specified within the simulation to ensure the best possible results.

Collect energy consumption data

Energy consumption on spindle pumps does not form part of the entities where specific monitoring equipment are installed. In most cases, spindle pumps will form part of the underground electrical load sub-system. Individual pump measurements are, therefore, not being monitored and actual consumption of the spindle pump thus remains largely unknown.

To accurately verify current system consumption, measurements need to be taken manually. Portable measuring equipment such as DENT loggers are best suited for power, current and voltage measurements. Figure 65 in Appendix A provides a visual description of a portable DENT logger measuring device [80]. To ensure accuracy of logger values, these loggers are required to be calibrated regularly and tests be repeated on the same pumps with backup calibrated loggers.

The DENT logger can be installed on the pump starter box connecting the Current Transmitters and Voltage Transmitters (CTs and VTs) of the DENT logger to the corresponding wiring of the pump starter box. The connection enables the DENT logger to draw power from the pump starter box and the logger can, therefore, remain connected to obtain data without an external battery source being required. The typical setup for the DENT logger will differ depending on the pump type. The most common connection used is the 3-phase 4-wire setup but may differ for certain operations. Figure 66 in Appendix A provides more information on the DENT logger setup [81], [82].

Software that is compatible with the DENT logger portable meter includes the ELOG 15 power meter data processing program by DENT instruments. Prior to logger installation on the spindle pump starter box, power supply to the spindle pump system should be established. The usual power supply to spindle pumps is typically a 525 V supply (secondary voltage) [27]. Using design information obtained on the spindle pumps, the data logger setup needs to be completed to ensure logging results are as accurate as possible.

In South Africa, the line frequency value used is 50 Hz throughout [83]. The Potential Transformer (PT) ratio is determined by dividing the main electrical supply (primary voltage) with the step-down supply (secondary voltage) used at each mine [84]. The objective of the measurements is to obtain a balanced system in terms of load. The phase shift angle is, therefore, kept at default of 1.1° [85]. The logging interval will depend on the values measured. If certain fluctuations such as larger or smaller water loads on the pump need to be documented, smaller time intervals would be best suited for the application. If average consumption under normal Business-As-Usual (BAU) conditions are to be monitored, then a longer time interval would be best suited.

Calibrating the program while the logger is being installed rather than beforehand is recommended to ensure calibration is done correctly. This ensures the information obtained on the spindle pump system before installation and the actual values obtained can be compared prior to the extended logging period of each pump. If possible, the power logger measurements should be done in coalition with delivery flow measurements of the pumps. Obtaining delivery flows for the different pump sizes will assist with future calculations.

Sample size determination

Due to the quantity of spindle pumps installed, it would not be viable to install portable power loggers on all the operational target spindle pumps. Using statistical analysis methods, the sample size of the pumps measured for energy consumption can be determined.

Various methods have been researched on sample size determination of a quantitative set of data. In 2011, Liang *et.al* [86] conducted a study where the focus was on the sample size determination of buildings' energy consumption in large metropolitan areas. Various sampling methods were discussed after the best suited method was chosen. Group sampling classify entities into clusters with similar characteristics [86]. Further advantages of group sampling include the following:

1. Group sampling improves a survey's representativeness – Sampling can more accurately represent the distribution of the population [86]. Classifying entities into groups containing similar characteristics assists with the processing of relevant data. Classifying pumps with a similar size into one group rather than pumps situated in the same or nearby location, regardless of the pump size, would be preferred [86].
2. Group sampling decreases the influence of population variance on the sampling error – Sample cells selected in different categorized clusters, and the corresponding variance that affects the sampling error, is limited to the variance in each cluster [86]. Using data from similarly sized pumps from each cluster would assist in the simplification of the data processing.

Obtaining an initial set of data from a target pump within the process boundary is essential to establish the parameters required to successfully determine the target sample size of each pump size within the process boundary. A confidence interval is a term in statistics which refers to the probability that a population parameter will fall between a set of values for a certain proportion of times [87]. This is used to help eliminate the uncertainty of an estimate value within a population data set [88]. Due to the classification method used, similarly sized pumps will be grouped in clusters when analysed; therefore, it can be assumed that most of the measured values under BAU conditions would deliver similar results [88], [86]. A confidence level of 95% can be used. Table 4 shows the common relationships between degree of probability and confidence level ($F(t)$ and (t) , respectively). [86].

Table 4: Relation between degree of probability and confidence level

t	1	1.3	15	1.96	2	3	4
F(t)	68.27%	80.64%	86.64%	95.00%	95.45%	99.73%	99.99%

Consequently, a large population size is expected to have a lower degree of confidence, while a smaller population size is more probable to consist of a higher degree of confidence [86]. Sample size determination is determined according to Equation 9 [86].

Equation 9: Sample size determination formula

$$n = \frac{Nt^2\sigma^2}{N\Delta x^2 + t^2\sigma^2}$$

Where:

n = Sample size of similar pumps within the process boundary

N = Quantity of all pumps of similar sizes in the process boundary

t = Degree of probability related to confidence interval (most common 1.96)

Δx = Sample mean classified as x ; Limited error of the sample mean ($\Delta x = 0.1 x$)

σ = Standard deviation from sample mean

If the population size (N) is very large, the sample size can simply be computed by Equation 10 [86].

Equation 10: Sample size determination of a large population

$$n = \frac{t^2\sigma^2}{\Delta x^2}$$

After the sample sizes are determined for similar pump sizes, strategically chosen pump locations should be selected to include all possible spindle pump applications. These would include bullnose pumps situated at XC entrances, East-West splits, new developments, and XC at haulage ends.

Quantifying current system energy consumption

After data collection for the indicated pumps is completed, the total system energy consumption is calculated. Average values obtained will be scaled according to the quantity of each indicated pump size within the process boundary. Information obtained regarding pump operation is used to establish an average consumption profile. Identified pumps with the same operating size should be grouped together to ensure overall quantification is simplified. Pump operation which entailed variable use throughout the day will be translated into running hours to obtain the overall consumption and will be grouped separately. Pumping cost is determined with the use of tariffs allocated to the year of calculation.

For the purpose of this thesis, the **FY22** Eskom Megaflex tariff structure will be used to quantify cost (Megaflex tariffs are used for large industrial operations) [1]. Mine A falls within <300km transmission zone [1].

The FY22 Eskom tariffs allocated to kWh consumption are shown by Table 5.

Table 5: FY22 Eskom Megaflex Time-Of-Use tariff structure

Electricity costs ($\leq 300\text{km}$)		
Time-Of-Use (TOU)	c/kWh	R/kWh
Summer Peak	150.12	1.5012
Summer Standard	108.37	1.0837
Summer Off-peak	74.65	0.7465
Winter Peak	426.94	4.2694
Winter Standard	140.58	1.4058
Winter Off-peak	83.72	0.8372

**The tariffs used include electrification and rural network subsidy charge, affordability subsidy charge, and ancillary service charge, which are also allocated per consumed kWh (16.13c/kWh total [1]).*

The Eskom tariff structure follows a TOU cost distribution. Allocation of the standard, peak and off-peak times are represented by Figure 21 [89] [1].

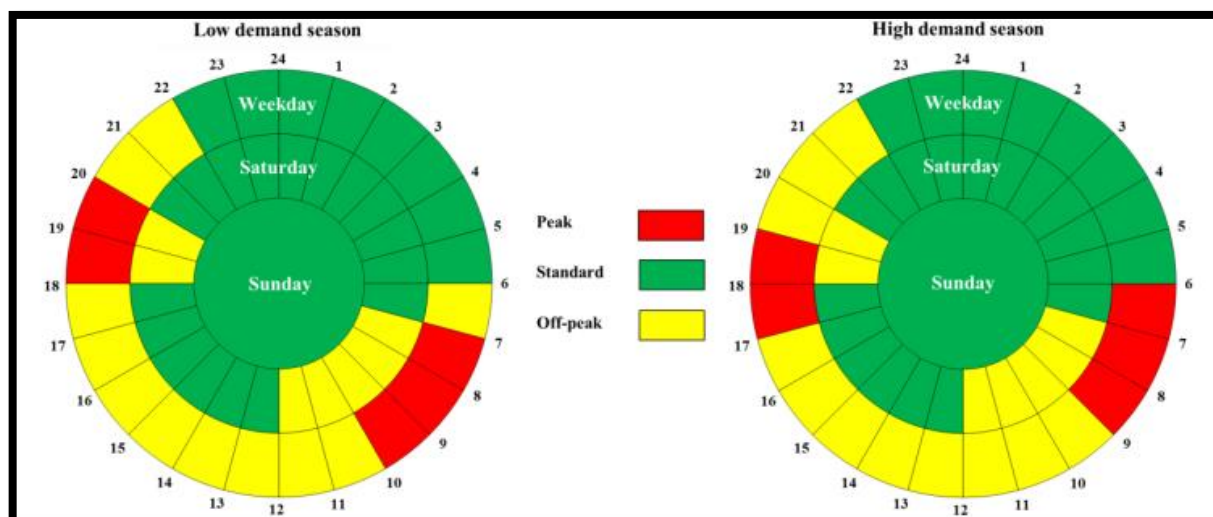


Figure 21: Eskom Megaflex Time-Of-Use seasonal and hourly allocation

As shown in Figure 21, the TOU structure is allocated according to weekdays, Saturdays (public holidays follow Saturday tariffs) and Sundays. There are also two demand seasons linked to the TOU operational structure. The low-demand season (summer) comprises calendar months January – May and from September – December. The high-demand season (winter) comprises June – August. The Eskom billing months follows a financial year period from July – June the following year. The days within an Eskom month remain the same each year to ensure consistency. The Eskom months billing dates and allocated seasons are shown below in Table 6.

Table 6: Yearly Eskom billing dates and season demand allocation

Demand Season	Eskom Month	Start date	End date
High	Jul	06/17	07/17
	Aug	07/18	08/17
High/ Low	Sep	08/18	09/18
Low	Oct	09/19	10/19
	Nov	10/20	11/20
	Dec	11/21	12/17
	Jan	12/18	01/19
	Feb	01/20	02/19
	Mar	02/20	03/20
	Apr	03/21	04/18
	May	04/19	05/17
High/ Low	Jun	05/18	06/16

**The Eskom months of June and September are both allocated to high and low season due to the demand seasonal allocations following calendar months.*

Due to the tariffs following a structure where peak, standard and off-peak times are allocated to different days of a week, it is essential to establish the quantities of days within a given Eskom month. Table 7 below illustrates the quantities of each collectively grouped day of the week.

Table 7: FY22 Eskom month days distribution

Eskom Month	Weekdays	Saturdays (incl. public holidays)	Sundays	Eskom month days
Jul-21	22	5	4	31
Aug-21	22	4	5	31
Sep-21	22	6	4	32
Oct-21	21	5	5	31
Nov-21	23	5	4	32
Dec-21	19	4	4	27
Jan-22	22	6	5	33
Feb-22	22	5	4	31
Mar-22	20	4	5	29
Apr-22	18	7	4	29
May-22	19	6	4	29
Jun-22	21	5	4	30
Total days				365

**During leap years, an extra day is allocated to the March Eskom month.*

Public holidays are charged as Saturday tariffs according to Eskom's cost allocation [90].

Depending on the operation of the identified pumps within the process boundary, the consumption cost can be calculated in two ways. The different modes of operation are:

- Constant operation, and
- variable operation.

1. Constant operation

Pumps operating on a constant basis are not as severely affected by the differing TOU distribution as pumps with a degree of control applied. To simplify comparison, monthly effective tariffs can be calculated according to a weighted distribution of weekdays, Saturdays and Sundays. The weighted effective tariff for each distinguishable **day** in Figure 21 for the FY22 Eskom year is calculated using Equation 11- Equation 13 (method adapted from [91]).

Equation 11: Weekday weighted tariff calculation (low- and high demand season)

Weekday tariff =

$$\left(\left(\frac{P_t}{Daily_{wchr}} \right) \times P_{wchr} \right) + \left(\left(\frac{Std_t}{Daily_{wchr}} \right) \times Std_{wchr} \right) + \left(\left(\frac{OP_t}{Daily_{wchr}} \right) \times OP_{wchr} \right)$$

Where:

Weekday tariff = Weighted calculated tariff allocated to weekdays of low- and high-demand seasons (R/kWh)

P_t = Tariff allocated to low or high demand weekday peak times (R/kWh)

P_{wchr} = Hours allocated per day to weekday peak times (hours)

$Daily_{wchr}$ = Total hours in a day (hours)

Std_t = Tariff allocated to high or low demand weekday standard times (R/kWh)

Std_{wchr} = Hours allocated per day to weekday standard times

OP_t = Tariff allocated to high or low demand weekday off-peak times (R/kWh)

OP_{wchr} = Hours allocated to weekday off-peak times (hours)

The calculation of the tariff for a Saturday is done by using Equation 12.

Equation 12: Saturday weighted tariff calculation (low- and high demand season)

$$Saturday\ tariff = \left(\left(\frac{Std_t}{Daily_{wchr}} \right) \times Std_{sahr} \right) + \left(\left(\frac{OP_t}{Daily_{wchr}} \right) \times OP_{sahr} \right)$$

Where:

Saturday tariff = Weighted calculated tariff allocated to weekdays of low- and high-demand seasons (R/kWh)

Std_{sahr} = Hours allocated per day to Saturday standard times (hours)

OP_{sahr} = Hours allocated per day to Saturday off-peak times (hours)

For Sundays, both the low- and high-demand seasons only consist of off-peak tariffs. This is represented by Equation 13.

Equation 13: Sunday weighted tariff calculation (low- and high demand season)

$$Sunday\ tariffs = OP_t$$

Where:

Sunday tariffs = Weighted calculated tariff allocated to weekdays of low- and high-demand seasons (R/kWh)

The seasonal split months of **June** and **September** are required to be normalised between a split of days allocated to the high season and low season. This additional calculation step is required to ensure provision is made for the high- and low-season demand transition. A normalised peak, standard and off-peak tariff is first calculated before the steps shown in Equation 11– Equation 13 are followed. The normalised TOU tariffs calculation for the split Eskom months are shown below in Equation 14 – Equation 16 [91].

Equation 14: Eskom split month peak tariff calculation

$$Split\ month\ peak\ tariff = \left(\left(\frac{HD_{pt}}{Total\ days} \right) \times HD_{days} \right) + \left(\left(\frac{LD_{pt}}{Total\ days} \right) \times LD_{days} \right)$$

Where:

Split month peak tariff = Weighted calculated split month peak tariff (R/kWh)

HD_{pt} = High-demand Eskom peak tariff (R/kWh)

Total days = Total days within the Eskom month (days)

HD_{days} = Total days allocated to high-demand season within the Eskom month (days)

LD_{pt} = Low-demand Eskom peak tariff (R/kWh)

LD_{days} = Total days allocated to low-demand season within the Eskom month (days)

The split month standard tariff calculation is obtained by using Equation 15.

Equation 15: Eskom split month standard tariff calculation

$$Split\ month\ std\ tariff = \left(\left(\frac{HD_{std\ t}}{Total\ days} \right) \times HD_{days} \right) + \left(\left(\frac{LD_{std\ t}}{Total\ days} \right) \times LD_{days} \right)$$

Where:

Split month std tariff = Weighted calculation of the split month standard tariff (R/kWh)

$HD_{std\ t}$ = High-demand standard Eskom tariff (R/kWh)

$LD_{std\ t}$ = Low-demand standard Eskom tariff (R/kWh)

The split month off-peak tariff calculation is obtained using Equation 16.

Equation 16: Eskom split month off-peak tariff calculation

Split month off – peak tariff =

$$\left(\left(\frac{HD_{op\ t}}{Total\ days} \right) \times HD_{days} \right) + \left(\left(\frac{LD_{op\ t}}{Total\ days} \right) \times LD_{days} \right)$$

Where:

Split month off – peak tariff = Weighted calculation of the split month off-peak tariff (R/kWh)

$HD_{op\ t}$ = High demand off-peak Eskom tariff (R/kWh)

$LD_{op\ t}$ = Low demand off-peak Eskom tariff (R/kWh)

After the daily effective tariff calculations are completed, the monthly effective tariff is determined. Equation 17 shows the calculation of the monthly effective tariffs.

Equation 17: Monthly effective tariff calculation

Monthly effective tariff =

$$\left(\left(\frac{Weekday_t}{EM_{days}} \right) \times Weekday_{days} \right) + \left(\left(\frac{Saturday_t}{EM_{days}} \right) \times Saturday_{days} \right) + \left(\left(\frac{Sunday_t}{EM_{days}} \right) \times Sunday_{days} \right)$$

Where:

Monthly effective tariff = Weighted monthly effective tariff (R/kWh)

Weekday_t = Weighted weekday tariff (R/kWh)

Weekday_{days} = Total weekdays in Eskom month (days)

EM_{days} = Total days in Eskom month (days)

Saturday_t = Weighted Saturday tariff (R/kWh)

Saturday_{days} = Total Saturdays in Eskom month (days)

Sunday_t = Weighted Sunday effective tariff (R/kWh)

Sunday_{days} = Total Sundays in Eskom month (days)

Yearly tariff increases announced for Eskom tariffs take effect in the calendar month of April during an Eskom financial year [92]. The Eskom month of April is, therefore, required to follow the same steps as Equation 14 – Equation 16 to obtain a normalised peak, standard and off-peak tariff to ensure an effective tariff is calculated accordingly.

During the calendar month of April 2022, Eskom introduced a 9.61% tariff hike [92]. This required the remaining months of the FY22 Eskom financial year to be adjusted by the tariff percentage increase. The weighted effective tariff calculated per month, by using Equation 11 – Equation 17, of the FY22 Eskom financial year is represented by Table 8 below.

Table 8: Monthly weighted effective tariffs (FY22)

FY22	Weekday tariff (c/kWh)	Saturday tariff (c/kWh)	Sunday tariff (c/kWh)	Monthly tariff (c/kWh)
Jul-21	181.29	101.13	83.72	155.77
Aug-21	181.29	101.13	83.72	155.21
Sep-21	138.84	109.67	78.62	125.84
Oct-21	105.83	98.54	74.65	99.62
Nov-21	105.83	98.54	74.65	100.79
Dec-21	105.83	98.54	74.65	100.13
Jan-22	105.83	98.54	74.65	99.78
Feb-22	105.83	98.54	74.65	100.63
Mar-22	105.83	98.54	74.65	99.45
Apr-22	112.29	104.56	82.06	106.25
May-22	116.24	108.24	79.25	109.48
Jun-22	160.35	123.13	87.37	144.41
Average effective tariff for FY22				116.45

The single effective tariff used to calculate the consumption of spindle pumps within the Mine A process boundary for the FY22 Eskom financial year is determined as **R1.165 R/kWh**. The quantity of pumps to be measured (each identified pump size) is calculated by the sample size determination (Equation 10). The average consumption values obtained for each pump size can be used in the calculation criteria to obtain the overall system cost per annum. Costs are to be grouped according to consumption per level to simplify responsibility areas should potential configuration changes be recommended. The cost calculation method is also used by energy efficiency consultants as part of savings determinations on industrial operations [26]. Estimate cost calculation per level is done by using Equation 18 below.

Equation 18: Formula to determine spindle pump total level cost

$$\text{Level cost} = \text{pump quantity} \times \text{avge kW} \times \text{running hrs p.a.} \times \text{avge Eskom tariff}$$

Each level's pump operation and running cost should be added to obtain the total yearly cost of the spindle pump system within the operational process boundary.

2. Variable Operation

If the pumps identified within the process boundary operate on a basis of variable consumption (switched on and off during the day), Eskom tariffs can be applied according to an hourly cost for a weekday, Saturday and Sunday for the various demand seasons. Table 9 below represents the daily tariff distribution for low- and high-demand seasons (summer and winter).

Table 9: Hourly Eskom TOU allocations (high- and low demand)

Summer Tariff				Winter Tariff			
Hour	Weekday	Saturday	Sunday	Hour	Weekday	Saturday	Sunday
0	74.65	74.65	74.65	0	83.72	83.72	83.72
1	74.65	74.65	74.65	1	83.72	83.72	83.72
2	74.65	74.65	74.65	2	83.72	83.72	83.72
3	74.65	74.65	74.65	3	83.72	83.72	83.72
4	74.65	74.65	74.65	4	83.72	83.72	83.72
5	74.65	74.65	74.65	5	83.72	83.72	83.72
6	108.37	74.65	74.65	6	426.94	83.72	83.72
7	150.12	108.37	74.65	7	426.94	140.58	83.72
8	150.12	108.37	74.65	8	426.94	140.58	83.72
9	150.12	108.37	74.65	9	140.58	140.58	83.72
10	108.37	108.37	74.65	10	140.58	140.58	83.72
11	108.37	108.37	74.65	11	140.58	140.58	83.72
12	108.37	74.65	74.65	12	140.58	83.72	83.72
13	108.37	74.65	74.65	13	140.58	83.72	83.72
14	108.37	74.65	74.65	14	140.58	83.72	83.72
15	108.37	74.65	74.65	15	140.58	83.72	83.72
16	108.37	74.65	74.65	16	140.58	83.72	83.72
17	108.37	74.65	74.65	17	426.94	83.72	83.72
18	150.12	108.37	74.65	18	426.94	140.58	83.72
19	150.12	108.37	74.65	19	140.58	140.58	83.72
20	108.37	74.65	74.65	20	140.58	83.72	83.72
21	108.37	74.65	74.65	21	140.58	83.72	83.72
22	74.65	74.65	74.65	22	83.72	83.72	83.72
23	74.65	74.65	74.65	23	83.72	83.72	83.72

The consumption profile of the spindle pumps within the boundary can be allocated to each hour's tariff of every distinguishable day of the two seasons. The total summer and winter cost of the spindle pump consumption is shown by Equation 19 and Equation 20.

Equation 19: Yearly low demand hourly allocated cost calculation

$$LD\ cost = \left(\frac{(LDwk_{cost} \times 5) + (LDSat_{cost}) + (LDSun_{cost})}{Nr\ of\ days\ in\ week} \right) \times LDtotal_{days}$$

Where:

$LD\ cost$ = Low demand/summer cost of consumption (R)

$LDwk_{cost}$ = Cost of an average low-demand weekday consumption (R)

$LDSat_{cost}$ = Cost of average low-demand Saturday consumption (R)

$LDSun_{cost}$ = Cost of average low-demand Sunday consumption (R)

$LDtotal_{days}$ = Total quantity of days in low-demand season (days)

$Nr\ of\ days\ in\ week$ = Total number of days in a week (days)

The high-demand season cost can be determined by Equation 20.

Equation 20: Yearly high demand hourly allocated cost calculation

$$HD\ cost = \left(\frac{(HDwk_{cost} \times 5) + (HDSat_{cost}) + (HDSun_{cost})}{Nr\ of\ days\ in\ week} \right) \times HDtotal_{days}$$

Where:

$HD\ cost$ = High demand/winter cost of consumption (R)

$HDwk_{cost}$ = Cost of an average high-demand weekday consumption (R)

$HDSat_{cost}$ = Cost of average high-demand Saturday consumption (R)

$HDSun_{cost}$ = Cost of average high-demand Sunday consumption (R)

$HDtotal_{days}$ = Total quantity of days in high-demand season (days)

The total cost of the spindle pump consumption for the year following a variable mode of operation is obtained by Equation 21.

Equation 21: Total yearly consumption cost calculation

$$Total\ yearly\ cost = LD_{cost} + HD_{cost}$$

Where:

Total yearly cost = Total yearly cost of the spindle pumps electrical consumption (Rand)

The steps in Equation 19 – Equation 21 should be followed for each level in the operational boundary. The yearly cost increase in the calendar month of April should also be noted when following the variable operation calculation method to ensure accuracy.

The total yearly cost of the spindle pump electrical consumption will be used as an operational baseline to determine potential cost savings.

Determining best operating and efficiency point

Best Operating Points of pumps is an essential part of improved system operation and is described as the point along the pump performance curve at which efficiency is at its highest attainable value [93]. This is usually specified at approximately 85% of the shutoff head of the pump [94]. It is not always possible to achieve the Best Efficiency Point (BEP), but by using actual measurement data for a pumping system, the closest possible operating alternative may be achieved. Some of the consequences of running a pump too far left or too far right off its pumping curve include early pump failure and unnecessary additional power consumption [94]. An example of a BEP on a pump performance curve is shown in Figure 22 [95].

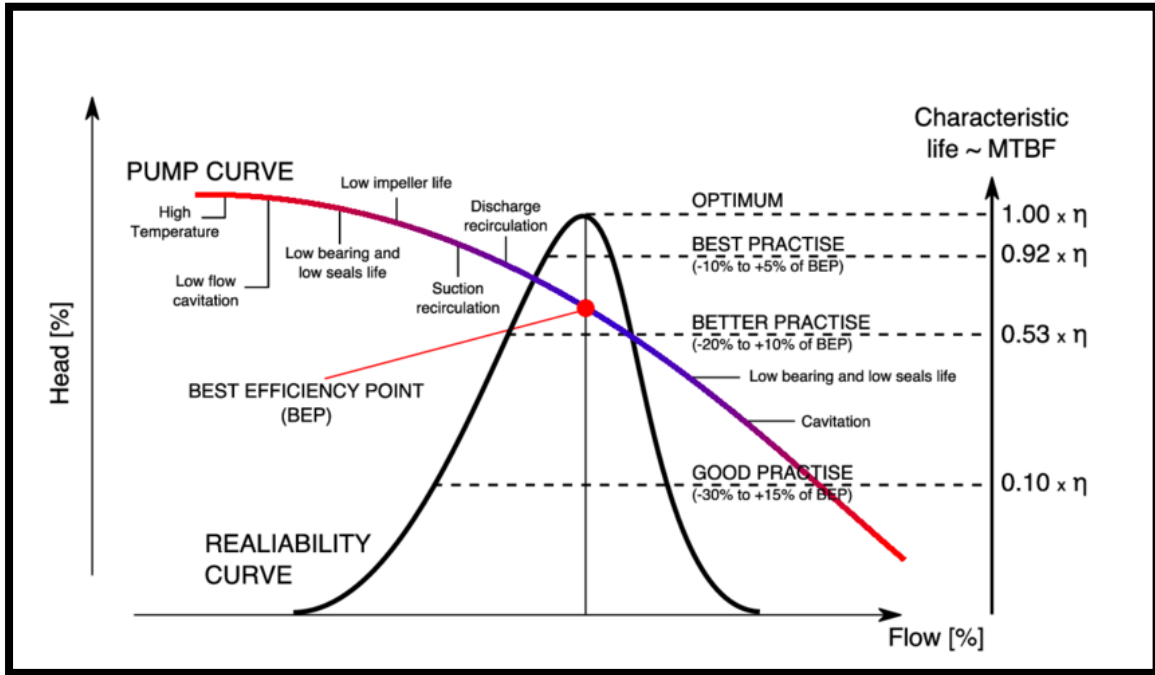


Figure 22: Best efficiency point determination on a pumping performance curve

By using the obtained flows through the pump measurements conducted, the current operating point on each pump size performance curve can be calculated (through use of pump specific curves). Identification of poor performing system pumps could preliminary determine where changes are needed, and potential alternatives may be necessary to achieve operation as close to BEP as possible. With the total system pumping cost already determined, it can be predicted whether it would be financially beneficial to alter the existing quantity of inefficient pumps. This can establish further modelling requirements of the system after the completion of the suggested routine audit.

2.4 Step 2 – Modelling the current system configuration through simulation

Simulation software adds the benefit of verification after initial measurements and calculations have been done. Detailed simulations additionally assist in providing valuable information while considering a vast number of network constraints allowing both a localised and holistic overview of an entirely modelled system [96]. Various simulation software systems have been in use in the mining industry during the past few decades. Certain mining companies prefer specific simulation software, mostly due to familiarity.

It was seen upon comparison, however, that there are some shortcomings to some of the most used software entities. These comparisons are shown in Table 10.

Table 10: Simulation software comparison

Simulation software	Benefits	Disadvantages	Previously used case studies
VUMA (Coolflow)	- Widely used throughout the mining industry - Successes in previous water application simulations	- Does not allow water reticulation system to be fully integrated into one model - Steady state solver	[97] [98]
US Patent nr. 6366889 by Zalloom & US Patent nr. 6178362 by Woolard et.al	- Can provide real-time data values - Main focus in providing costing errors by analysing consumption trends	- Simulation tools are not continuous - Lacks the option of automated control	[99]
H20NET	- Assists identifying the best network combinations relating to hydraulic design and performance	- System is not able to provide real-time values - Primarily developed for industrial water systems (not UG)	[100] [101]
SA Patent nr. 2004/1172 by TEMM Int. (Pty) Ltd	- Easily implemented control system - Improvement is based on predictive loads and energy prices over 24 hours - Control system can be used for underground mines	- Control is not done in real-time - Can only function on a Citrix SCADA	[16] [102]
Real-Time Energy Management System (REMS) pumps	- Can provide real-time values - Used to predict potential of load shifting projects	- Focuses mainly on large UG pumps - Does not integrate all components of a water reticulation system	[52]
Process Toolbox (PTB3D)	- Accurate for mining applications - Can solve for transient applications - Can be integrated into the SCADA system with Management Toolbox (MTB) software to provide real-time values - Applicable for mine dewatering and distribution systems	- New to market - Requires training to build simulation models - Limited licensing access available for use	[51] [4] [96] [29] [103]

The construction of the horizontal transfer pumping system will be done using Process Toolbox (PTB3D). PTB3D is a transient thermal flow solver which enables the solving of complex systems using a wide array of contributing parameters [96].

The simulation will be used as an integrated verification evaluation to assist in establishing accurate parameters by using the data collected in Step 1 of the methodology.

More than one simulation model will be developed throughout the methodology to ensure the current and potential future configuration, once established, is properly evaluated before final conclusions can be made. Calibration will be used to ensure the starting parameters used for the models provide accurate values when compared to the manual measurements. Furthermore, the simulation model will be used to determine the optimal system configuration to obtain the most energy efficient and cost-effective operation with current and future water demands. Fundamental calculations of the simulation software can be viewed in Appendix B.

2.5 Step 3 – Improve the system energy consumption and configuration

After proper calibration and verification of the model is completed, potential changes to the system can be considered. Measured and simulated performance results of the current system are used as a baseline for the potential changes to the system.

Savings potential verification

To establish the savings potential attainable through a system configuration change, a few conclusions and follow-up questions need to be derived from the obtained simulation results for each of the pumps **from each level**. Answering these questions would narrow down and establish the potential savings attainable (each level to be evaluated individually) [54].

Current system evaluation

1. What are the maximum flow requirements of each pump (from current data)?
2. How far are the distances between the pumps?
3. Do the pumps require additional head other than the distance to the return line?
4. Are the pumps performing poorly in relation to its BEP?
5. What are the operating pressures of each pump?
6. Are the pumps operating close to their maximum pressures?

7. Are the pumps sized correctly for the application?
8. Would a differently sized pump perform more effectively in this application?
9. Are the pumps suggested for configuration changes?
10. Which preliminary pump size would better suit the application?

After the suggested pumps on the levels are identified for change, each of the applications will be properly investigated to obtain a suitable substitute for the current entity. The feasibility of the replacement pumps should also be assessed **by applying the criteria relating to the specific operations' payback period standards** (CAPEX vs OPEX). If a pump is to be replaced, pumping parameters such as **flow, power consumption, operating pressure and head requirements** are used to establish the suitability of the replacement.

Specific solutions development

Vertical spindle pumps are a wide array of versatile pumps suitable for most applications of mine water drainage [54], [58], [70]. Pumping performance curves of vertical spindle pump ranges are required to establish which pump size would be better suited for the application. The comparison of the different performance curves establishes a better suited alternative. Figure 23 provides a good example of performance curves **comparisons** of spindle pumps [70].

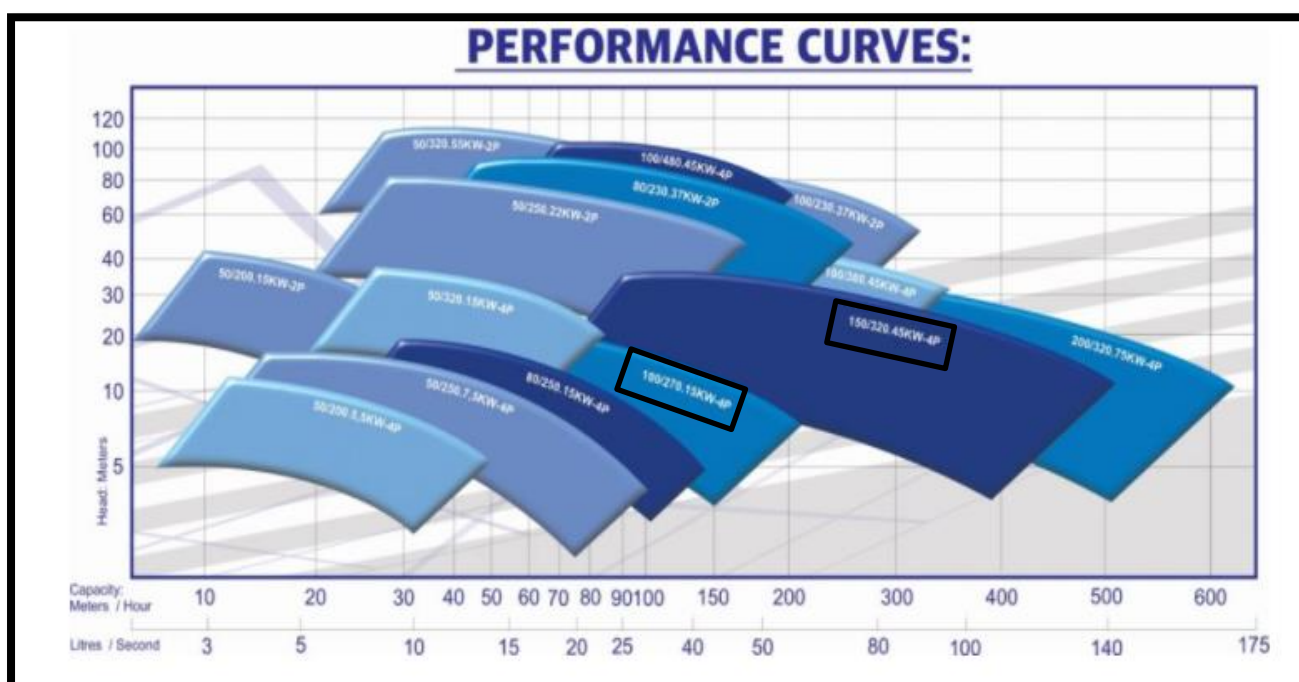


Figure 23: Spindle pump performance curve comparison

If the identified application can be replaced by a different sized pump, the performance curve of the newly suggested pump needs to be incorporated into the simulation at each instance of suggested change. The same set of system evaluating questions will be addressed for the recommended system changes after simulation integration. Preliminary outcomes of the newly incorporated pumps into the simulation will provide results on the key parameters discussed in the paragraph above. Actual preliminary pilot test results of the suggested pumps before system replacement provide a better insight into the real-world industrial performance, confirms or denies simulation results, and is duly recommended.

After the current system has been evaluated, configuration suggestions have been incorporated and pilot testing has been conducted, the potential savings after configuration changes can be computed. For spindle pumps following a constant mode of operation, the monetary savings value of suggested changes from each level can be determined by Equation 22, incorporating the level cost values determined by Equation 18 [26].

Equation 22: Spindle pumps individual level cost savings calculation (constant operation)

Level savings =

Level cost – (*changed pump quantity* × *avge kW* × *running hrs p. a* × *Avge Eskom tariff*)

For the variable operation of spindle pumps, the monetary savings can be determined by the difference in electrical consumption for each hour of the day for the two seasons by using Table 9 for each of the indicated levels. Equation 23 – Equation 24 will be used to establish the monetary savings of spindle pumps with variable mode of operation for a given financial year.

Equation 23: Low demand spindle pumps individual level cost savings (variable operation)

LD savings =

$$\left(\frac{((LDwk_{cost} - LDwk_{newcost}) \times 5) + (LDSat_{cost} - LDSat_{newcost}) + (LDSun_{cost} - LDSun_{newcost})}{Nr\ of\ days\ in\ week} \right) \times LDtotal_{days}$$

Where:

LD savings = Total cost savings during the low-demand season (R)

LDwk_{newcost} = New low demand weekday consumption cost after changes (R)

$LD Sat_{newcost}$ = New low-demand Saturday cost after changes (R)

$LD Sun_{newcost}$ = New low-demand Sunday cost after changes (R)

Equation 24: High-demand spindle pumps individual level cost savings (variable operation)

$$HD \text{ savings} = \left(\frac{((HDwk_{cost} - LDwk_{newcost}) \times 5) + (HDSat_{cost} - HDSat_{newcost}) + (HDSun_{cost} - HDSun_{newcost})}{Nr \text{ of days in week}} \right) \times HDtotal_{days}$$

The total yearly savings can be computed by the addition of both seasons' monetary value as seen in Equation 25.

Equation 25: Total yearly spindle pump cost savings per level for variable operation

$$Total \text{ yearly savings} = LD_{savings} + HD_{savings}$$

The saving contributions from each calculated level is added to obtain the total mine-wide potential savings through configuration changes. Initial savings potential determination is an important step in the method due to it providing a base quantity for potential savings. After the initial base quantity is verified and deemed feasible, additional investigations to ensure adaptability can proceed.

2.6 Step 4 – Dynamic adaptability and sustainable solutions incorporation

Dynamic adaptability and sustainable solutions are key elements to the success of any given project. Past identified projects, which delivered promising initial results, have failed due to a lack of dynamic adaptability and sustainable solutions integration. According to [104], the main attributing factors to project failure are the following:

1. Project scope change,
2. internal conflicts between project and departmental tasks,
3. resource contention,
4. lack of resource and project performance tracking,

5. lack of project allocated resources,
6. deviation from or lack of project management methodologies,
7. lack of a defined software project management methodology framework,
8. conflicting project prioritisation,
9. simultaneously assigned tasks to originally allocated resources,
10. poor software quality, and
11. unrealistic project expectation and lack of future change planning.

Dynamic adaptability

Dynamic adaptability is shown as a metalevel capability relating to the variability of the focused application [105]. In order to integrate dynamic adaptability into engineering models, three kinds of conformance models are mainly used. These are:

1. Rule-based adaptation – This is feasible for the purpose of determining which actions should be performed due to monitored or environment changes [106].
2. Goal-oriented adaptation – This mechanism is extensively popular in the engineering community as the approach explicitly factors uncertainty into the requirements analysis process [107].
3. Control loop-based system model – This mechanism envisions computing systems that can manage duties independently relating to maintenance and improvement [108].

Due to the system operation of spindle pumps being classified as a continuous operation, constant process monitoring is needed to ensure system changes are swiftly noted. The approach used for this study comprises a combination of the three approaches listed above. The specific criteria from all three adaptation methods applicable to the study at hand are the following:

Rule-based integration

As previously stated, spindle pump system monitoring has not been a focus point in deep-level mines. Individual pump performance monitoring remains a challenge due to equipment cost feasibility relating to pump costs. Pump design principles are used to determine a more suitable pump (specific solutions development) for the application if the investigation reveals confirmation [109]. Safety design factor rules for engineering disciplines differ according to the applications at hand. For most pressure and load related applications, the norm is to operate on a safety design factor of 2 [110], [111]. For this application, water load demand is the parameter which will most notably influence the design of the spindle pump system.

Alternative pumps chosen for the application should be able to pump water at twice the current established demand to compensate for fluctuations within the system. Certain water flow limits, operating according to step-based increases or decreases in flow, need to be established for system operation to ensure contingency plans are in place. Monitoring the water flows is obtainable through either instrumentation installation at strategically identified locations to measure the entire system flow, or individually equipping XC spindle pumps with flowmeters.

Simulation integration with the SCADA enables access to real-time water flow values obtained at the location in question. Real-time monitoring access is key to monitoring project success.

Different tag blocks built for all relevant locations within the simulation are available to view real-time data measured by instrumentation. Limits and alarms can be added to certain monitored parameters to compare operation with the intervals identified for normal operation. Operational limits for system operation are divided according to a seven-step operational monitoring system once installed system capacity is calculated [112]:

1. Low-low system flow (0-10% system capacity),
2. low system flow (10-20% system capacity),
3. low-medium system flow (20-40% system capacity),
4. medium system flow (40-50% system capacity),
5. high-medium system flow (50-65% system capacity),

6. high system flow (65-85% system capacity), and
7. high-high system flow (>85% system capacity).

The seven-step system is an operational warning interval establishment used on the SCADA system of deep-level mines to ensure enough time is allocated for maintenance should the limits be surpassed [112]. The establishment of operating regimes assists with timelines for remedial actions to be taken if an alert interval of flow is measured. It should be noted that a time constraint should be considered when interval level conditions are satisfied. Each of the monitored XCs are investigated to establish a blueprint for water usage quantity throughout the day as mining activities differ for every shift.

These blueprint values will determine the cause for the change in consumption. Considering the safety design factors used for system operation (factor of 2) and outlier interval conditions are satisfied, efficient remedial actions are required. Table 11 provides guidelines of remedial actions when each interval condition is satisfied.

Table 11: Generic water flow interval summary for production levels

Interval	Operating time (condition satisfied)	Remedial actions
Low-low system flow	>1-2 hours (depending on margin from 10% capacity surpass)	Install properly sized pumps in areas where low water use is reported. Re-evaluate system configuration if deemed necessary.
Low system flow	>1 day	Investigate areas for reported decreased use of water, establish the cause and derive a potential solution. Ensure properly sized standby replacement pumps are ready for installation should it be required.
Low-medium system flow	Operating regime closest to BEP	No action required.
Medium system flow		
High-medium system flow		
High system flow	>1 day	Investigate areas for reported increased use of water, establish the cause and derive a potential solution. Ensure properly sized standby replacement pumps are ready for installation should it be required.
High-high system flow	>1-2 hours (depending on margin from 100% capacity surpass)	Install properly sized pumps in areas where high water use is reported. Re-evaluate system configuration if deemed necessary.

Goal-oriented integration

Deep-level mining operation is an ever-changing dynamic process, especially when considering water consumption. Unexpected occurrences are, therefore, a common phenomenon within the water reticulation network. Mining water demand is established through proper mine planning and can be determined for the current operation size. Provision needs to be made for other quantities of water **not** originating from the mining water demand. Some sources of mine water ingress are identified as the following [113], [114]:

- Water recharge due to rainfall,
- groundwater seeping into workings,
- sewage and stormwater systems,
- closure of nearby connected mining shafts' fissure water networks,
- seepage from mine residue deposits,
- natural fissure water sources,
- nearby river water through interconnected underground streams, and
- surface streams losing water to shallow mine workings.

Some of the above-mentioned sources are seasonal dependent and differ throughout the year, while other identified sources are mining induced. Contingency for additional water sources can be made through the analysis of the patterns throughout recent years to establish an estimate of what the expected additional water ingress will amount to [115]. It is suggested that mine drainage infrastructure be evaluated timeously to ensure shaft flooding is prevented. Mine-based geologists continuously evaluate the ground structure and potentially newly developed sections' water demand to integrate their findings with mine planning [116]. Various strategies of water diversion have been researched to mitigate pumping costs on active mines [116].

Valuable information can be obtained from geologists when establishing water demand due to non-mining activities-related water ingress. Figure 24 provides a visual representation of the steps to follow to determine the potential water ingress relating to the current water demand for the spindle pump system.

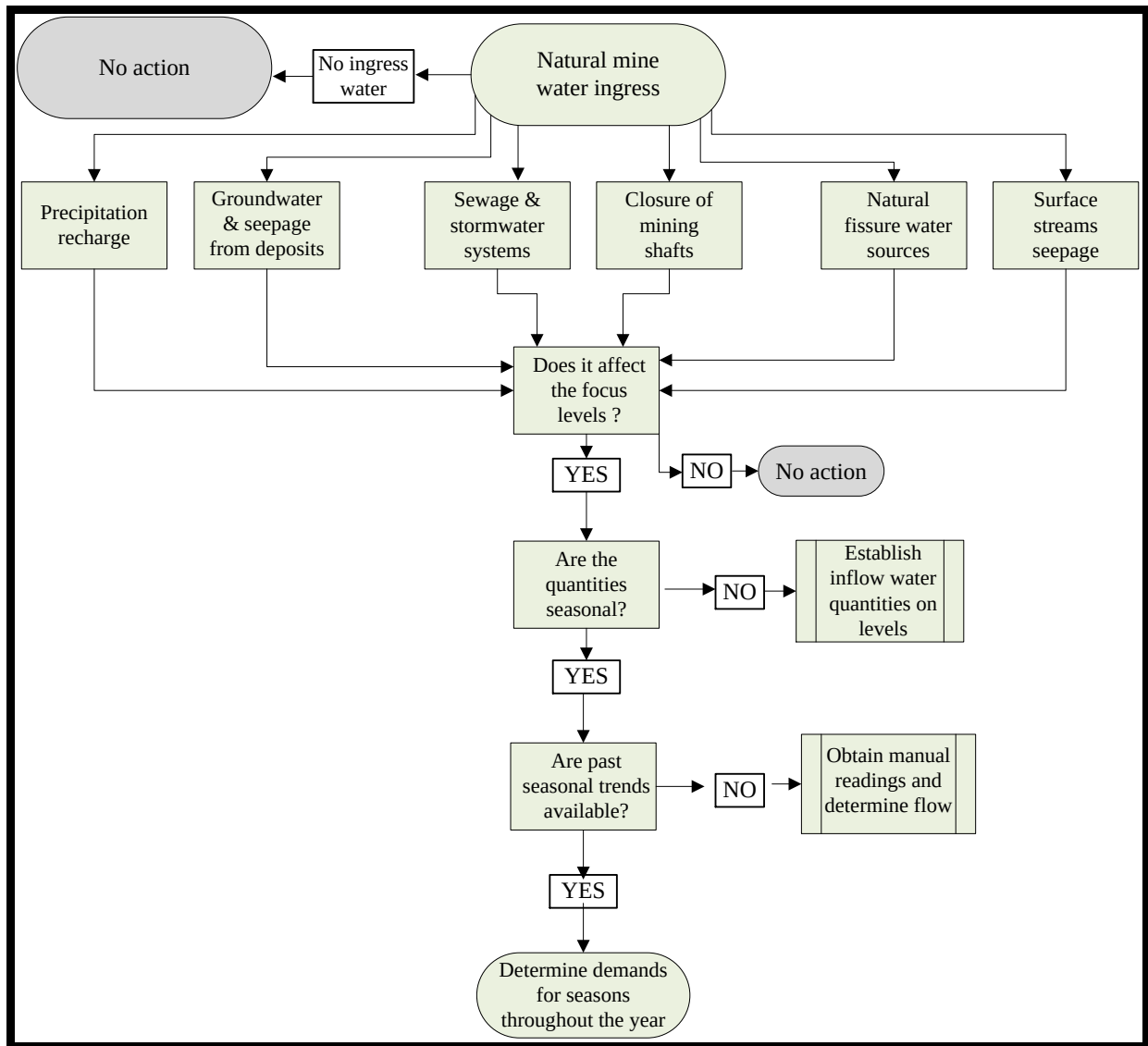


Figure 24: Water ingress flow diagram

After additional water demands for the year have been determined, analysis to ensure proper configuration planning is completed can be done to ensure the spindle pump system operates efficiently throughout the year.

Control-loop based model integration

Deep-level mines are continuously developing ways to mitigate water usage to reduce OPEX costs or increase production [40], [117]. Projects with the goal of mitigating water usage in mines or increasing production should be incorporated into the evaluation of the spindle pump system. These projects can either assist in the improvement of the spindle pump system or force changes to be made due to increased water consumption in attempts to boost production.

Upon implementation of the projects, the following project-based questions should be answered (adaptation from [118] and [119]):

- Do the implemented projects reduce or increase the return water quantities from the working areas?
- Are operating schedules involved in the operation of these projects?
- Are the necessary infrastructure entities in place to properly monitor the change in water demand due to the implemented projects?
- Which parameters should be monitored to ensure projects' compatibility?
- What are the savings/additional costs of the implemented projects compared to current return water system operation?
- Are there integration strategies to ensure potential negative counteractions are avoided?
- Are configuration changes to the spindle pump system necessary due to the implementation of these projects?

Project influence on systems is a crucial part of planning. Ways to integrate the spindle pump system improvement and new project implementation to reap benefits from both entities is the main goal for this step of dynamic adaptation. Communication will play a key role in the success of this step as important parameters for monitoring are identified to ensure an acceptable balance between spindle pump system improvement and new project success.

Sustainable improvement

Sustainability can be described as the process of sustaining a change in a balanced manner and is one of the most important parameters to consider when starting a project [120]. Project sustainability in deep-level mines has been difficult to maintain for extensive periods of time. It is essential to consider certain aspects of sustainability when implementing a project to ensure the project benefit is prolonged. A study conducted by [118] aimed to use digital mining solutions, such as simulations, as an integral part of a holistic sustainability model for deep-level mining projects.

It is important to identify the reasons for project failure to develop solutions to counteract these factors. Some of the challenges faced during project implementation are [121], [122]:

- Practical challenges and delays,
- control, management and maintenance limitations, and
- lack of future development incorporation.

Using the above-mentioned reasons as a base for sustainable project implementation, a suitable sustainability model can be derived. Figure 25 is a visual representation of a sustainability model adapted to meet the current project needs [118], [123], [124].

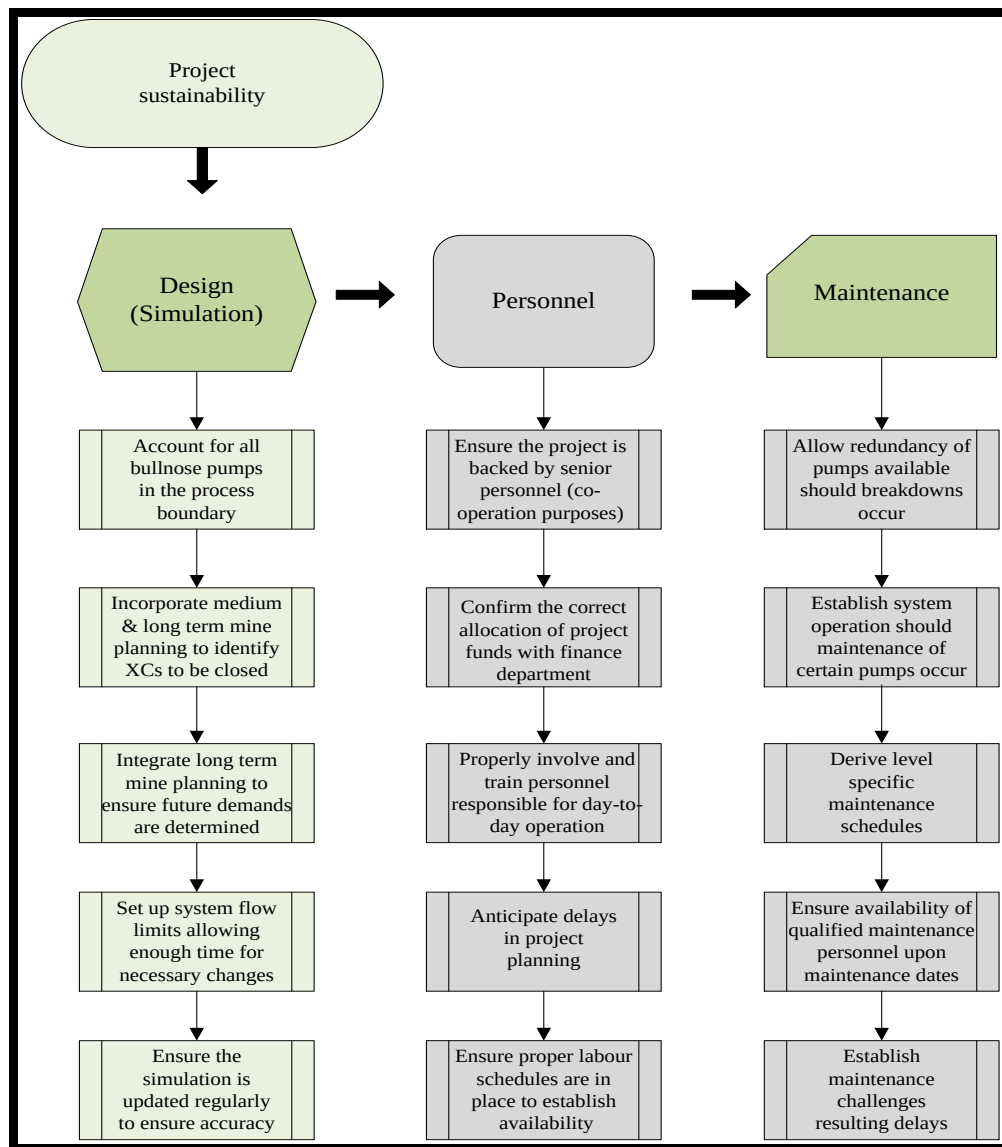


Figure 25: Sustainability model flow diagram

The incorporation of the steps derived in Figure 25 mitigates project failure before and after project implementation. The model can also assist potential inexperienced project managers to keep the project on course.

2.7 Step 5 – Implementation tracking and results analysis

Implementation

Project implementation can be a challenging task in a deep-level mine, often due to the mismanagement of resources and the lack of communication between departments. The key to project implementation comprises comprehensive planning prior to actual implementation [125]. A proper implementation plan streamlines the process of implementation and ensures project completion within the allocated timeframe and budget if followed correctly. Thus, project implementation steps, adapted for the current project at hand, are the following [125], [126], [127], [128]:

- Set up a project implementation timeline – Timelines are an important factor in project implementation as the rest of the planning revolves around the time set out for project completion. The timeline should clearly state when and where the proposed changes are to be made and compensate for potential unexpected occurrences. Project Gantt charts are good examples of an effective visual timeline representation indicating various responsibilities.
- Ensure task and responsibility allocation is indicated clearly – More often than not, responsibilities within project management are not allocated clearly. This often leads to confusion and miscommunication resulting in the allocated task not being completed.
- Confirm labour schedules to incorporate time for project implementation – Labour arrangements in deep-level mines is a complex task and requires extensive planning. Involve upper management while scheduling labour for task implementation to enhance project prioritisation and ensure labour availability according to the project timeline.
- Arrange training sessions for allocated technical staff - Staff responsible for actual pump exchanges should be trained properly to ensure efficient installation of pumps. This reduces any unnecessary confusion regarding spindle pump operation.

- Prepare the infrastructure – The acquired pumps indicated for exchange need to be readily available for installation at the designated locations. An added logistic constraint in deep-level mines entails logistic complexity. Transport arrangements for infrastructure need to be made well in advance with the relevant logistic co-ordinators to ensure the pumps reach their final destinations in time for installation. Any existing infrastructure changes are to be arranged with the technical staff simultaneously with transport personnel.
- Monitor the implementation budget – Budget monitoring during this step is important due to certain labour costs being dependent on time allocation and contract work. Ensure budgeting is constructed in a manner that compensates for unexpected delays.
- Monitor the quality of work – Quality monitoring should be incorporated into implementation to ensure installations are done correctly and according to schedule. Physical underground visits to the indicated sections are recommended to confirm the installations are up to standard and communicate the results to the allocated parties.
- Monitor system performance – Sections where configuration changes were made are to be monitored closely to ensure operation proceeds as normal. Any complications in operation need to be addressed with the necessary contingency plans already in place.

The above discussed implementation steps can be visually expressed in a flowchart depicted by Figure 26.

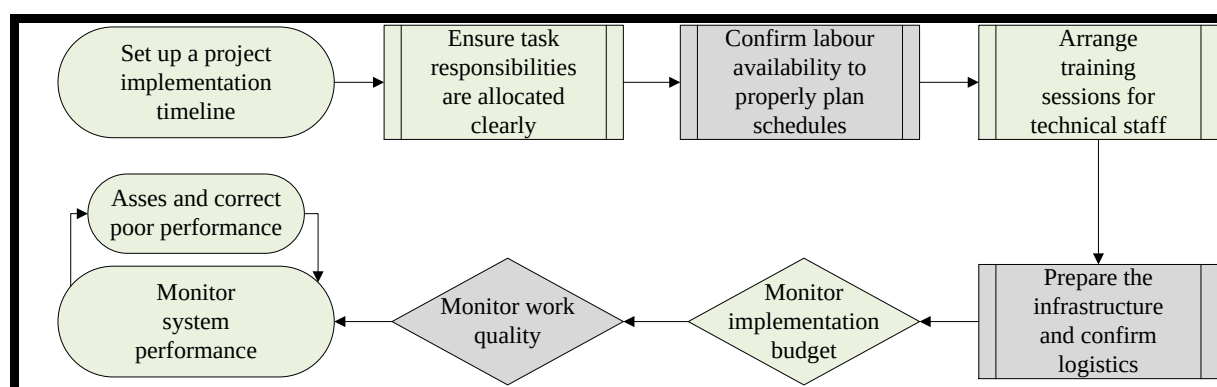


Figure 26: Implementation steps flow diagram

Results analysis

After project implementation, the performance of the newly implemented system needs to be assessed to determine the benefit of the project. Analysis forms an essential part of the final project stages and can be described as the benchmark for project success. It is recommended, if applicable, that results analysis should be conducted as a continuous process throughout implementation and should not be left until project completion [129].

There are mainly two types of basic data analysis [129]:

- Data description – The evaluation of raw data obtained with the purpose of describing and representing raw processed data in meaningful ways (for example, characterising obtained values according to data mean, median, variance, standard deviation or frequency).
- Hypotheses testing – Once data descriptions are determined, they can be used to confirm or deny predictions made by models or simulations developed during the project development phase. For the purpose of this study, the data obtained and processed will be converted into a monetary project benefit.

Results evaluation will comprise an adapted model derived from [119], [130] and [131].

Monitoring

- Translation of established objectives into level-specific performance indicators and targets – The target electrical consumption of each level is determined through the configuration changes recommended from the simulation model [130].
- Routine data collection on new configurations – Data is to be collected from the newly installed pumps in the manner specified in the detailed investigation (Step One of the methodology) of the initial pump audits [130].

Data processing

- The obtained sets of data will be analysed per level and compared to actual preliminary measurement results prior to implementation and to predicted simulation data.

- Actual savings prediction – Electrical cost savings obtained on each level are determined using the data collected from new installations and converted to monetary savings using Equation 22.
- Conclusions on BEP are also to be made from the sample size measurements of the new installations.

Evaluation

- Analysis into why certain predicted results were or were not achieved by the configuration changes. Any contributions to results variations should be documented.
- Examination of the implementation process. Any challenges encountered during the implementation process should be reported on.
- Preliminary solutions and suggestions to problems encountered during the project should be addressed. Recommendations for future improvement to be derived.

The developed data analysis model is visually represented by Figure 27.

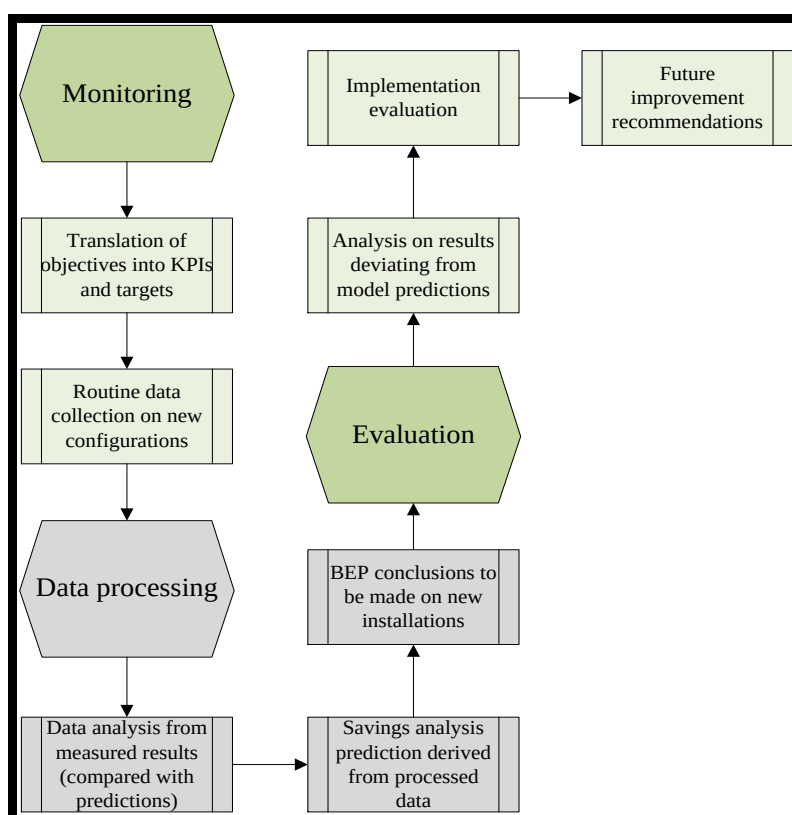


Figure 27: Data analysis flow diagram

The results analysis ultimately determines the success of the project and evaluates the reasons for certain failed predictions or project shortcomings.

By using the recommendations derived from the results analysis, future projects on pumping systems operations can be efficiently adapted to eliminate failures identified within pioneer projects.

2.8 Summary

Chapter 2 elaborated on the methodology developed for the study at hand and discussed each of the derived steps in detail. The strategy was meticulously developed to ensure each of the outlined objectives are achieved and verified. The steps allocated to each objective are shown in Table 12.

Table 12: Strategy and objectives overview

#	Objectives	Corresponding strategy steps
1	Integrate current and future water demands through simulations to reduce OPEX costs.	1, 2, 3 & 5
2	Increase water demands forecasting accuracy for better capital allocation.	4
3	Test scenarios of horizontal water management improvement and the effects on water demand prior to implementation.	2, 3 & 4
4	Add a system-monitoring aspect to previously unmonitored and under-equipped systems.	4

A visual flowchart summary of the methodology steps is displayed in Figure 28. The required simulation inputs can be viewed in Appendix B and results of the applied methodology will be discussed in the following chapter.

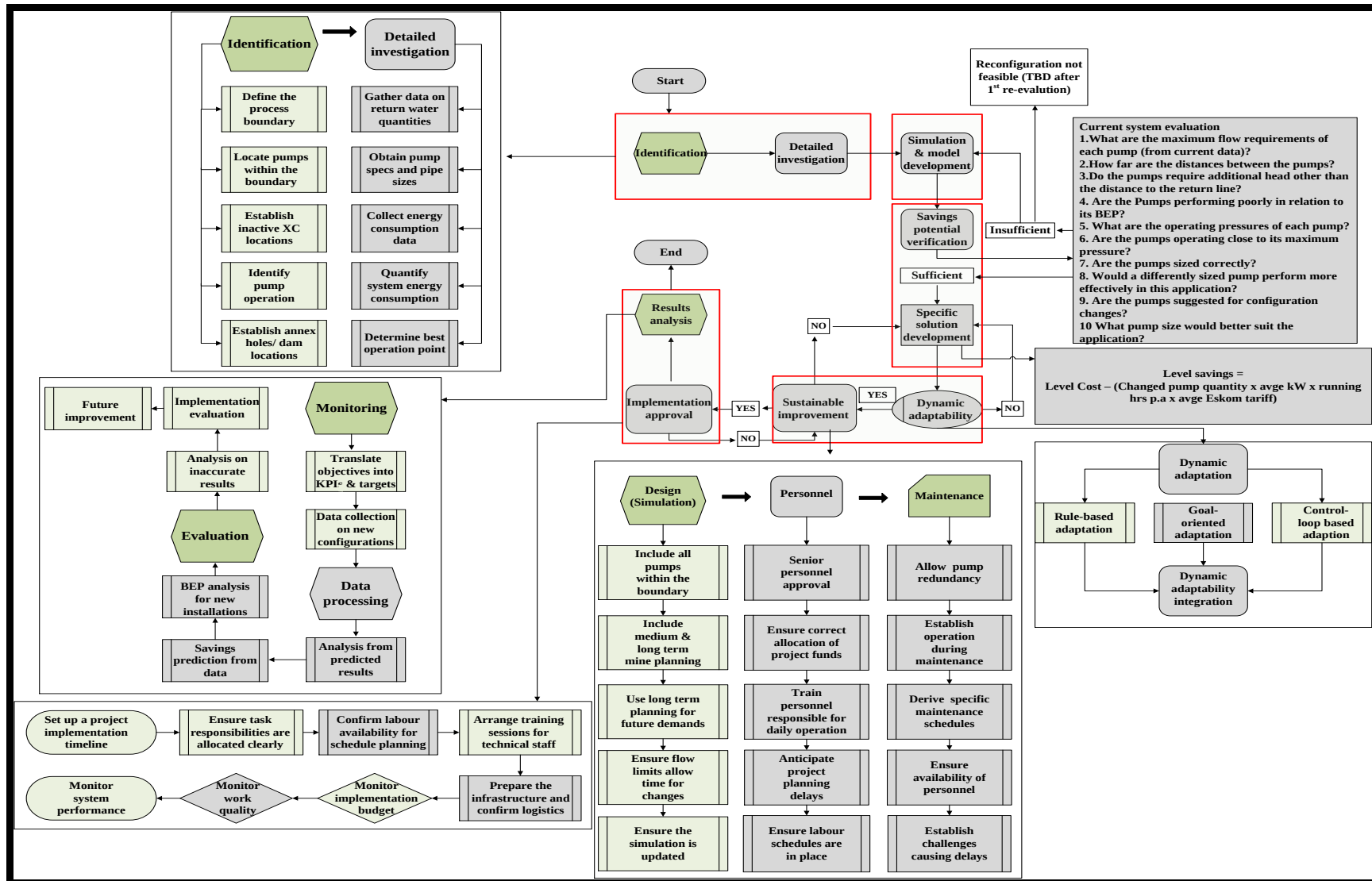


Figure 28: Flow diagram of the complete methodology development

3

CHAPTER 3

RESULTS AND DISCUSSION

“The man of science has learned to believe in justification, not by faith, but by verification.”

— Thomas H. Huxley

3 RESULTS AND DISCUSSION

3.1 Preamble

In this chapter, the developed methodology steps will be applied to a case study at Mine A (stipulated in Figure 13), situated in the Gauteng province in South Africa. The strategy will be applied to the case study following the sequence set out in Figure 28. The results of the case study will be evaluated and presented in the same sequence as the five-step strategy developed in Chapter 2.

Case Study Background

Mining activities at Mine A date as far back as the 1980s and is mined at an average depth of 2 800 – 3 400 m below surface [132]. Mine A is considered one of the world's richest mines in terms of gold reserves and follows a sequential grid-mining strategy due to its operating depths [132]. Mine A has been the object of several deepening projects over the past few decades to extend the Life-of-Mine (LOM). This contributes significantly to underground environmental challenges due to accompanying mine deepening complexities such as temperature gradient and logistic constraints. Mine A consists of three main ore producing levels and three supplementary ore producing levels. The latter is scheduled to be non-beneficial within the next few financial years.

As new development occurred at the operations, old, outdated horizontal water transport management techniques continued to be used. Chilled water is supplied to the mining sections via a U-tube system. After the chilled water is utilised for cooling and mining activities, the utilised chilled and service water is moved towards the level holding dams by means of the spindle pump system, as indicated in Figure 5. Initial underground visits revealed scope to investigate the spindle pump system due to observed inefficient operation.

3.2 Step 1 – Performing a pumping system audit

Identification

Define the process boundary

The process boundary at Mine A focuses on the **main** ore producing levels due to mining and cooling activities being firmly emphasised by management in these locations. All bullnose and East/West split spindle pumps are included within the process boundary. Figure 29 is a visual representation of the process boundary at Mine A included within this study.

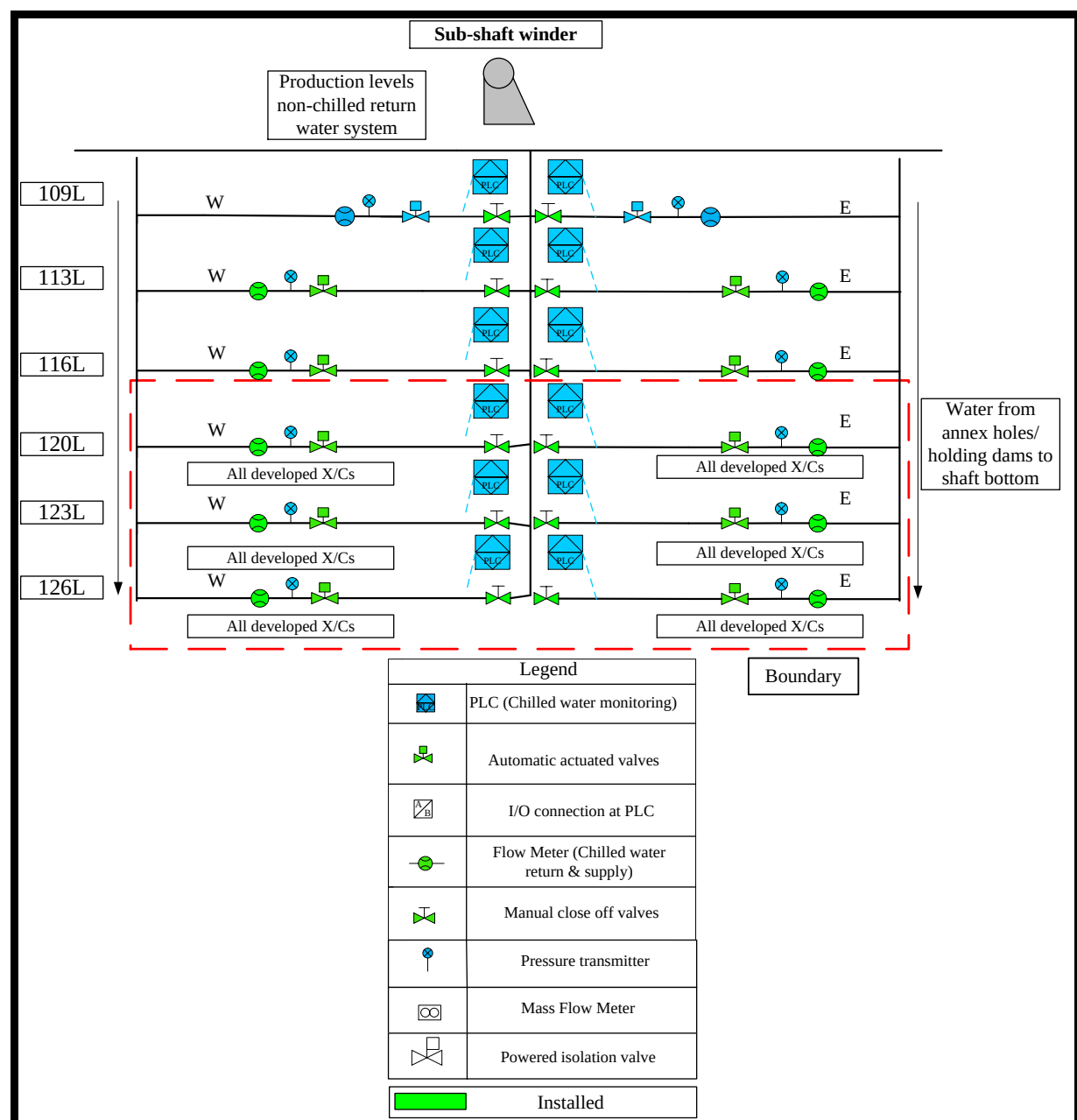


Figure 29: Mine A spindle pump process boundary

The process boundary selection is limited to the main production levels to ensure the investigation scope is narrowed down to the most relevant current mining sections and levels where development is still ongoing.

Spindle pump quantity, inactive XCs and pump operation identification

Initial information on the production level spindle pumps was obtained from relevant engineering foremen and section managers before underground audits commenced. Preliminary information provided a good indication of focus areas on the main production levels. Table 13 - Table 15 provides the results from the initial underground audits focused on operating bullnose spindle pumps.

Table 13: 120L identified bullnose spindle pumps at Mine A

120L Bullnose spindle pumps						
Section	XC Location	Size (kW)	Pump type	XC activity	Pump operation	Running hours p.a.
East	66	45	RNE	Yes	Constant	8760
	65	45	RNE	Yes	Constant	8760
	64	45	RNE	No	Constant	8760
	63	45	RNE	No	Constant	8760
	62	45	RNE	Yes	Constant	8760
	61	45	RNE	Yes	Constant	8760
	57	45	RNE	Yes	Constant	8760
	56	45	RNE	Yes	Constant	8760
	52	45	RNE	Yes	Constant	8760
	51	45	RNE	Yes	Constant	8760
West	49	45	RNE	Yes	Constant	8760
	48	45	RNE	No	Constant	8760
	45	45	RNE	No	Constant	8760
	44	45	RNE	No	Constant	8760
	42	45	RNE	No	Constant	8760
	40	45	RNE	No	Constant	8760
	39	45	RNE	Yes	Constant	8760
	38	45	RNE	Yes	Constant	8760
	36	45	RNE	Yes	Constant	8760
	35	45	RNE	Yes	Constant	8760
	34	45	RNE	Yes	Constant	8760
	33	45	RNE	Yes	Constant	8760
	32	45	RNE	Yes	Constant	8760

Table 14: 123L identified bullnose spindle pumps at Mine A

123L Bullnose spindle pumps						
Section	XC Location	Size (kW)	Pump type	XC activity	Pump operation	Running hours p.a.
East	63	45	RNE	Yes	Constant	8760
	62	45	RNE	Yes	Constant	8760
	61	45	RNE	Yes	Constant	8760
	57	45	RNE	Yes	Constant	8760
	56	45	RNE	Yes	Constant	8760
	52	45	RNE	Yes	Constant	8760
	51	45	RNE	Yes	Constant	8760
	49	45	RNE	Yes	Constant	8760
	48	45	RNE	Yes	Constant	8760
West	45	45	RNE	Yes	Constant	8760
	42	45	RNE	Yes	Constant	8760
	40	45	RNE	Yes	Constant	8760
	39	45	RNE	Yes	Constant	8760
	38	45	RNE	Yes	Constant	8760
	36	45	RNE	Yes	Constant	8760
	35	45	RNE	Yes	Constant	8760
	34	45	RNE	Yes	Constant	8760
	33	45	RNE	Yes	Constant	8760

Table 15: 126L identified bullnose spindle pumps at Mine A

126L Bullnose spindle pumps						
Section	XC Location	Size (kW)	Pump type	XC activity	Pump operation	Running hours p.a.
East	52	45	RNE	Yes	Constant	8760
	51	45	RNE	Yes	Constant	8760
	49	45	RNE	Yes	Constant	8760
	48	45	RNE	Yes	Constant	8760
West	45	45	RNE	Yes	Constant	8760
	42	45	RNE	Yes	Constant	8760
	40	45	RNE	Yes	Constant	8760
	39	45	RNE	Yes	Constant	8760
	38	15	RNE	Yes	Constant	8760

The audits revealed that **all** the identified bullnose pumps within the process boundary operated on a **permanent** basis. Management revealed that flow-level switches were not installed on the pumps due to the persistent problems caused primarily by the flow switch lodged in the suction. Some of the problems include the level switch being lodged into the pump suction when the sump consists of low water levels, especially during off-peak mining hours.

One supplier is used for all the spindle pump installations across the operations. Previous operation entailed the standardisation of the 45kW spindle pump on XC bullnoses due to standardised procedure and the assumption of high water return flows (without any investigation) from the operating stopes within the XCs and haulage footwalls [11]. It was observed that one 15kW spindle pump was installed on a 126L 38XC bullnose due to the unavailability of 45kW pumps when replacement was required. Inactive XCs were primarily identified on 120L, where scope exists for possible spindle pump removal at certain inactive XCs (depending on haulage water return volumes). This will be factored into the simulation development to ensure the best possible solution is obtained. The initial identification audit revealed the quantity of pumps within the process boundary, pump sizes and operation (running hours). Table 16 displays the summary of the results obtained during the audit.

Table 16: Lower production level annual pump running hours

Lower production level pump hour quantities		
Level	Bullnose pump quantity	Total yearly running hours (all pumps combined)
120	23	201 480
123	18	157 680
126	9	78 840
Total	50	438 000
45kW	49	
15kW	1	

Annex hole location/holding dam locations

The holding dams ensure the used return water is accumulated on each level after which it is pumped into the main dewatering system. According to [133] and [134], the rock topography and rigidity must be analysed before dam locations are established. The dams are recommended to be situated a distance (close to shafts and declines) from the primary mining activities' locations to avoid any water influxes in the active sections should the drainage system not operate according to design. The locations of the holding dams on the levels are essential to the evaluation of the spindle pump return system. The distance from the holding dam, in relation to the last spindle pump before the return water enters the converging drainage system, plays an important role in simulation development. The pump needs to consist of the required pressure to transport the water to holding dams on each individual level [133], [134]. The process boundary reaches its end at the East/West split of the production levels.

120L consists of a much longer haulage before reaching the East/West production split. Due to the larger haulage, spindle pumps were installed throughout the travelling distance towards the East/West split, which are outside the process boundary. 123L and 126L consist of shorter haulages. The distances are essential for accurate representation within the simulation environment and for potential future changes. Figure 67 – Figure 69 in Appendix A shows the distance as measured within PTB3D.

Current configuration measurements show the distances from the split are 335m, 270m and 228m for 120L, 123L and 126L, respectively, and water reaches the holdings dams easily with current operation. The information obtained is used to provide answers to the questions derived in the methodology step in Chapter 2 as well as simulation calibration. Table 17 provides a summary of the results.

Table 17: Methodology evaluation questions

Methodology evaluation questions	120L	123L	126L
What is the distance from the level specific annex hole to the nearest spindle pump in the system (m)?	335	270	228
What is the size of the nearest spindle pump in the system in proximity to the annex hole (kW)?	45	45	45
Are there any holding dams situated near the annex holes?	Yes	Yes	Yes

Detailed investigation

Gather data on return water quantities

Mine A consists of permanently installed chilled water flow monitoring systems which is integrated with REMS. Return water quantities have been logged since the start of the study to establish whether any flow changes occur closer to project implementation. The return water quantities of the included levels will ultimately determine which pumping configuration will be better suited for the application. Data was obtained for the specific level total system flows, as well as individual XC flows to evaluate the generalisation estimate for XC return water flows. Figure 30 - Figure 32 display the most recently measured weekday and weekend return water flows on the focused production levels which will be used in the simulation.

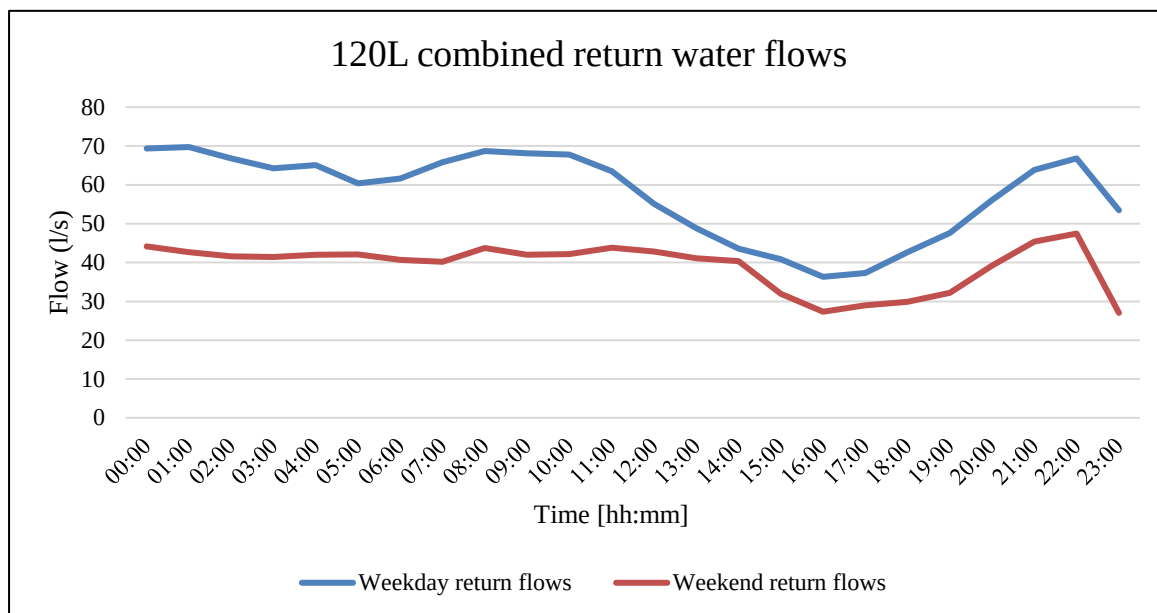


Figure 30: 120L combined non-chilled water return flows (2022)

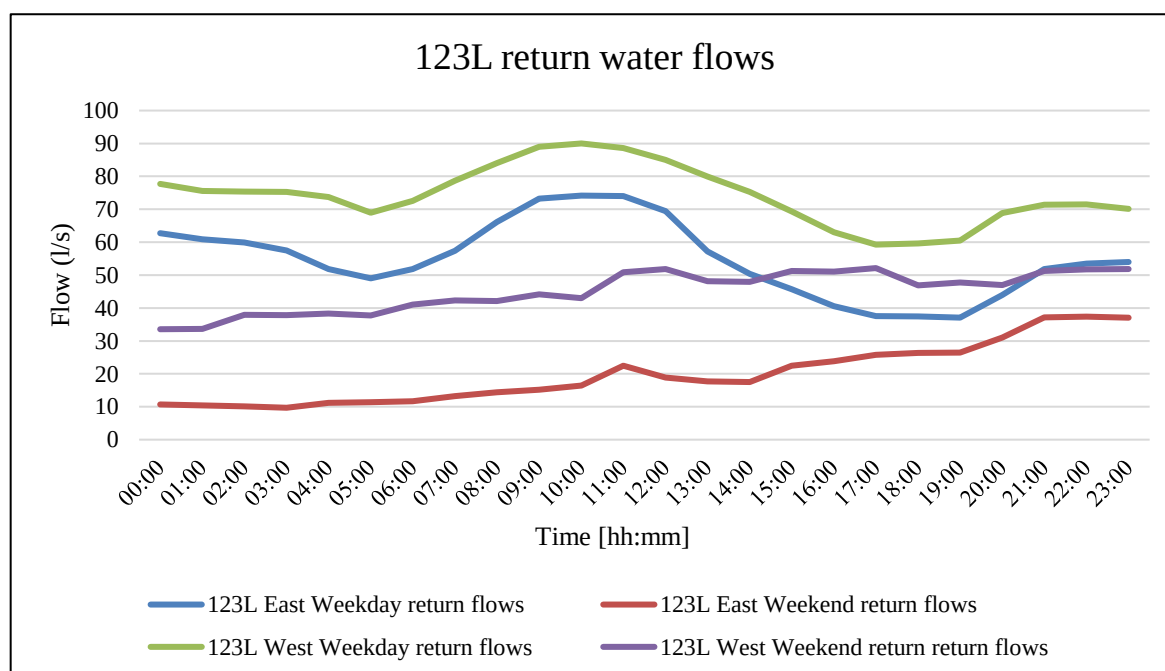


Figure 31: 123L East and West non-chilled water return flows (2022)

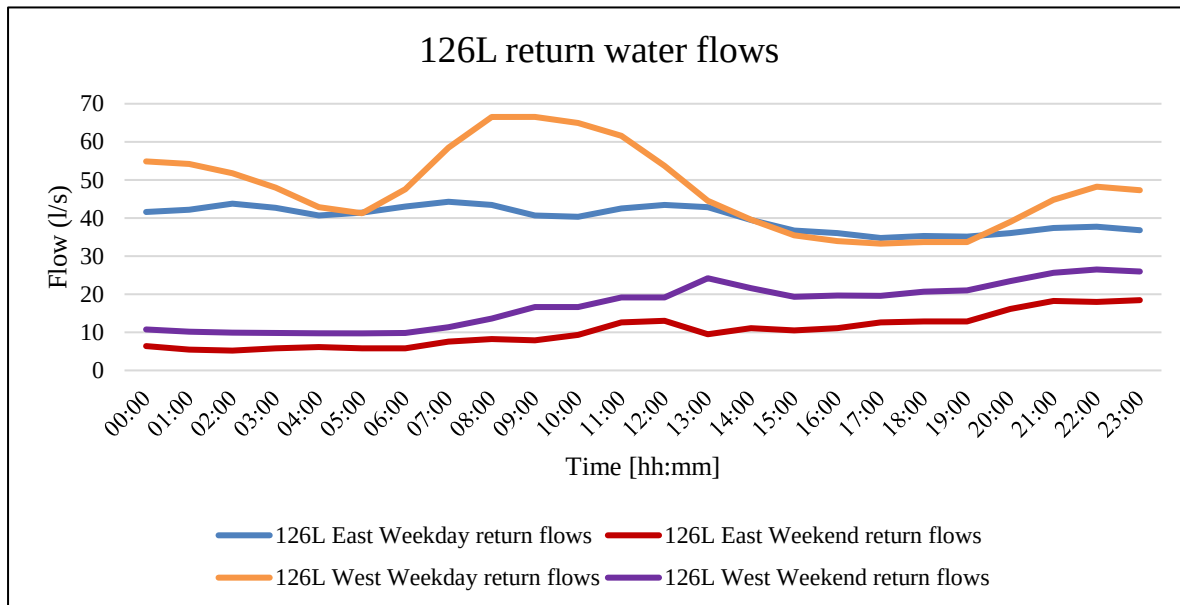


Figure 32: 126L East and West non-chilled water return flows (2022)

Analysis of the 2021 flow measurements revealed a substantial difference between the flows obtained in 2022, which substantiates the dynamic state of the return water system. Expansion took place on 123L and 126L (46 and 29% weekday increase), whereas mining activities scaled down on 120L (11% weekday decrease). Weekend return flow quantities (no mining) also decreased by 27% on 120L and increased by 16% and 33% on 123L and 126L, respectively.

Individual XC measurements, together with permanent flow meter installations on XCs, were analysed to establish the average flow per XC. No mining takes place between 16:00 and 20:00 on weekdays. Figure 33 and Figure 34 display the average week and weekend XC flow.

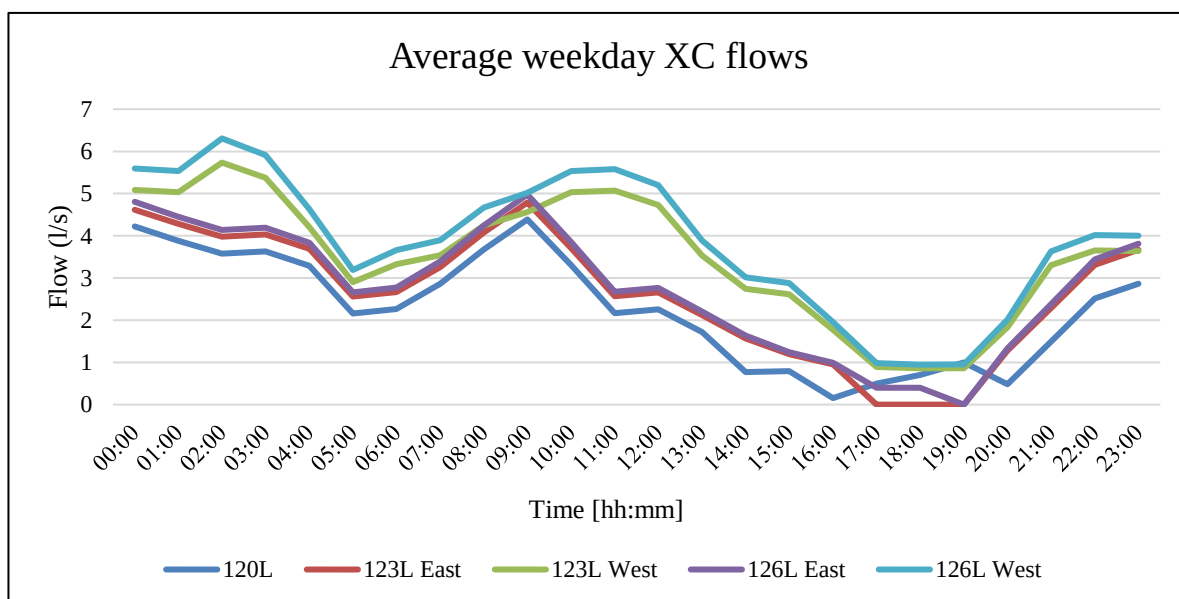


Figure 33: Average measured weekday XC flows

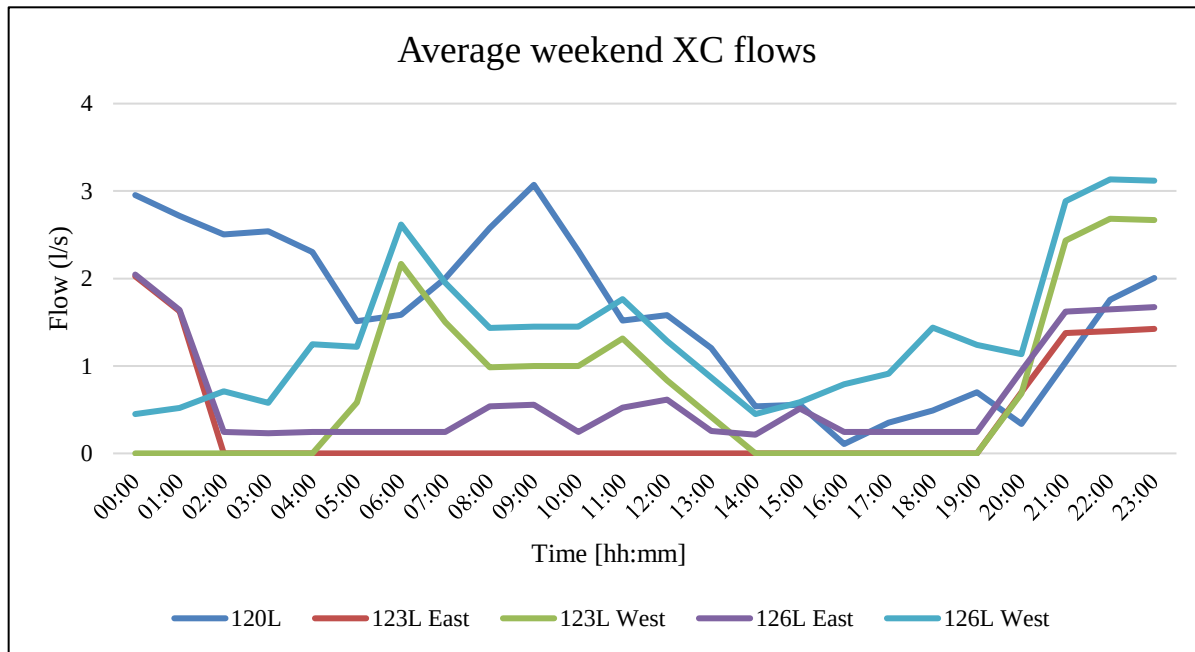


Figure 34: Average measured weekend XC flows

The values obtained from the measurements will be compared to the calculation of the active XCs count used in relation to the level return flows to determine an average XC return water flow for the simulation. It is important to note that some of the measured XCs have automated isolation valves installed which close over the weekend periods to ensure the inefficiencies in the stopes do not result in water wastage. The return quantities of the lower production levels increased on two of the three levels since project identification. The analysis shows the rate of change within a water system due to development, decreased mining activities, inefficiencies on the water lines underground and highlights the importance of continuous monitoring.

Data acquisition of spindle pump designs and haulage return pipe sizes

Underground audits revealed Mine A uses a uniform pump size and supplier. RNE pumps are well-known in the submersible pump procurement industry and are used at various underground operations in South Africa [70]. Nearly all the bullnose spindle pumps within the process boundary were identified as 45kW pumps with a solitary 15kW spindle pump used at a XC bullnose on 126L. Design specifications for these pumps were obtained and the pumping performance curves for the 45 and 15kW pumps are displayed in Figure 35 [36] [135] [136].

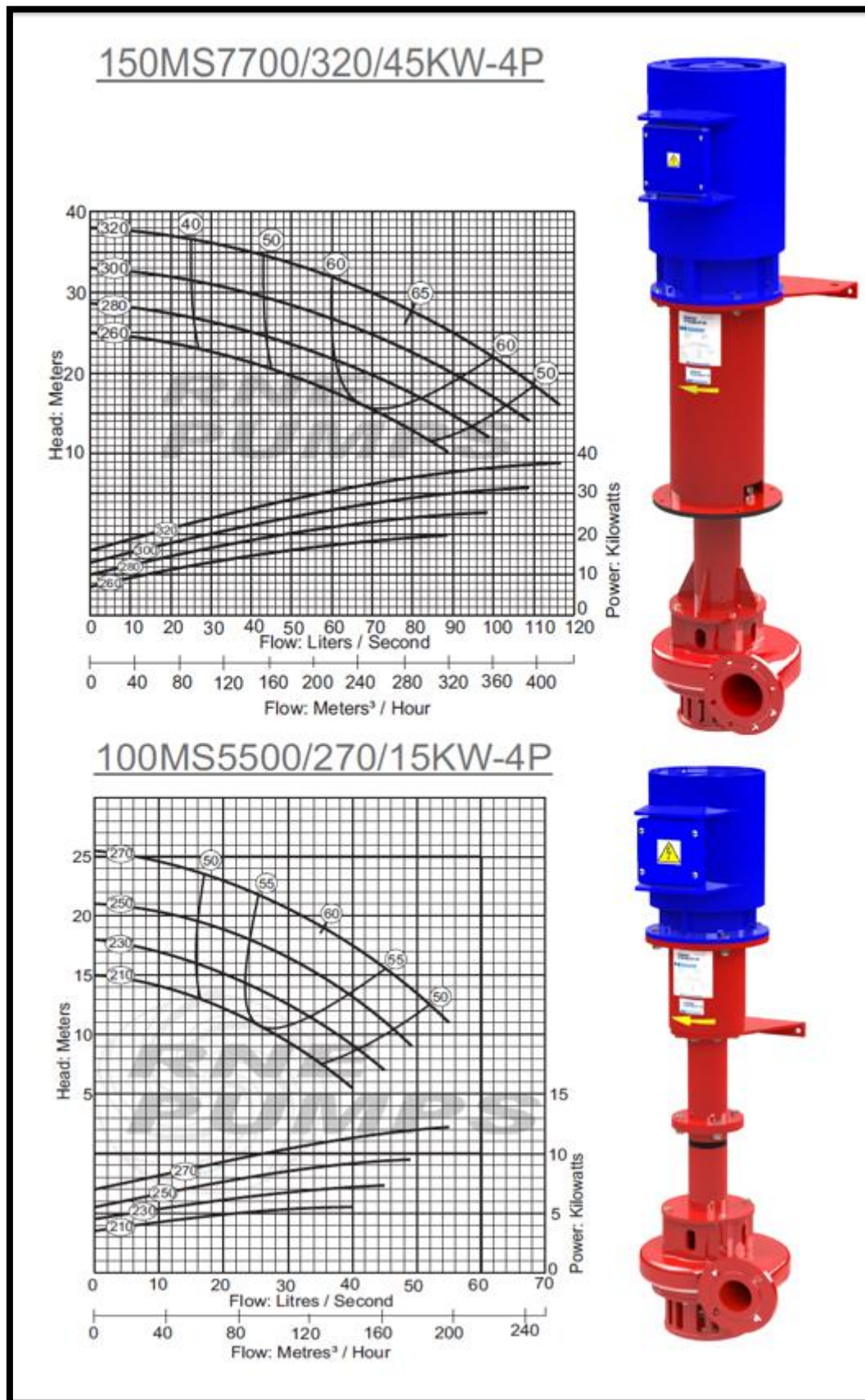


Figure 35: 45kW and 15kW spindle pump performance curves

The material application of the installed pumps consists of high chrome Iron 600+ Brunel and is applied for abrasion and no corrosion [70]. It is specified that the 5500-15kW series operates at a sump depth of 500mm, and the 7700-45kW series (suggested for high flow applications) is proposed to operate at a sump depth of 700mm [70]. Information obtained from the Original Equipment Manufacturer (OEM) revealed that the spindle pumps are manufactured in specific standardized sizes [70].

Haulage return pipe sizes

Pipe sizes play a less significant role in low-pressure water distribution systems such as the spindle pump system but should still be applied correctly based on water demands. The pipe sizes and configuration for the return water system at Mine A were identified during the underground audits conducted to correctly model the system within the simulation environment. It is important to be aware of the pipe height compared to the haulage or XC floor to compensate for fluid head in the simulation. The pipe sizes and configurations used for the simulation can be viewed in Figure 70 – Figure 85 in Appendix A.

Collection of energy consumption data and sample size determination

The underground audits revealed the normal operation of all the included spindle pumps entailed a constant mode of operation, regardless of water demands at any given time. Due to the lack of mentioned monitoring equipment on spindle pumps, the DENT logger measuring device displayed in Figure 65 was used to measure the energy consumption of spindle pumps during weekdays and weekends. The corresponding software compatible with the DENT logger instrument, ELOG 15, was used to create a setup table which was sent to the logger to obtain the correct voltage, current and power measurements based on the electrical feeder infrastructure at Mine A. The mine consists of a primary voltage of 11000V, and a secondary voltage supplied to the spindle pumps of 525V, equating to a PT ratio of 20.95. The current allocated on the spindle pumps' feeder boxes is specified as 80A. Normal current phase angles between a three-phase four-wire configuration is 120° [85]. Obtaining a balance between the three connected phases in large systems is rarely obtainable due to consumers requiring variable loads at different times [85]. The spindle pump system's load will depend on the water demand and whether the pump is fully submerged in water. It was observed throughout the audits that the sump level remains constant due to the incoming water being immediately pumped out of the sump. The phase shift of the wire connections was kept at the default value

of 1.1° on the data logger table due to the objective of obtaining balanced loads on all three of the phase currents connected to the logger [85]. Installation of the logger assists in determining the power factor and, in turn, the phase angle of the current and voltage of each phase.

Once the correct data table setup has been established, the quantity of pumps to be measured based on the sample size determination, using Equation 9 [86], needs to be calculated prior to commencement of all underground consumption measurements. According to [86], initial pilot sample measurements of each pump size need to be conducted to establish an average consumption throughout the day (A normal approximation is followed by the 45kW sample measurements). Two pump sizes were identified, 45kW and 15kW pumps. The two loggers were installed on a 45kW pump located on 123L 48XC and on the 15kW spindle pump located at 126L 38XC. The results were distinguished between weekly and weekend values. The logger results from both sets of measurements can be seen in Table 18 and Table 19.

**Pump not switched off to fill sump during weekend consumption*

Table 18: 123L 45kW and 15kW weekday measurements

123L 48XC 45kW Weekday measurements				
	Volts	kW	Amps	Avge. Measured power factor
Max	551.3	26.8	41.9	-
Min	493.7	19.0	33.1	
Average	529.6	21.4	34.8	0.67
126L 38XC 15kW Weekday measurements				
	Volts	kW	Amps	Avge. Measured power factor
Max	535.0	13.9	22.0	-
Min	498.9	10.5	17.9	
Average	523.7	11.5	18.8	0.68

Table 19: 123L 45kW and 15kW weekend measurements

123L 48 XC 45kW Weekend measurements				
	Volts	kW	Amps	Avge. Measured power factor
Max	535.0	20.9	33.6	-
Min	502.0	16.3	27.9	
Average	524.3	19.1	31.4	0.67
126L 38 XC 15kW Weekend measurements				
	Volts	kW	Amps	Avge. Measured power factor
Max	541.8	11.6	18.1	-
Min	514.2	10.3	17.0	
Average	526.5	10.9	17.5	0.68

Maximum logger values were obtained by switching the pumps off to fill the sump completely, after which it is turned back on (weekly measurements). This meant the suction of the spindle pump was completely submerged in water, which is not the case with normal operation. The maximum values were thus noted for the short period of time (<15s) when the sump was being emptied. Normal operation resulted in near empty sumps in both the 15kW and 45kW pump installations due to water demands from the XCs at the time of logger installation. Figure 36 shows a graph of the comparison between a 15kW and 45kW pump during weekdays and weekends.

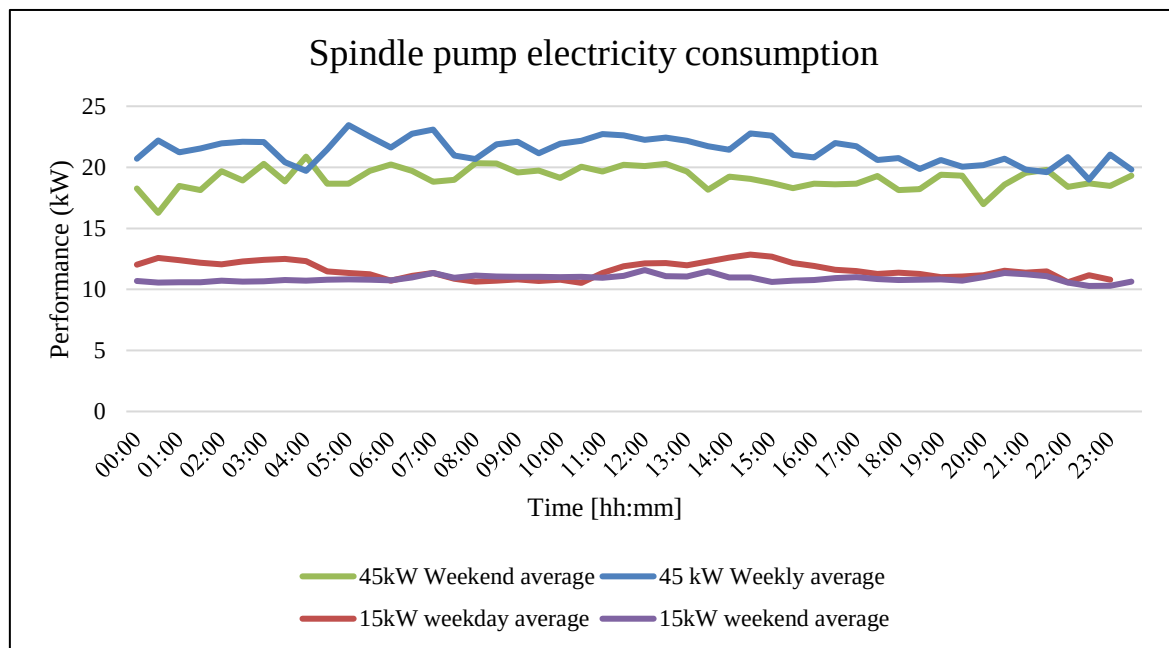


Figure 36: 45kW and 15kW pump consumption comparison

Investigation into the power factor of the main mining feeder feeding both the measured pumps was done to verify the accuracy of the power factor measurements [27]. The main mining level feeder's measured power factor was measured as 0.695 [27].

It is seen that both logger measurements obtained power factor figures within 3.6% accuracy of the power factor measured on the feeder during the logging period.

The value indicated on the main mining feeder would differ slightly from the pumps' measurements due to the loggers considering the power factor at the pumps itself. After the initial measurements have been taken, Equation 9 is used to determine the quantity of pumps to be measured to accurately depict the consumption of all the pump sizes within the process boundary by means of confidence interval approximation. The **45kW** pumps were noted as the majority of the pumps installed and will be used in the calculation of the sample size.

The average consumption will be calculated using a weighted average between weekdays and weekends throughout the year [1], [26]. The weighted average determination is shown in Equation 26.

Equation 26: Weighted average consumption calculation

$$\text{Weighted ave} = \text{Week kW} \times \frac{\text{Weekdays p. a.}}{\text{Total days p. a.}} + \text{Weekend kW} \times \frac{\text{Weekend days p. a.}}{\text{Total days p. a.}}$$

Where:

Weighted ave = Weighted average of the weekday and weekend consumption (kW)

Week kW = Average measured weekday consumption (kW)

Weekend kW = Average measured weekend consumption (kW)

Weekdays p. a. = Total number of weekdays in the year

Weekend days p. a. = Total number of weekend days in the year

Total days p. a. = Total combined days in the year

The specific 45kW average pump consumption for Mine A is determined as follows:

$$\text{Weighted ave (45kW pump)} = 21.4 \times \frac{259}{365} + 19.1 \times \frac{106}{365}$$

$$\text{Weighted ave} = \mathbf{20.73 \text{ kW}}$$

$$\text{Weighted ave (15kW pump)} = 11.5 \times \frac{259}{365} + 10.9 \times \frac{106}{365}$$

$$\text{Weighted ave} = \mathbf{11.32 \text{ kW}}$$

The sample size to be chosen for measurements is determined below [86]:

$$n = \frac{Nt^2\sigma^2}{N\Delta x^2 + t^2\sigma^2}$$

Where:

n = Sample size of similar pumps within the process boundary

N = Quantity of all pumps of similar sizes in the process boundary (50 pumps)

t = Degree of probability related to confidence interval (used as 1.96)

Δx = Sample mean classified as x ; limited error of the sample mean ($\Delta x = 0.1 \times 20.73$)

σ = Standard deviation from sample mean (1.49, **low** variation from mean)

$$n = \frac{(50) \times (1.96)^2 \times (1.49)^2}{(50) \times (0.1 \times 20.73)^2 + (1.96)^2 \times (1.49)^2}$$

$$n = 1.91 \approx 2 \text{ pumps}$$

According to the statistical evaluation adapted from [86], two 45kW pumps need to be measured with the current evaluation parameters. An additional logger was installed on 123L 39XC to determine the consumption of the bullnose spindle pump for weekday and weekend periods. These results are shown in Table 20 and compared with the previous 45kW pump measurement results in Figure 36.

Table 20: 123L 39XC logger measurement results

123L 39XC 45kW Weekday measurements				
	Volts	kW	Amps	Avge. measured power factor
Max	542.5	24.7	38.7	-
Min	496.9	15.9	27.1	
Average	525.4	20.0	32.3	0.68
123L 39XC 45kW Weekend measurements				
	Volts	kW	Amps	Avge. measured power factor
Max	547.1	21.2	34.4	-
Min	519.9	15.9	27.2	
Average	538.9	19.1	31.5	0.65

The measured weekday and weekend values differ on average by 7% and 6%, respectively. The combined values will be used to quantify the total energy consumption of the currently installed spindle pumps on the various focus levels. The new combined weighted average for the 45kW spindle pumps is calculated as **20.73 kW**. The profile comparison is shown in Figure 37.

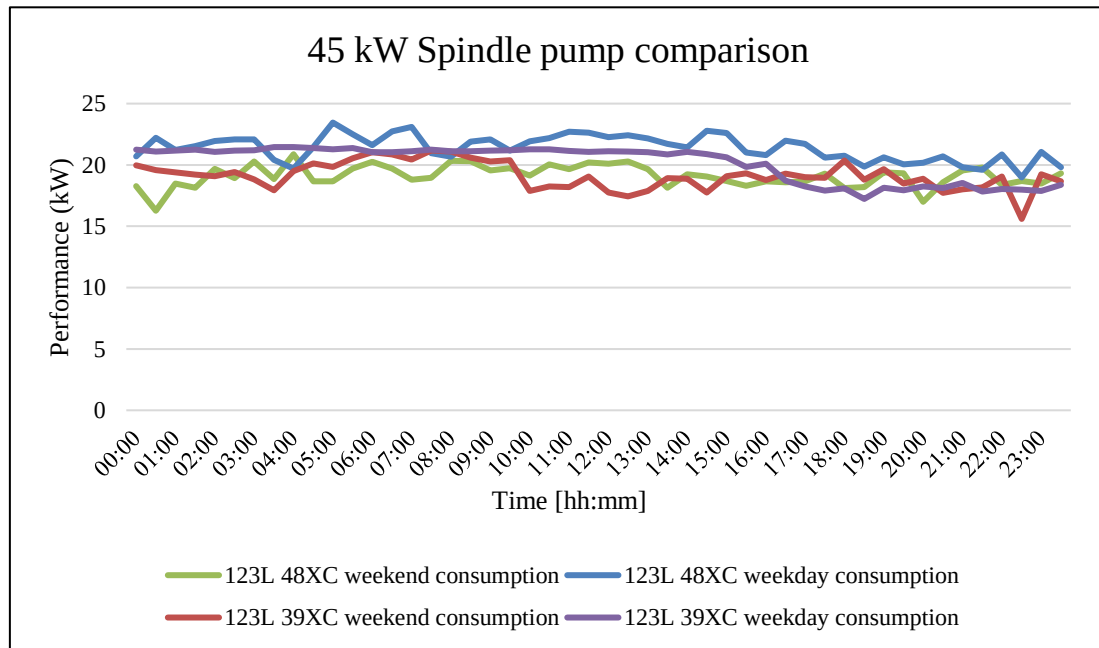


Figure 37: 123L 39 & 48XC weekday and weekend electrical consumption results

Quantifying current system energy consumption

The operation of the spindle pumps was established to be **constantly operational**. The running pump costs of each production level will, therefore, be determined by using Equation 18, Table 8, Table 16 and the different weighted averages for the measured 15kW and 45kW pumps. The level cost evaluation calculations are shown below.

$$120L \text{ cost} = 23 \times 20.73 \times 8760 \times 1.165$$

$$120L \text{ cost} = R4\ 865\ 832$$

$$123L \text{ cost} = 18 \times 20.73 \times 8760 \times 1.165$$

$$123L \text{ cost} = R3\ 808\ 042$$

$$126L \text{ cost} = (8 \times 20.73 \times 8760 \times 1.165) + (1 \times 11.32 \times 8760 \times 1.165)$$

$$126L \text{ cost} = R1\ 807\ 989$$

Table 21 shows a summary of the total pump cost throughout an operational year based on the data collected.

Table 21: Mine A lower production level spindle pump energy running cost (FY2021-2022)

Mine A production level spindle pump energy costs	
120L cost	R4 865 832
123L cost	R3 808 042
126L cost	R1 807 989
Total	R10 481 863

Due to the lack of monitoring on the spindle pump system in the past, the overall contribution to total electrical cost has never been evaluated. On large deep-level mines a yearly energy cost of R10.48 million may not be substantial (given that distribution pumps make up only 11% of costs as seen in Figure 9 [5], [26], [27]) ; however, with ever-rising electrical costs in South Africa, the cost contribution of the spindle pump system is worth improving.

Determination of best operating and efficiency point

Best operation points in pumps are not always achievable, even if a better suited pump is used for the application. Previous literature states that the best operating point of a pump is approximately 80-85% (**80% lower limit** to be used) of the shut-off head specified for the pump [94]. Pumping curves for the spindle pump system have been obtained for both installed pump sizes. The first objective is to use the **water flow and power logger measurements** to establish where the current pumps are operating on its performance curve. Thereafter, the established water demands for XCs are to be used to establish possible alternative pump sizes better suited for the application. Operational performance of three operating scenarios is constructed to illustrate the pumping performance at different flows. These are:

- Normal operation – Pumping performance during normal operation with the spindle pump permanently running. This operation entails the pump not being permanently submerged due to the reported water demands from the XCs.
- Submerged suction – The pumping performance when the sump is filled by switching off the pump. This leaves the suction of the pump being completely submerged by water. The sump is emptied quickly after which the pump returns to normal operation.
- Best operating point – This point on the performance curve is determined through theoretical calculation of the best operating point of the specific pump size.

The performances of the 45kW and 15kW pumps are illustrated in Figure 38 [70].

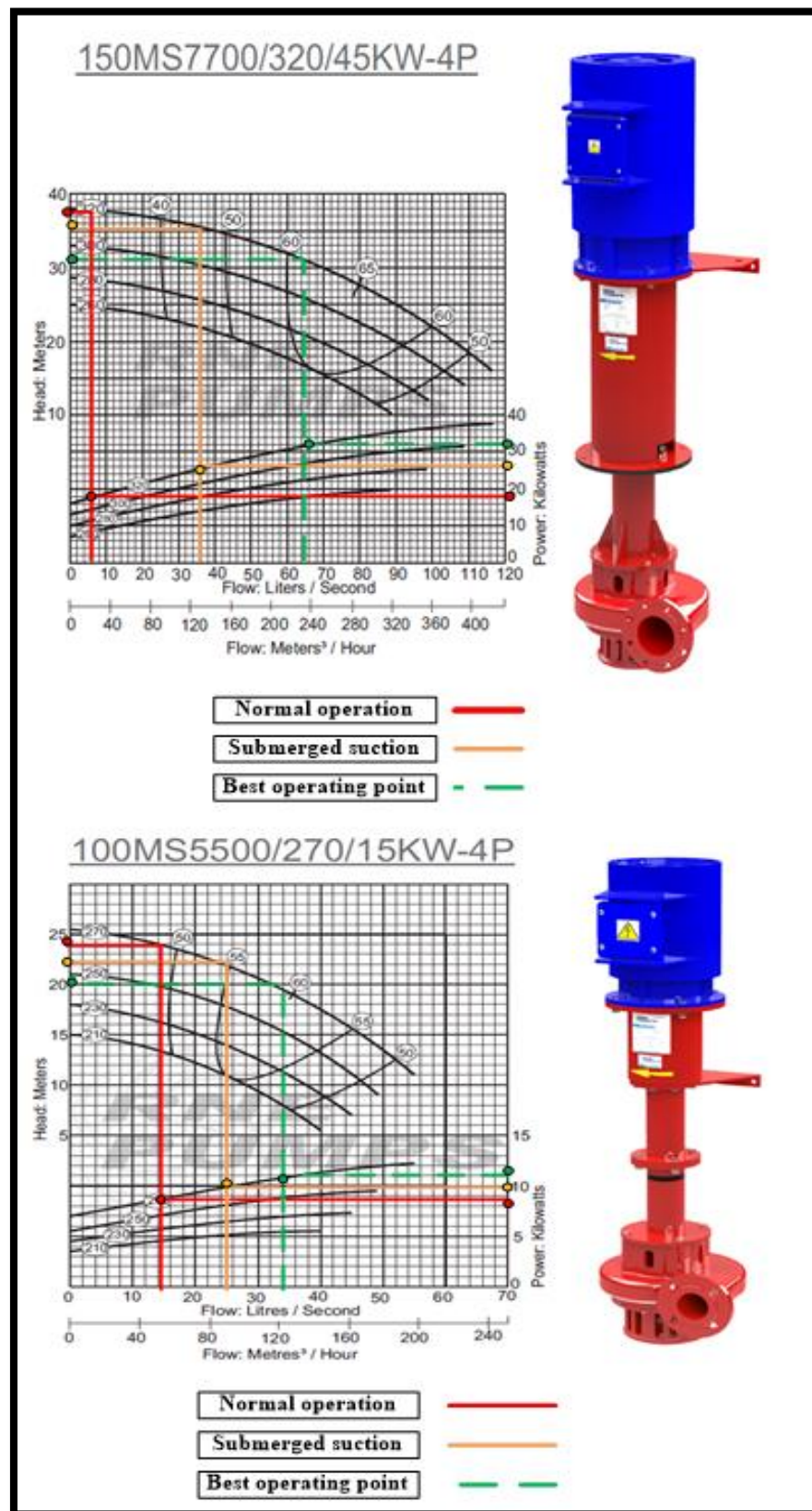


Figure 38: 45kW and 15kW spindle pump performances from initial measurements

45kW pump performance test conditions analysis

It is seen from the normal operation performance curve that the pump runs well left of its current calculated BEP. Allowing the suction of the pump to be fully submerged shifts the performance curve closer to its BEP but is still regarded as inefficient operation of the pump. After the pump is switched on, the sump is emptied in <10s, meaning the suction is only submerged for a very short time, even when considering sudden inrushes of water from XCs. It was noted that the sump sizes are approximately 0.9m in diameter and 1m in depth.

15kW pump performance test conditions analysis

Normal operation of the 15kW pump also rendered results of inefficient operation, but to a lesser extent than the 45kW. The submerged suction operation of the pump shifted the performance curve closer to the BEP than what is seen with the 45kW. The sump was emptied in <16s when it was allowed to fill, leaving the suction submerged for approximately 6s longer than the 45kW pump.

Analysis revealed the 15kW pump performed better than the 45kW under current operation relating to the best operation of each pump. Table 22 compares the deviation from the BEP of each pump and summary of results obtained under each tested operation.

Table 22: 45kW and 15kW pump's BEP calculation

45kW BEP pressure deviation calculation				
Operation type	Head (m)	Flow (L/s)	Power (kW)	Deviation (%)
BEP	32	64	32	-
Normal operation	39	6	18	17.7%
Submerged suction	37	36	26	13.0%
15kW BEP pressure deviation calculation				
Operation type	Head (m)	Flow (L/s)	Power (kW)	Deviation (%)
BEP	20	34	12	-
Normal operation	23	14	9	12.9%
Submerged suction	21	24	10	4.7%

The comparison revealed the 15kW deviated approximately 5% less than the 45kW from its BEP considering normal operation and deviated 8.4% less when the suctions of the pumps are completely submerged by water. According to best practice principles, the 15kW spindle pump is currently better suited for the dewatering application at the current water demands due to less deviation from its BEP [72].

3.3 Step 2 – Modelling the current system configuration through simulation

The 1st simulation model was developed by using PTB3D, which was specifically designed for large-scale applications in the mining industry. The model was constructed by using the information obtained throughout the underground audits to ensure its accuracy. The simulation was built throughout a period of five months in which consistent calibration took place as water demands changed. The underground non-chilled water return system was built using Digital Exchange Format (DXF) files to ensure all the haulages and XCs on the targeted levels are according to scale.

PTB3D allows the DXF files to be imported into the simulation environment according to scale. The files are then used to ensure all infrastructure included in the simulation are built in at the correct locations according to height in relation to surface. The simulation includes 642 calculation nodes and connections using the PTB3D solver to calculate all necessary parameters relating to the simulated system. Other components including water demands, dams, pipes, pumps and pressure boundaries are used in the simulation. For more information regarding the PTB3D solver, please refer to Appendix B. Figure 39 provides an overview of the simulation as constructed in PTB3D and indicates the components in the XC sections of the simulation.

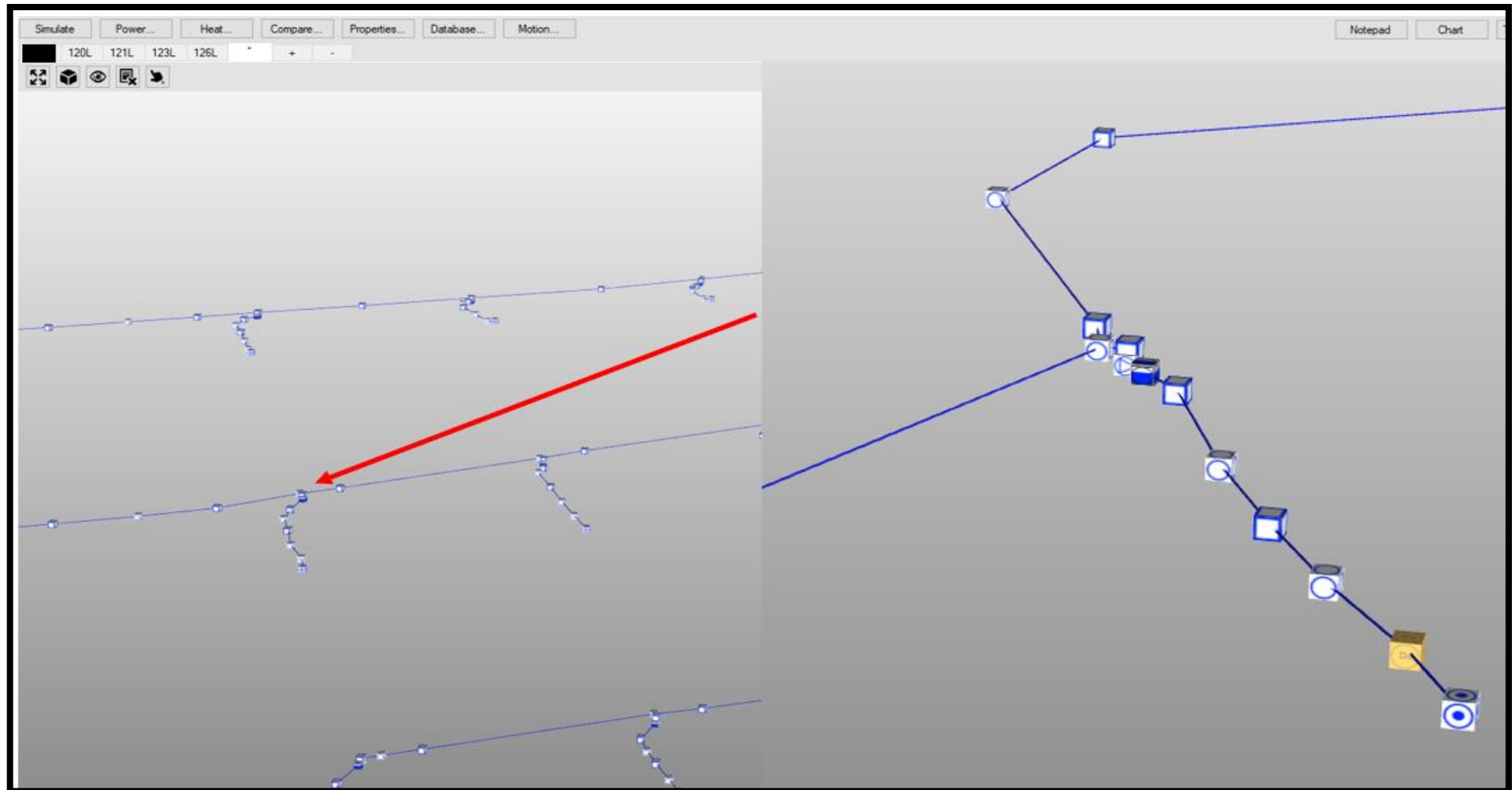


Figure 39: Simulation overview of XC and haulage water transfer infrastructure as constructed in PTB3D

The components in the XCs are added in a specific order to correctly establish the demand towards the spindle pump on the XC bullnoses. It is important to understand the function of each component to correctly configure and calibrate the simulation at hand. Table 23 provides a legend of the most applicable components to be used within the simulation.

Table 23: Summary of the components used in PTB3D

PTB3D - LEGEND	
	Water pipe
	Water node
	Water pressure boundary
	Water dam (Round)
	Water demand
	Water pump

Each of the indicated components consists of a specific function within the simulation. The included components are described as the following [137]:

- Water pipe – The flow network pressure losses are calculated within the pipe component. This component includes a variable valve fraction for flow or pressure control [137].
- Water node – Water height (network elevation) and volumes are specified within the water node component. All other network properties such as pressure, temperature, enthalpy, etc. are calculated with the water node component [137].
- Water pressure boundary – The pressure boundary has constant user-specific pressures and temperatures for every time period. This component is specifically used where the existing network connects to other sources or systems [137].
- Water dam – This component is a thermal hydraulic system break with variable thermal storage where the inlet and outlet flows are not functions of one another [137].

- Water demand – This component is used when a different water mass flow demand, at varying pressures, for each time period within a flow network is required (as is the XC level demands). A unique flow resistance can be specified for each time period [137].
- Water pump – The pump component generates a pressure difference in the flow network to induce water flow through the specified network. Pumping performance curves are used to specify the pump and are used to configure it within the simulation. The pump component generates heat in the fluid due to inefficiencies [137].

Water start and end boundaries were chosen as the stopes and holding dams on each level. For inclusive guidance on simulation design using the parameters obtained, refer to Appendix C.

Current system calibration

The preliminary goal of the simulation is to ensure it is calibrated according to current system specifications, after which additional scenarios will be simulated. Water demands were determined for each of the production levels to allocate specific XC flows towards the spindle pumps in each section. Flows were measured using permanently installed flowmeters and portable flowmeters as displayed in Figure 60 and Figure 61, respectively. The weekday level flows from the permanently installed flowmeters will be predominantly used for simulation calibration. Flows will be allocated per XC on the production levels according to XC activities and water demands established through calculation. Figure 40 displays the XC water demands.

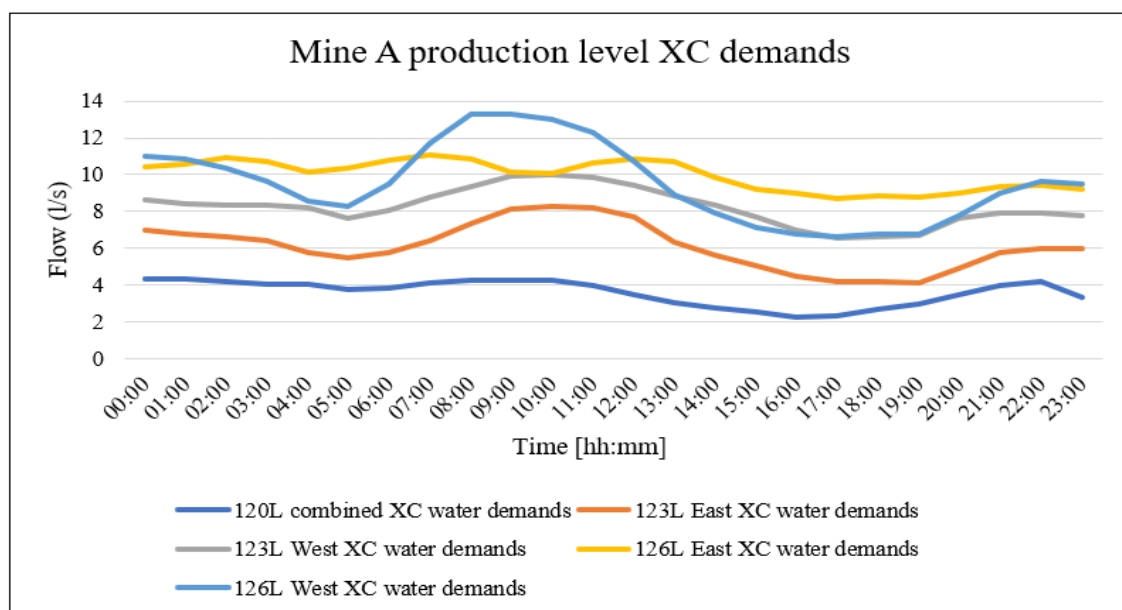


Figure 40: Mine A lower production level XC water demands

Each XC on the indicated levels is given a water demand at each time step according to the calculated flows per XC in Figure 40. An important aspect of PTB3D to note is the operational parameters of a pump's suction. Audits revealed that normal operation of the spindle pumps caused the sump to be partially submerged by water. Due to the pumps not being fully submerged by water, it is seen that the pumps did not efficiently run on its curve. This posed an added challenge to the calibration of the current system. PTB3D is integrated with hydraulic theoretical principles (found in Appendix B) and will operate as such when constructing a simulation. The calibration **results** of the current system can be viewed in **Appendix C** (Page 192 – 196).

Current system simulation – Maximum demand scenario

The 2nd simulation revolves around the establishment of the total water demand the **currently installed** system can transport from the various production sections towards the holding dams on each respective level. It should be noted that the simulation results depict the installed pumps running according to its pumping curve, which was not the case with the **calibration** of the installed system as the pumps are running inefficiently (real-world scenario simulation).

The pump sizes and quantities in the simulation will remain the same, with the main difference being the water quantities originating from each pump. Determination of the maximum demand capacity quantifies the system operational limit. The previously unmonitored system now consists of calculated parameters which are used to establish an action plan if changes to the system are required. It is important to be aware of the maximum demands of installed configurations to ensure the devised action plans can be carried out effectively should changes to the spindle pump return system be required. The results of the maximum demand scenario of the 45kW system can be viewed in Appendix C (Page 197 – 198).

3.4 Step 3 – Improving system energy consumption and configuration

Based on the results obtained from the constructed simulations, specific solutions for each level are required. This is done by critically evaluating the current system and thereafter suggesting the specific solutions for each of the levels included in the study.

Current system evaluation

Evaluation questions will be used for this section of the solution development and is adapted from [54]. Each half-level will be analysed individually to ensure the solutions obtained remain focused on isolated level operation due to the difference in water demands. The evaluation will focus on pump operating pressures and whether the pumps are best suited for the current application. The criteria for BEP is **80 – 85%** of the pumps' maximum shut-off head as stated on Page 106 (Max: 38m/ 372kPa for 45kW). The good practice limits are between less than 30% and more than 15% of the BEP's lower limit as seen in Figure 22. Table 24 – Table 29 contain level evaluations.

Table 24: 120L East 45kW spindle pump system evaluation

Evaluation question	Pump XC location									
	66	65	64	63	62	61	57	56	52	51
What are the current average weekday flow requirements for each pump (l/s)?	3.6									
How far are the distances between pumps (m, ranging from development to split)?	154	212	214	185	180	301	240	180	185	131
Do the pumps require additional head other than the distance to the return line?	No									
Are the pumps performing poorly in relation to their BEP?	Yes									No
What are the operating pressures of each pump (kPa)?	373	373	373	373	373	373	373	372	366	329
Are the pumps operating above their maximum pressure?	Yes								No	No
Are the pumps sized correctly for the application?	No									
Would a differently sized pump perform more efficiently in this application?	Yes									
Are the pumps suggested for configuration change?	Yes									
Which preliminary pump size would better suit the application (kW)?	15									

Table 25: 120L West 45kW spindle pump system evaluation

Evaluation question	Pump XC location												
	49	48	45	44	42	40	39	38	36	35	34	33	32
What are the current average weekday flow requirements for each pump (l/s)?	3.6												
How far are the distances between pumps (m, ranging from development to split)?	128	260	149	324	296	208	227	187	215	211	210	220	205
Do the pumps require additional head other than the distance to the return line?	No												
Are the pumps performing poorly in relation to their BEP?	No	Yes											
What are the operating pressures of each pump (kPa)?	272	354	372	373	373	373	373	373	373	372	373	373	373
Are the pumps operating above their maximum pressure?	No	No	Yes										
Are the pumps sized correctly for the application?	No												
Would a differently sized pump perform more efficiently in this application?	Yes												
Are the pumps suggested for configuration change?	Yes												
Which preliminary pump size would better suit the application (kW)?	15												

Table 26: 123L East 45kW spindle pump system evaluation

Evaluation question	Pump XC location								
	63	62	61	57	56	52	51	49	48
What are the current average weekday flow requirements for each pump (l/s)?	6.1								
How far are the distances between pumps (m, ranging from development to split)?	213	195	206	257	287	230	232	179	210
Do the pumps require additional head other than the distance to the return line?	No								
Are the pumps performing poorly in relation to their BEP?	Yes							No	
What are the operating pressures of each pump (kPa)?	373	373	373	373	371	371	355	330	281
Are the pumps operating above their maximum pressure?	Yes						No	No	No
Are the pumps sized correctly for the application?	No								
Would a differently sized pump perform more efficiently in this application?	Yes								
Are the pumps suggested for configuration change?	Yes								
Which preliminary pump size would better suit the application (kW)?	15								

Table 27: 123L West 45kW spindle pump system evaluation

Evaluation question	Pump XC location								
	45	42	40	39	38	36	35	34	33
What are the current average weekday flow requirements for each pump (l/s)?	8.3								
How far are the distances between pumps (m, ranging from development to split)?	183	140	360	277	224	205	221	213	213
Do the pumps require additional head other than the distance to the return line?	No								
Are the pumps performing poorly in relation to their BEP?	No	Yes							
What are the operating pressures of each pump (kPa)?	269	339	362	371	372	372	373	373	373
Are the pumps operating above their maximum pressure?	No	No	No	Yes					
Are the pumps sized correctly for the application?	No								
Would a differently sized pump perform more efficiently in this application?	Yes								
Are the pumps suggested for configuration change?	Yes								
Which preliminary pump size would better suit the application (kW)?	15								

Table 28: 126L East 45kW spindle pump system evaluation

Evaluation question	Pump XC location			
	52	51	49	48
What are the current average weekday flow requirements for each pump (l/s)?	10			
How far are the distances between pumps (m, ranging from development to split)?	220	234	253	335
Do the pumps require additional head other than the distance to the return line?	No			
Are the pumps performing poorly in relation to their BEP?	No	No	No	No
What are the operating pressures of each pump (kPa)?	339	332	318	281
Are the pumps operating above their maximum pressure?	No			
Are the pumps sized correctly for the application?	No			
Would a differently sized pump perform more efficiently in this application?	Yes			
Are the pumps suggested for configuration change?	Yes			
Which preliminary pump size would better suit the application (kW)?	15			

Table 29: 126L 45kW West spindle pump system evaluation

Evaluation question	Pump XC location				
	45	42	40	39	38
What are the current average weekday flow requirements for each pump (l/s)?	9.5				
How far are the distances between pumps (m, ranging from development to split)?	100	344	244	212	203
Do the pumps require additional head other than the distance to the return line?	No				
Are the pumps performing poorly in relation to their BEP?	Yes	No	No	Yes	No
What are the operating pressures of each pump (kPa)?	243	326	344	362	238 (15kW)
Are the pumps operating above their maximum pressure?	No				
Are the pumps sized correctly for the application?	No				Yes
Would a differently sized pump perform more efficiently in this application?	Yes				No
Are the pumps suggested for configuration change?	Yes				No
Which preliminary pump size would better suit the application (kW)?	15				-

It was seen that most of the installed pumps operate close to or over their maximum pressure, decreasing from the development end up until the split. All but one of the currently installed pumps are currently recommended for replacement due to inefficient operation (15kW at 38 XC 126L). The results from the audit and simulation indicate the **45kW pump is over specified** for the application. A smaller pump size is, therefore, preliminarily suggested. Standardised spindle pump sizes **smaller** than the 45kW range from 5.5kW, 7.5kW, 15kW, 22kW, and 37kW [70]. It is seen from the audit results that a 15kW pump is better suited for the application, which suggests that a 22kW and 37kW pump may also be over specified. The **preliminary** replacement pump size is, therefore, currently chosen as 15kW and will be proven through analysis of Table 31– Table 36. The current inefficient system results will be compared to the suggested configuration changes by incorporation within the simulation environment.

Specific solutions development

Preliminary audit measurements obtained for the 15kW pump installed on 126L will be used as a baseline for operation comparison. Simulation incorporation entails simulating the current water demands with the pumps indicated for exchange according to Table 24 – Table 29.

A system evaluation of the newly developed system simulation will be done to ensure the suggested solution is best suited for improved operation.

The new simulation steps can be viewed in Appendix C. The flow results for **current operational water demands**, obtained through incorporation of 15kW pumps, is shown below in Figure 41 - Figure 43.

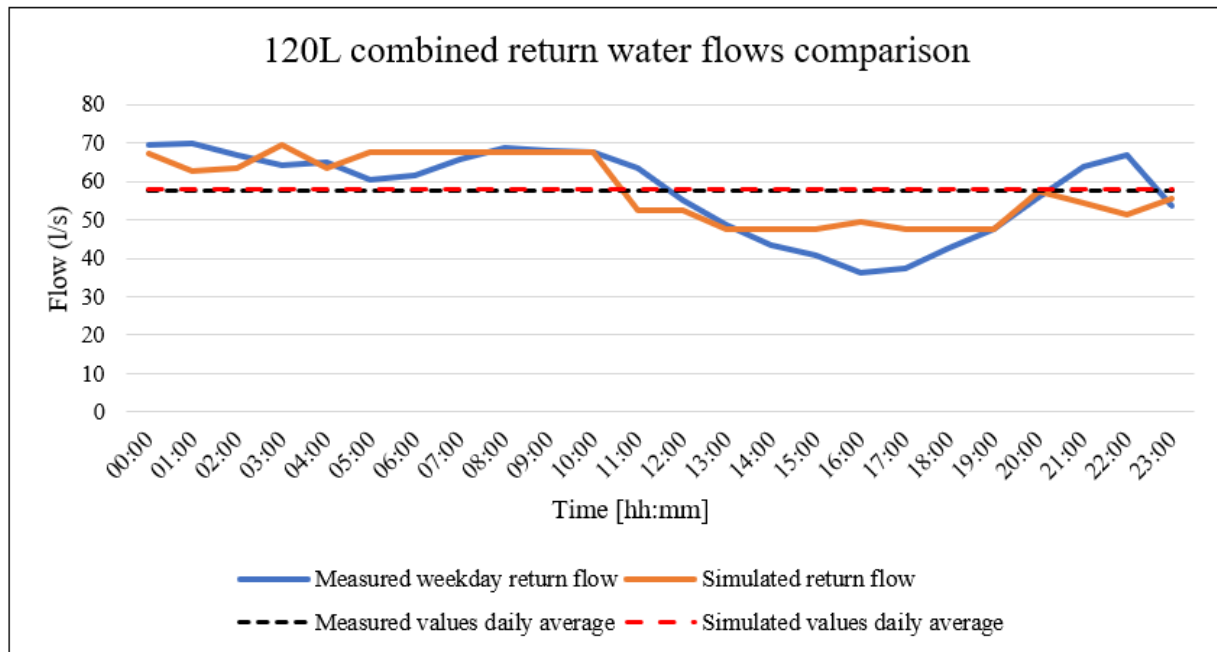


Figure 41: 120L Current operation simulation results with 15kW pump's incorporation

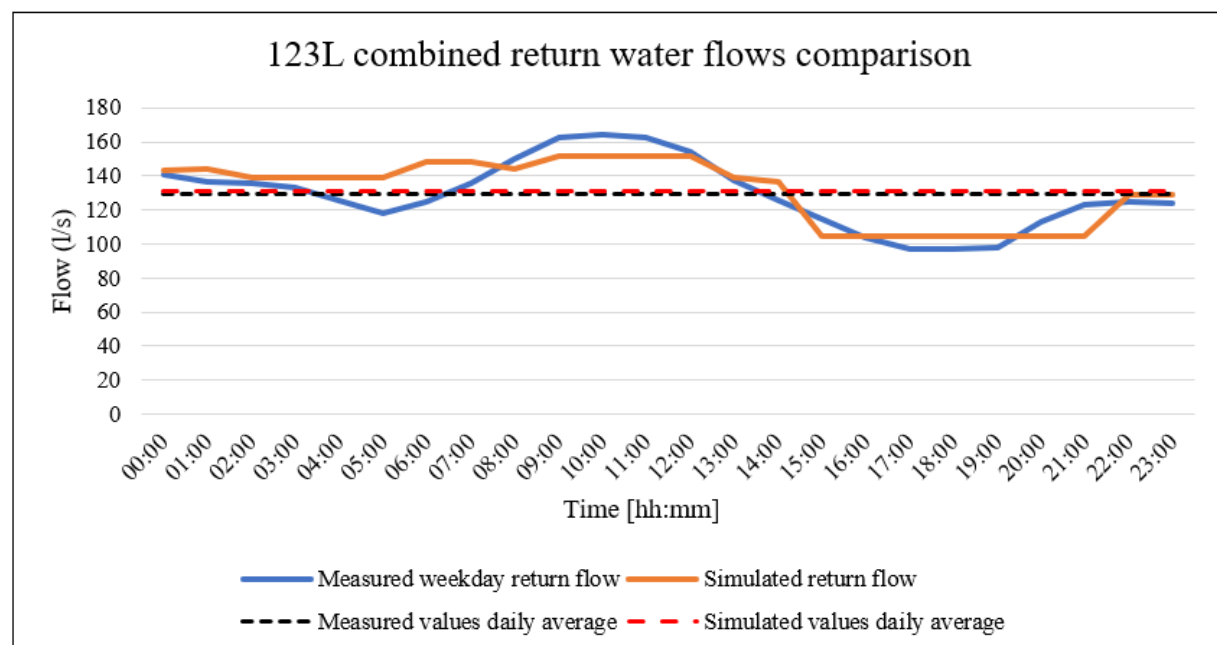


Figure 42: 123L Current operation simulation results with 15kW pump's incorporation

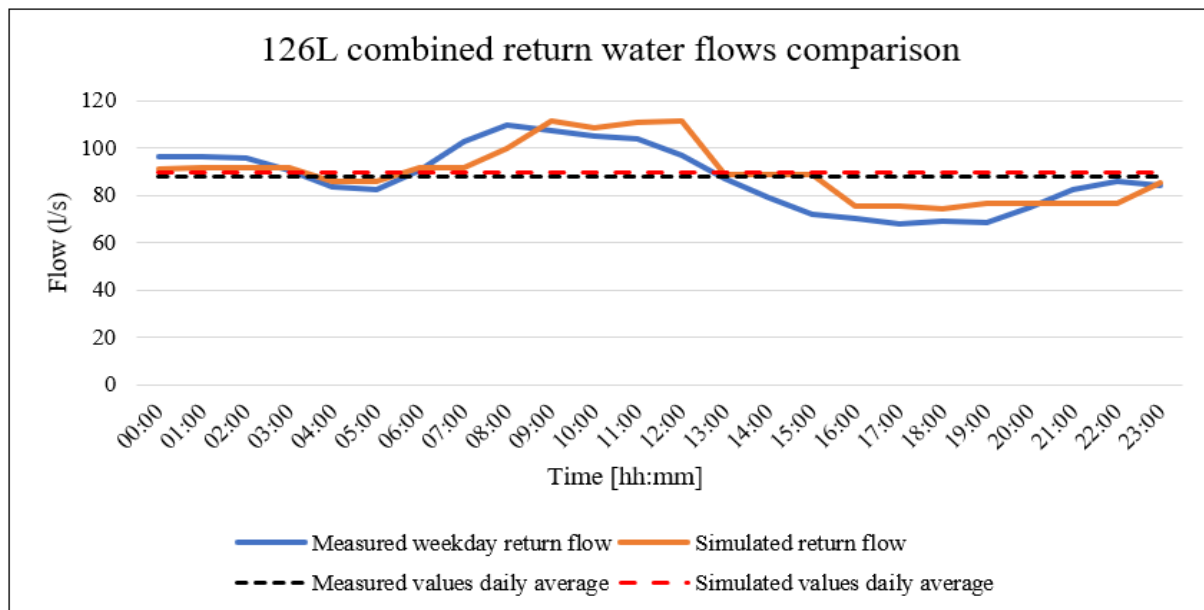


Figure 43: 126L Current operation simulation results with 15kW pump's incorporation

Flows were calibrated for current operation within 1%, 1.7% and 1.9% difference for 120L, 123L, and 126L, respectively. After calibration of the current water demand operation, the high demand scenario will follow. To ensure all operational bases are covered, an additional configuration change was incorporated into the simulation and investigated. According to the OEM of the spindle pumps used at Mine A [70], suggested the 7.5kW spindle pump can also be considered as a potential replacement possibility given the current demand requirements. The performance curve of the incorporated pump is show in Figure 44.

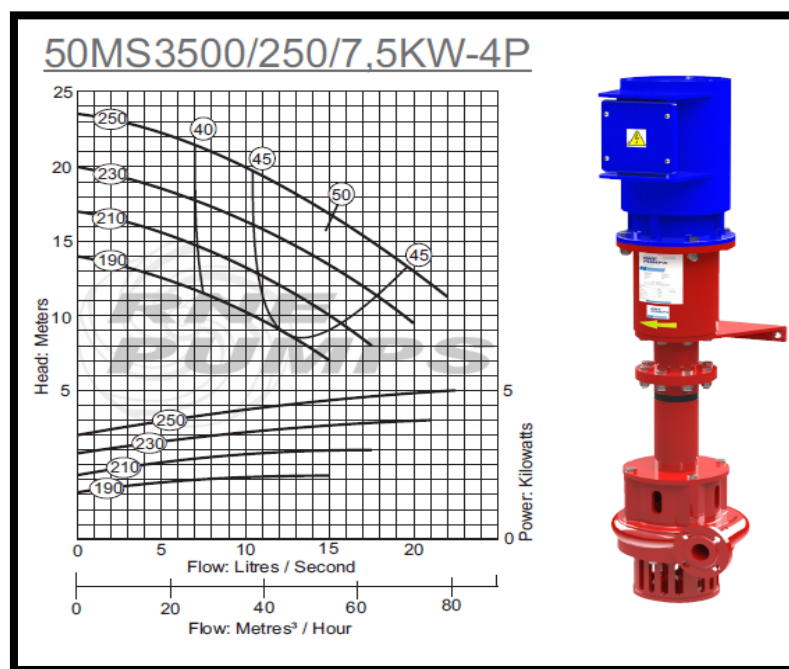


Figure 44: 7.5kW spindle pump performance curve

Three simulations scenarios were compared to the current system demand to illustrate the available capacity should demand requirements increase. This ensures limits are clearly identified to invoke action when needed. The high demand comparison results are shown in Figure 45 - Figure 47.

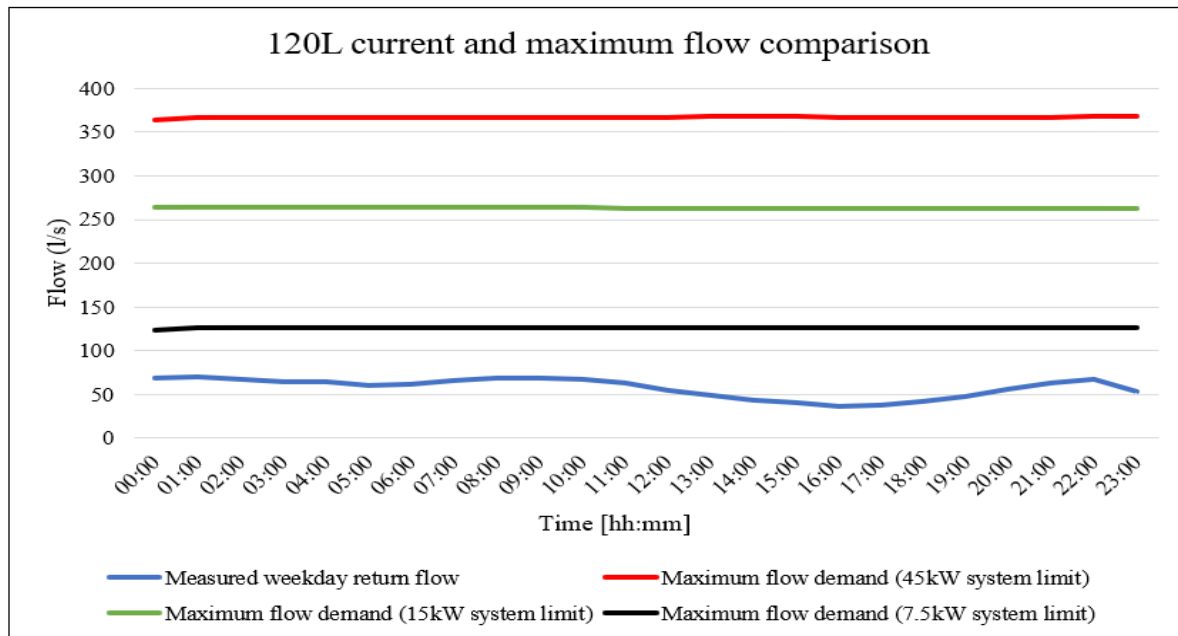


Figure 45: 120L maximum capacity comparison of the 45kW, 15kW and 7.5kW spindle pump systems

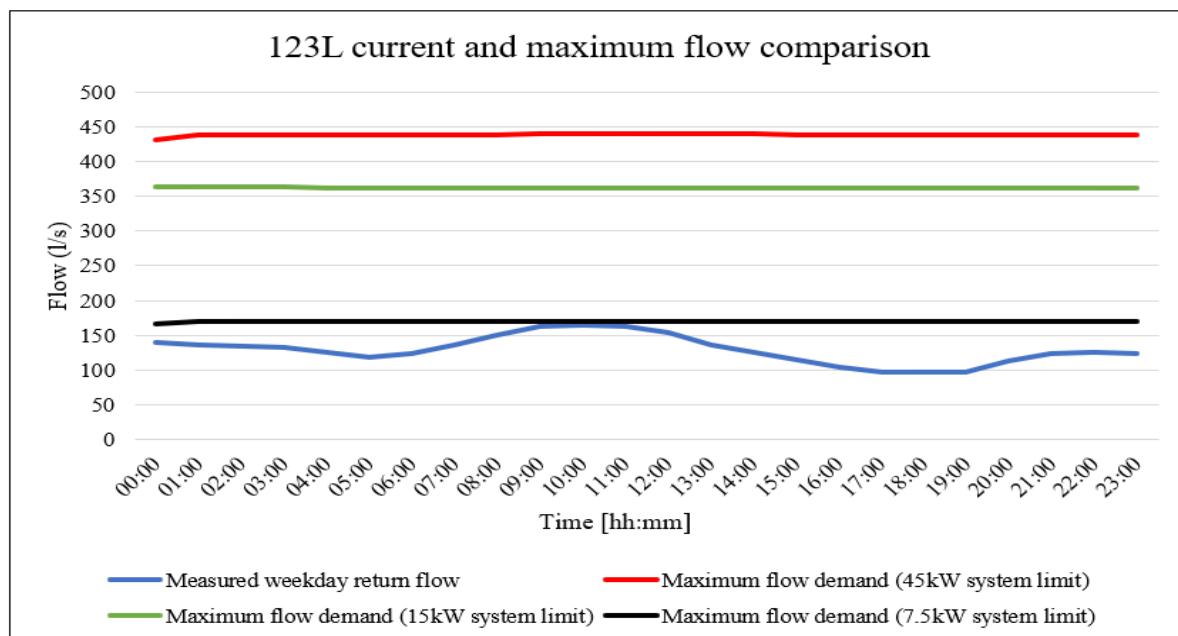


Figure 46: 123L maximum capacity comparison of the 45kW, 15kW and 7.5kW spindle pump systems

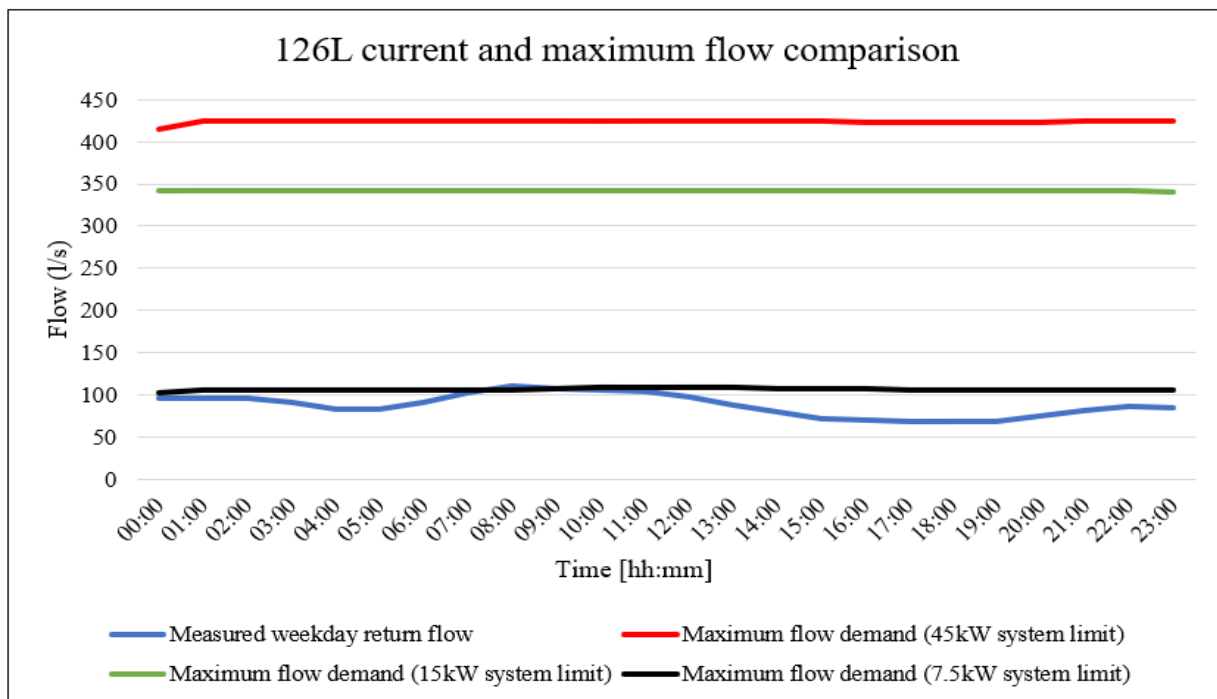


Figure 47: 126L maximum capacity comparison of the 45kW, 15kW and 7.5kW spindle pump systems

As can be seen from the figures above, the maximum demand limits for both the 15kW and 45kW systems remains clear of the current demands on the production levels. The 7.5kW system's maximum capacity still operates above the current demand during certain times of the day but operates close to the maximum limit during peak drilling times. Table 30 provides a summary of the current demands respective to the maximum capacity of the investigated pump sizes on the respective levels.

Table 30: Spindle pump systems operational point comparisons

Mine A average horizontal water transport operational point comparisons (compared to maximum system capacities)			
Level	45kW system operational point	15kW system operational point	7.5kW system operational point
120	15%	21%	46%
123	28%	36%	76%
126	20%	26%	82%

The results reveal that the 7.5kW spindle pump system would not be sufficient to transport the current water demand out of the respective sections during peak drilling time and is, therefore, not a suitable replacement for the 45kW. Levels which are planned to scale down mining activities may be considered for a configuration change with the 7.5kW pump.

The 15kW system operates closer to maximum system capacity than the 45kW system but remains well within the capacity boundaries and allows for a buffer should sudden influxes of water occur. The criteria for BEP is **80 – 85%** of the pumps' maximum shut-off head as stated on Page 106 (Max: 25.7m/ 253kPa for 15kW). The good practice limits are between less than 30% and more than 15% of the BEP's lower limit as seen in Figure 22.

The evaluation criteria for the 15kW system replacement is shown in Table 31 – Table 36.

**Evaluation questions with unchanged answers from Table 24 - Table 29 are omitted from the tables.*

Table 31: 120L East 15kW spindle pump system evaluation

Evaluation question	Pump XC location									
	66	65	64	63	62	61	57	56	52	51
Are the pumps performing poorly in relation to their BEP?	No									
What are the operating pressures of each pump (kPa)?	243	243	242	245	247	246	239	218	184	181
Are the pumps operating above their maximum pressure?	No									
Are the pumps sized correctly for the application?	Yes									
Would a differently sized pump perform more efficiently in this application?	Future investigation (for non-standardized pumps) as mining activities scale down is recommended									
Are the pumps suggested for configuration change?	No									
Which preliminary pump size would better suit the application (kW)?	-									

Table 32: 120L West 15kW spindle pump system evaluation

Evaluation question	Pump XC location												
	49	48	45	44	42	40	39	38	36	35	34	33	32
Are the pumps performing poorly in relation to their BEP?	No												
What are the operating pressures of each pump (kPa)?	177	218	233	245	246	247	249	246	242	239	246	240	239
Are the pumps operating above their maximum pressure?	No												
Are the pumps sized correctly for the application?	Yes												
Would a differently sized pump perform more efficiently in this application?	Future investigation (for non-standardized pumps) as mining activities scale down is recommended												
Are the pumps suggested for configuration change?	No												
Which preliminary pump size would better suit the application (kW)?	-												

Table 33: 123L East 15kW spindle pump system evaluation

Evaluation question	Pump XC location								
	63	62	61	57	56	52	51	49	48
Are the pumps performing poorly in relation to their BEP?	No								
What are the operating pressures of each pump (kPa)?	240	239	238	236	233	228	213	197	176
Are the pumps operating above their maximum pressure?	No								
Are the pumps sized correctly for the application?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Would a differently sized pump perform more efficiently in this application?	No								
Are the pumps suggested for configuration change?	No								
Which preliminary pump size would better suit the application (kW)?	-								

Table 34: 123L West 15kW spindle pump system evaluation

Evaluation question	Pump XC location								
	45	42	40	39	38	36	35	34	33
Are the pumps performing poorly in relation to their BEP?	No								
What are the operating pressures of each pump (kPa)?	192	207	221	230	234	236	238	237	240
Are the pumps operating above their maximum pressure?	No								
Are the pumps sized correctly for the application?	Yes								
Would a differently sized pump perform more efficiently in this application?	No								
Are the pumps suggested for configuration change?	No								
Which preliminary pump size would better suit the application (kW)?	-								

Table 35: 126L East 15kW spindle pump system evaluation

Evaluation question	Pump XC location			
	52	51	49	48
Are the pumps performing poorly in relation to their BEP?	No			
What are the operating pressures of each pump (kPa)?	169	171	182	163
Are the pumps operating above their maximum pressure?	No			
Are the pumps sized correctly for the application?	Yes	Yes	Yes	Yes
Would a differently sized pump perform more efficiently in this application?	Yes	Yes	Yes	Yes
Are the pumps suggested for configuration change?	Yes	Yes	Yes	Yes
Which preliminary pump size would better suit the application (kW)?	-			

Table 36: 126L West 15kW spindle pump system evaluation

Evaluation question	Pump XC location				
	45	42	40	39	38
Are the pumps performing poorly in relation to their BEP?	No				
What are the operating pressures of each pump (kPa)?	168	202	206	213	213
Are the pumps operating above their maximum pressure?	No				
Are the pumps sized correctly for the application?	Yes	Yes	Yes	Yes	Yes
Would a differently sized pump perform more efficiently in this application?	No				
Are the pumps suggested for configuration change?	No				
Which preliminary pump size would better suit the application (kW)?	-				

The evaluation of the simulated values revealed that none of the replaced 15kW pumps operate above their maximum pressure. A comparison between the simulation operating pressures between the 45kW and 15kW system was made. It was seen that **62% of the 45kW pumps** currently operate **above their maximum pressure**, while **none of the 15kW pumps** operated above their maximum pressure. **As a result of the simulation results comparison, the 15kW pump is, therefore, currently chosen as the uniform replacement for the 45kW pump at current water demands.**

Savings potential

Due to the new uniform pump chosen for configuration changes through investigation, the potential savings calculation because of the suggested changes is required. Initial consumption measurements conducted will be used as a base for savings potential if **all** the pumps within the boundary are replaced. Due to the constant mode of operation in effect, the electrical cost savings (using consumption obtained on Page 103) are determined by Equation 22.

$$120L \text{ savings} = R4\,865\,832 - (23 \times 11.32 \times 8760 \times 1.165)$$

$$120L \text{ savings} = R2\,208\,754 \text{ p. a.}$$

$$123L \text{ savings} = R3\,808\,042 - (18 \times 11.32 \times 8760 \times 1.165)$$

$$123L \text{ savings} = R1\,728\,589 \text{ p. a.}$$

$$126L \text{ savings} = R1\,807\,989 - (8 \times 11.32 \times 8760 \times 1.165)$$

$$126L \text{ savings} = R883\,787 \text{ p. a.}$$

$$\text{Total savings} = R4\,821\,131 \text{ p. a.}$$

To ensure the cost savings can be sustained for prolonged periods of time, the solution needs to be adaptable to change. It should be noted that this would be the highest attainable preliminary calculated savings if **all** suggested pumps are replaced with 15kW pumps. To ensure energy savings potential conservation for future use, the kWh avoidance for the year is calculated as **4 039 148 kWh**. **This firmly addresses the main novelty of obtaining better suited pump sizes for improved system operation and electrical cost savings.**

3.5 Step 4 – Dynamic adaptability and sustainable solutions development

Dynamic adaptability

Water reticulation systems in deep-level mines have been identified as dynamic operating systems with various instances of small changes throughout daily operation, and instances of extensive change when considering yearly operation. The three discussed adaptation techniques are applied thoroughly to this study and yielded the following outcomes:

Rule-based integration

Monitoring of the spindle pump system performance is key to ensure the suitability of the **new** configuration. Establishing operating limits assists with an action plan for each operating interval. Table 37 provides information on the different operating intervals and the actions allocated to each.

Table 37: 15kW spindle pumps operating flow intervals

Interval	Operating interval flows			Operating time (condition satisfied)	Remedial actions
	120L	123L	126L		
Low-low system flow (0-5%, l/s)	0-13	0-18	0-17	>1-10 hours (depending on margin from 5% capacity)	Install properly sized pumps in areas where low water use is reported. Re-evaluate system configuration if deemed necessary.
Low system flow (5 - 20%, l/s)	13-53	18-72	17-68	>1 day	Investigate areas for reported decreased use of water, establish the cause and derive a potential solution. Ensure properly sized standby replacement pumps are ready for installation should it be required.
Low-medium system flow (20-40%, l/s)	53-105	72-145	68-137	Operating regime closest to BEP	No action required
Medium system flow (40-50%, l/s)	105-132	145-181	137-171		
High-medium system flow (50-65%, l/s)	132-171	181-235	171-223		
High system flow (65-85%, l/s)	171-224	235-308	223-291	>1 day	Investigate areas for reported increased use of water, establish the cause and derive a potential solution. Ensure properly sized standby replacement pumps are ready for installation should it be required.
High-high system flow (>85%, l/s)	>224	>308	>291	>1-2 hours (depending on margin from 100% capacity surpass)	Install properly sized pumps in areas where high water use is reported. Re-evaluate system configuration if deemed necessary.

Real-time monitoring of the system forms an essential part of the reaction time should the flow intervals be surpassed. Platforms (REMS) providing alarm limits for the operating flows are already integrated at Mine A. An example of the real-time alarm limit setup and flow monitoring integration can be viewed in Figure 89 in Appendix D. **Integration of the simulation with the digital twin real-time monitoring system firmly addresses the novelty of developing an integrated monitoring technique for low-priority water transfer systems.**

Goal-oriented integration

Return water demands on each production level linked to mining activities is the primary system demand requirement for each quarter of the financial year. It is, however, necessary to consider any additional natural ingress water that may influence the return quantities to be moved by the horizontal water transport system throughout the year.

Figure 48 portrays the steps followed to determine any additional water sources affecting the return flow quantities on 120L, 123L and 126L.

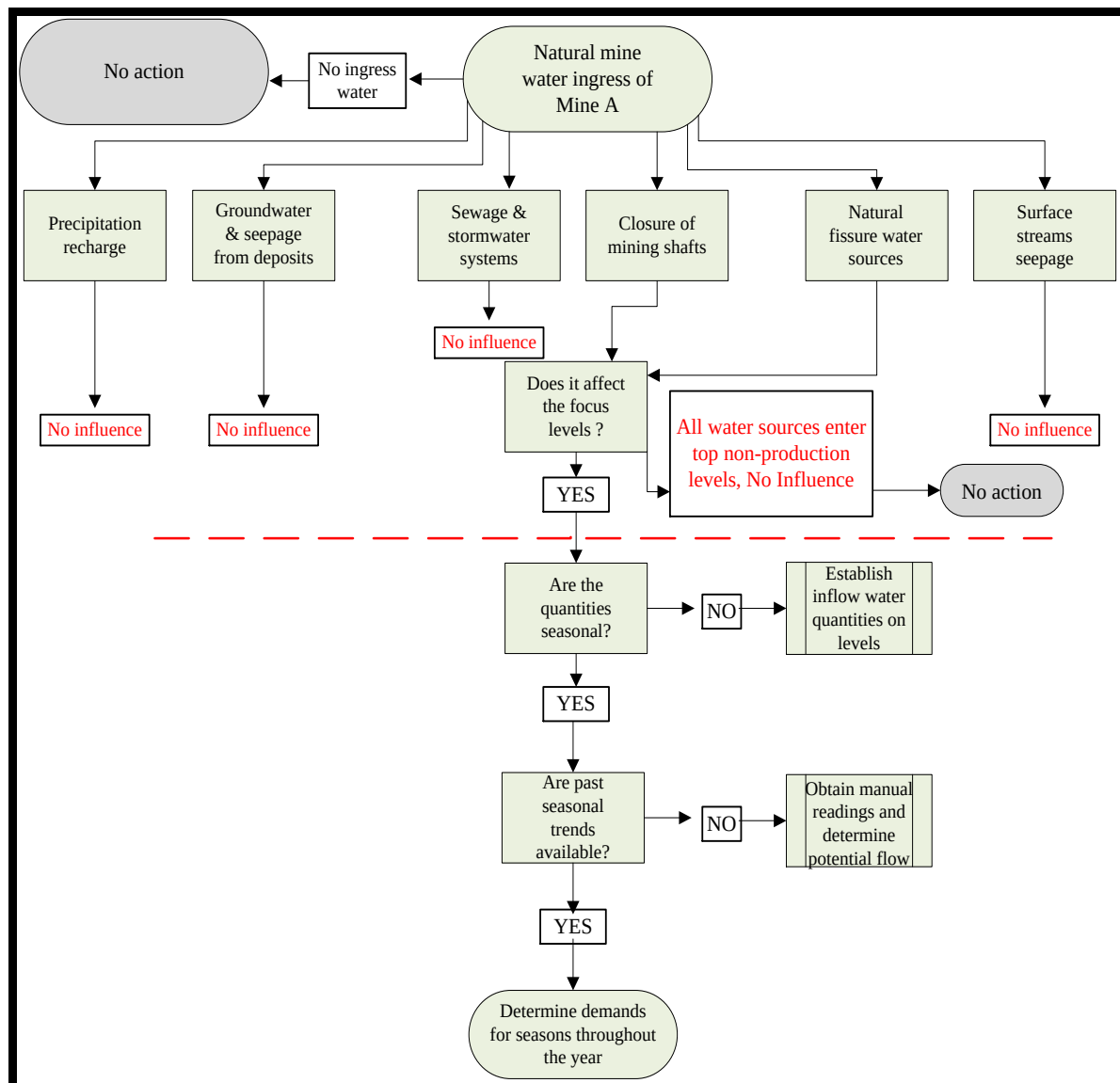


Figure 48: Flowchart to determine additional fissure water sources effects

All currently accounted for mining water from surrounding shafts and fissure water enter and exit Mine A through **non-production levels** and do not influence the lower production levels' return water quantities. Demand forecasts are required for each quarter of the year based solely on the mining activities planned for the respective sections.

Control-loop based integration

Various projects influencing the spindle pump return water demand have been introduced to deep-level mining throughout the past few years. This dynamic adaptability technique establishes the influence of such projects on the system being analysed.

At Mine A, one such project has been identified. The project scope consists of installing automated control valves on the return chilled line after the cooling car in a XC. This aims to reduce the water wastage in the stopes with inefficiencies during off-peak mining times.

Ten additional automated control valves were ordered for 120L and 123L at Mine A. Through analysis, it was determined that approximately 7.1 l/s per XC would additionally remain in the chilled water line from 17:00 – 21:00 on weekday evenings. Additional information on the valve installations in the XCs can be found in Figure 91 in Appendix D.

The flow demands for the affected levels are required to be considered for the spindle pump configuration changes as well. The predicted weekday flows for 120L and 123L are shown in Figure 49.

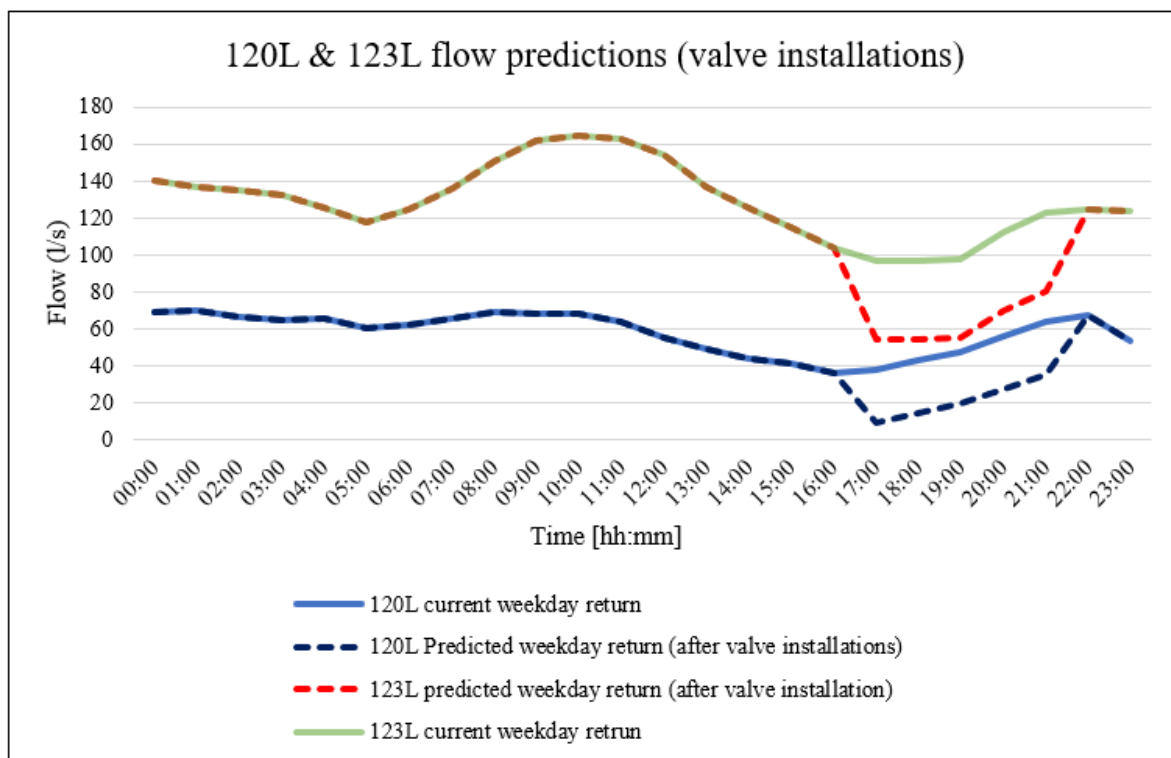


Figure 49: 120L and 123L non-chilled water return flows due to the SIV installations

The primary project focus is keeping more utilised chilled water in the U-tube system. This enables the water to loop through the cooling car and return to the 110L ice dam instead of being pumped all the way to surface. Estimate pumping cost savings are calculated as R 4.5 million (excluding weekends).

The evaluation of the effects the automated valve project is suspected to have will be done by providing answers to the following evaluation questions:

- Does the implemented project reduce or increase the return water quantities from the working areas? – *The project currently assists to mitigate the return water quantities in the non-chilled water return line by ensuring chilled water remains within the U-tube system. This, in turn, takes strain off the spindle pump system.*
- Are operating schedules involved in the operation of these projects? – *Operating schedules are involved during the weekday mining times. The automated valves will be closed according to level-specific mining schedules to ensure more water returns to the 110L ice dam. The primary focus will be placed on 17:00 – 21:00 during the week.*
- Are the necessary infrastructure entities in place to properly monitor the change in water demand due to the implemented projects? – *Mine A is currently also rolling out a stope SCADA monitoring system. This will specifically focus on the water flow and pressure quantities that is provided to each XC's respective stoping area. An example of the stope monitoring SCADA is shown in Figure 92 in Appendix D.*
- Which parameters are to be monitored to ensure projects compatibility? - *Water temperatures in and out of the cooling car, water supply to the stope area, pressure in the water lines and total daily water quantity to the stoping area. The supply to the stope area is effectively what returns per XC via the XC return line into the bullnose sumps.*
- What are the savings/additional costs of the implemented projects compared to current return water system operation? – *The project will yield additional savings of R 4.5 million.*

- Are there integration strategies to ensure potential negative counteractions are avoided?
– *The only change comprising the automated valve project is the forecasted demand which will decrease during certain periods of the day. All other project aspects indicate a positive influence on the spindle pump configuration changes. This project will also keep the XCs dry and may affect the ambient temperatures of the XC positively due to a reduced quantity of non-chilled water from the stopes **not** ending up in the XC footwalls or floor.*
- Are configuration changes to the spindle pump system necessary due to the implementation of these projects? - *Due to the focus periods of these valves only including a small time period of four hours, the water demand reduction is not significant enough to enforce a re-evaluation of the currently suggested spindle pump configuration changes.*

By ensuring all the integrating factors of all three dynamic adaptability techniques are properly monitored, understood and communicated to all relevant personnel, the cumulative success after implementation will be enhanced. **This aspect of control loop integration firmly addresses the secondary novelty by using the integrated developed simulation to analyse the resulting water demands additional initiatives may have on the spindle pump return system.**

Sustainable development

Prolonged project success will ultimately be determined by the ability to continuously provide sustainable solutions to challenges encountered before and after project implementation. Using the developed sustainability model in Figure 28 of Chapter 2 as a guideline, each step in the model will be discussed in this section.

Design

Account for all bullnose pumps in the process boundary – Due to the dynamic nature of a deep-level mine operation, forced configuration changes may occur to adapt to certain problems that arise due to inefficient communication with management. Follow up audits of all the bullnose pumps within the boundary are necessary to ensure all the pumps included in the simulation are still the same size and type as documented in the initial audits of the pumps in the boundary.

Follow-up audits on Mine A revealed that the configuration, size and pump type remained the same as with the initial audits.

Incorporate medium and long-term mine planning to identify XCs to be closed – Mine planners are required to provide detailed plans of the sections to be mined, opened up and closed for the year ahead. These plans can be used to identify sections on the production levels where spindle pumps may not be necessary and can potentially be removed. Certain stopes may not produce ore but still consist of reclamation activities before the XC is sealed off for services and ventilation purposes. The reclamation activities may delay the project plan to alter the spindle pump configuration system. A visual representation of the mine planning incorporated into the water demand forecasting for Mine A can be viewed in Figure 93 - Figure 97 in Appendix D.

A total of 18 XCs on the lower mine production levels are scheduled to stop mining activities before FY24 ends. A summary of the XCs can be viewed in Table 40 in Appendix D.

At the time of the indicated dates, information on the XC reclamation should be obtained to establish a potential new water demand for the XCs. Further evaluation on the XC sealing should be done to set up a timeline for potential bullnose pump removal should it be feasible.

Incorporate long term mine planning to ensure future water demands are determined – Water demand forecasting determines timelines for system evaluation and serves as a comparative baseline of operation. An effective method of water demand forecasting is using the actual intensity of the mining water, which is shown below in Equation 27 [26].

Equation 27: Mining water intensity calculation

$$\text{Mining intensity} = \frac{\text{Mining water used (non - chilled water return)}}{\text{Tonnes produced}}$$

Where:

Mining intensity = Value to indicate the measure of water used per tonne of rock produced (kL/tonne)

Mining water used = The quantity of water used specifically for mining activities

Mining water is calculated by using the return difference or the return quantity of the non-chilled water i.e. water that proceeds to the stopes and ends up in the spindle pump sumps (kL).

Tonnes produced = Tonnes produced per section of the production block (t)

Each of the production level sections were analysed over the period of the previous financial year to obtain a preliminary water intensity which will be used for future water demands. It should be noted, however, that the water intensity may vary throughout the financial year. Only predicting the water demand two quarters in advance (representing similar seasons) using the previous financial year's section water intensity is recommended. Applying the forecasting technique to longer periods may render inaccurate results. Intensity values are currently calculated daily by means of an automated report to track the intensity throughout the month. By application of intensity tracking, it can easily be picked up if there is a deviation within the water intensity and adjustments to the demand forecasts can be made accordingly.

Inefficiencies within the chilled water distribution system do exist and a baseload of non-chilled water return quantities will be present on each level, regardless of mining activities. An analysis was done throughout February 2022 to determine the “non-productive” water distributed to the production levels. The analysis entailed establishing the baseline quantity of non-chilled water return present on the production levels when mining does not take place (when available stope isolation valves are kept closed between 16:00 – 21:00 PM). This is the water that does not return to the 110L ice dam via the U-tube due to it ending up in the footwalls of XCs from leaking cooling cars or stope inefficiencies. Figure 50 shows results from the analysis indicating non-productive water for the respective production levels.

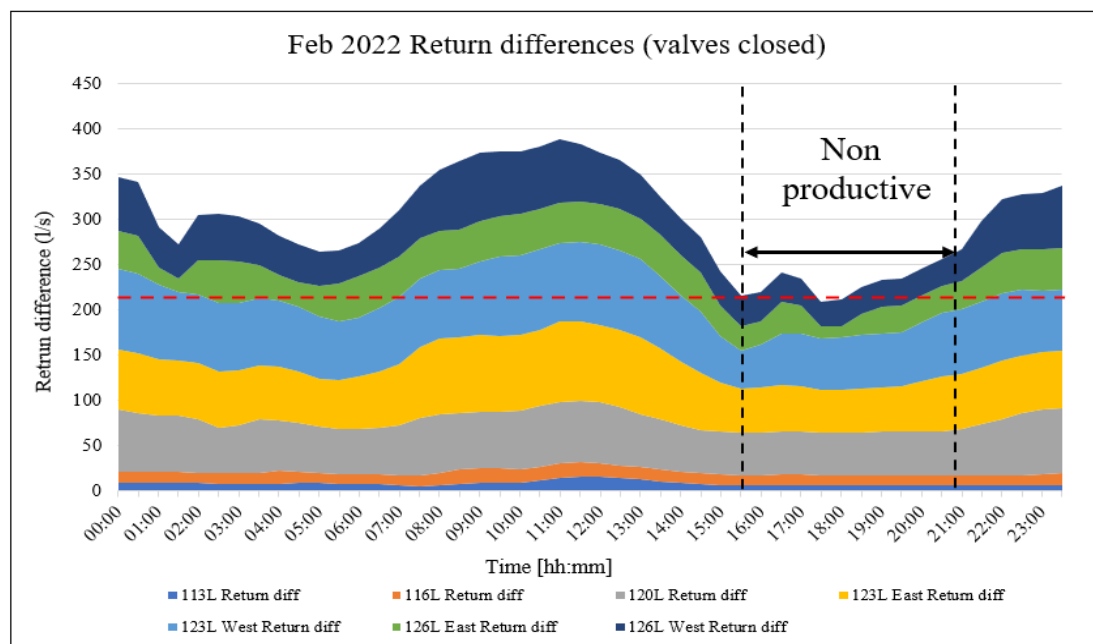


Figure 50: All production levels non-productive water consumption comparison

The focus hours are the off-peak mining hours from 15:30 – 21:00 in which no mining activities take place. The flows will be used as a baseload water demand, considering the current inefficiencies remain. Sections where the stope isolation valves will be additionally installed will only affect the off-peak mining hours as indicated in Figure 50. Figure 51 shows the baseload water demands extrapolated for all hours of the day for the lower production levels.

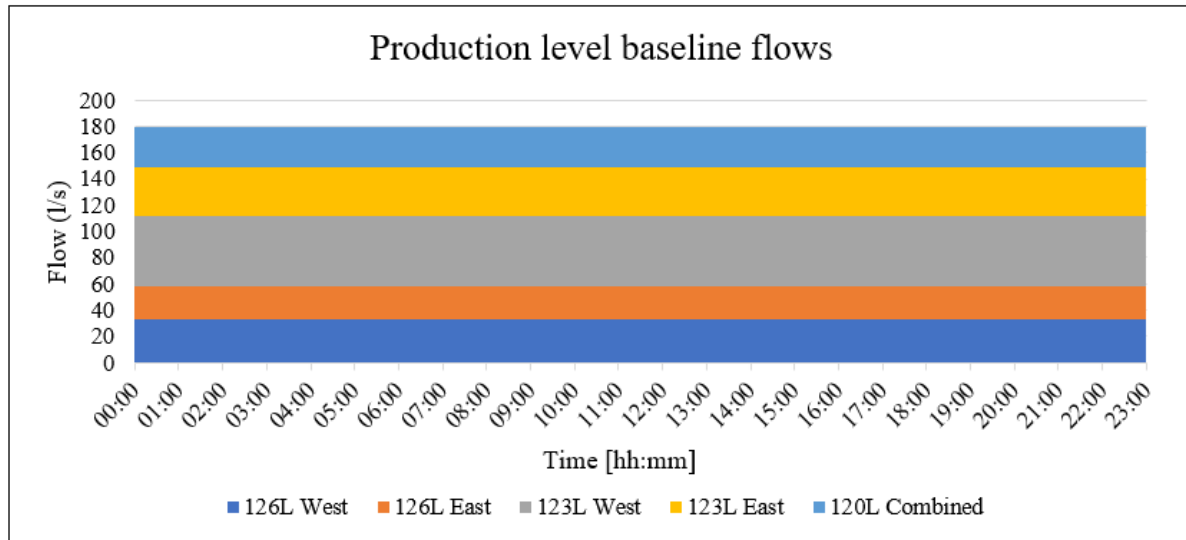


Figure 51: Lower production levels baseline return water flows (excluding mining activities)

The baseline flows will be used as forecast guidance to establish when mining activities on levels scale down or stop completely. Flows for the second and third quarter of FY23 were forecasted using the water intensities and baseload water demand in Figure 52 - Figure 53.

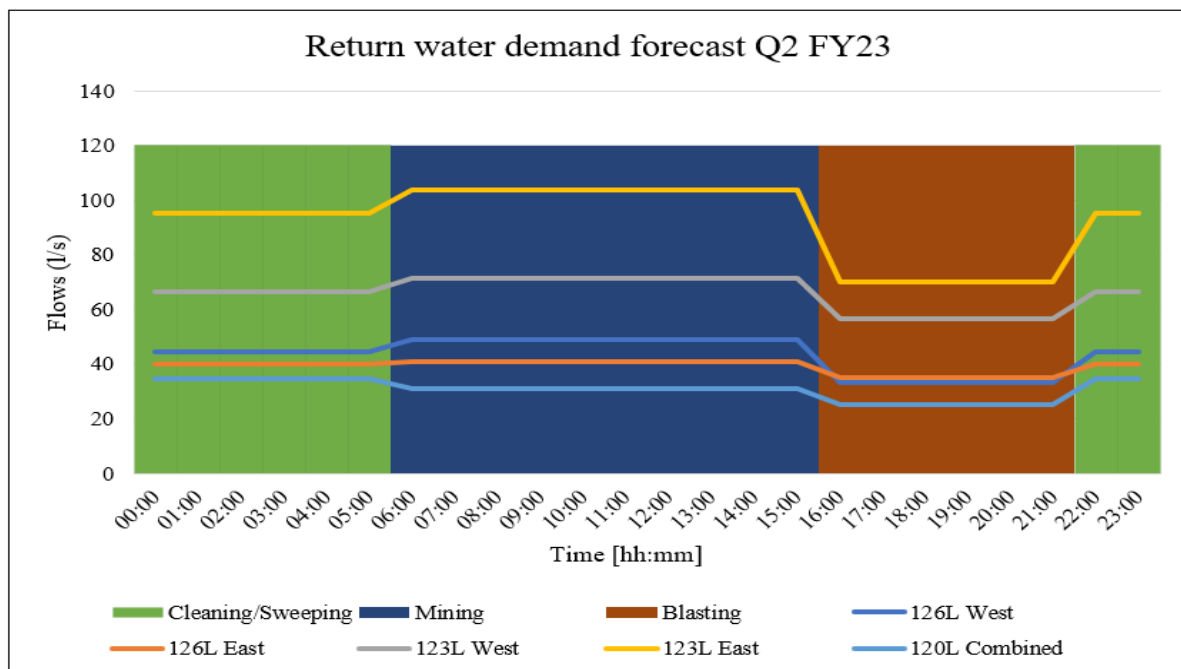


Figure 52: Lower production levels FY23 Q2 non-chilled water return demand forecast

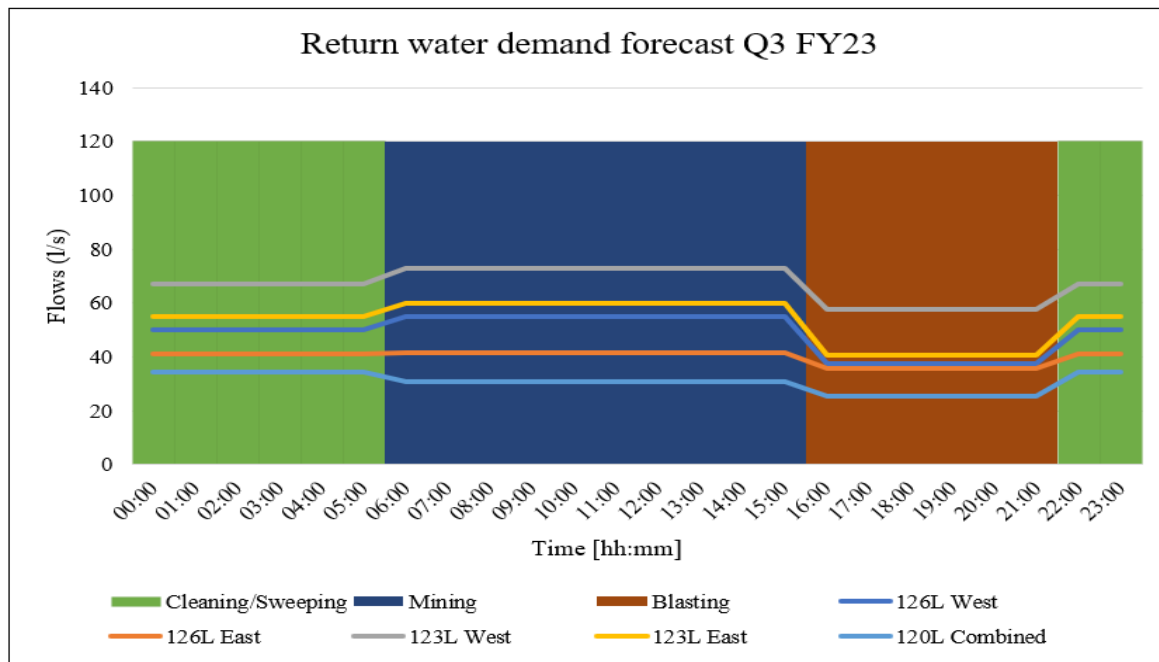


Figure 53: Lower production levels FY23 Q3 non-chilled water return demand forecast

Each level's water demand is displayed according to the time period of each mining activity. Forecasts should be **evaluated each quarter** to ensure it remains updated if changes occur.

Set up system flow limits allowing sufficient time for changes to occur – Established system limits were added to the digital twin monitoring system to ensure constant comparisons can be made relating to the system performance. The highest limit was preliminarily added to the digital twin due to the current restriction of one limit addition for all the systems displayed. The interface of the system limits for 126L can be viewed in Appendix D.

Ensure the simulation is updated regularly to ensure accuracy – Upon the start of the project , 2021 non-chilled water return flows were used for the initial simulation calibration. The simulation was updated with FY22 Q3 flows to ensure the latest return flows are used. Due to daily return flow monitoring, the evaluation of the flows used for the simulation are easily attainable. As soon as a consistent change is noted on the return water flows, the simulation should be adjusted with the newly recorded flows. Proceeding quarterly forecast values should be evaluated if notable changes are seen within the preceding quarter.

The design aspect of sustainable development firmly addresses the novelty of using the simulation to forecast the return water quantities for the spindle pump system.

Personnel

Ensure the project is backed by senior personnel – Senior personnel was made aware of the project scope upon identification. An essential aspect of project success entails the buy-in of senior personnel throughout the pre-implementation project lifetime. Regular updates were provided to management and thoroughly discussed with all the relevant personnel. The management backing resulted in various regularly reported project delays such as labour scheduling priority being avoided.

Confirm the correct allocation of project funds with the finance department – Project funds are based on the preference of replacing the indicated pumps with either refurbished pumps from Mine A's inventory or new pumps from the OEM. New pumps will ensure longer pump life than already used, refurbished pumps. A phased approach was used for project budgeting as the replacement of all 49 pumps with newly purchased pumps may put strain on already stretched project budgets. The phased approach allows gradual changes to be made to the system while the analysis of the changes took place simultaneously. The installation of 45kW pumps were stopped and all new future installations of bullnose pumps will be done according to water demands.

Prior to implementation, spindle pump audits were extended to the top mine levels where mining activities came to an end. The audits revealed that **18** spindle pumps can be removed for reclamation. Reclaimed pumps were used for initial exchange with several new 15kW pumps, depending on the condition of the removed pumps. The finance department were made aware of the exchange strategy and this was incorporated in the short-term budget cycle.

The reclaimed pumps were used as a preliminary project test to establish whether the developed strategy did indeed perform as forecasted.

Properly involve and train personnel responsible for the day-to-day operations – Replacing and removing pumps requires a boilermaker or fitter, an electrician and a rigger. Training sessions with personnel allocated to all three production levels were conducted to ensure all are aware of the process of pump installation, removal and operation.

Anticipate delays in project planning – Project delays are an inevitable occurrence, especially in the labour-intensive mining environment. Delays for each project step were identified and used to establish realistic timeframes for project completion.

Some of the delays encountered are common occurrences and are important to consider. These delays can be viewed in Appendix D.

Ensure proper labour schedules are in place to establish availability – Due to the support from senior personnel classifying the project as priority, more personnel were allocated to the project. Proper labour rotational schedules were set up which included regular off time and backup personnel should unexpected labour jobs arise at Mine A.

Maintenance

Allow redundancy of pumps available should breakdowns occur – Mine A consists of pumping workshops on the shaft, which are specifically contracted to refurbish older, reclaimed pumps and place them back into stock for potential future use. The personnel at the workshops were made aware of the initiative during the early development stages to ensure readiness as the project progresses. The workshop was also tasked to ensure several redundant pumps are available for the foreseeable future because the system is now being monitored.

Establish system operation should maintenance of certain pumps occur – XCs with the highest water demand will undoubtedly pose the most challenges when maintenance is required.

XCs with smaller water demands are easier to regulate and can even be done during the peak mining periods without any additional isolation of water. The whole spindle pump system needs to be considered to ensure which of the bullnose pumps have the highest water demands and which of the pumps can remain off without any significant repercussions of flooding. At the time of writing, the identified high demand XCs on the levels were the following:

120L – 33 and 66XCs,

123L – 33, 34, 35, 36, 38, 57, 61, 62, 63 and 64XCs,

126L – 35, 36, 38, 39, 40, 42, 48, 49, 51, 52 and 56XCs.

Should maintenance occur on the identified XCs, it should be aligned with off weekends in order to isolate the water manually after the cooling car in the XC to reduce the water demand. It should be noted, however, that the XCs should be re-evaluated sequentially due to dynamic water demand changes on the mining levels. All other bullnose XC pumps maintenance can be done during the week due to lower water demands and reduced haulage flooding risks.

Derive level-specific maintenance schedules – Levels with higher mining activities are prioritised above the lower ore producing levels. The maintenance schedule order was, therefore, determined by first allocating the maintenance personnel to 126L, 123L, and finally to 120L. However, it was considered that some bullnose pumps' maintenance activities can occur during the week and can be scheduled ahead of the priority levels. Both East and West maintenance crews will be utilised to ensure maintenance on the half levels occurs simultaneously.

Ensure the availability of qualified maintenance personnel upon maintenance dates - Due to the training sessions conducted, all engineering personnel situated on the levels are capable of removing spindle pumps, are aware of the spindle pumps operation, and can conduct maintenance should it be needed. Labour is scheduled two to three weeks in advance for necessary preparations to be made.

Establish maintenance challenges resulting in delays – Most maintenance scheduled job delays occur due to unexpected breakdowns on other mining infrastructure (pipes, fans etc). Due to the proper training and increased quantity of personnel able to conduct maintenance on the pumps, delays are already mitigated. All available pumps from the exchange store are required to be readily available, proper standby personnel scheduling is required and jobs prohibiting the isolation of water on the focused XCs need to be clearly noted to align the work to be done.

Properly sustained projects indicate a long and prosperous project life. Monitoring and sequential evaluation of all sustainability factors is required to ensure project productivity.

3.6 Step 5 – Implementation tracking and results analysis

Implementation

Implementation can be treated as an individual project due to all the integrating parts needed to successfully ensure completion. Timelines were set up using a Gantt chart to keep track of the implementation steps. Continuous implementation monitoring is required, as this is the most important step within the project. The implementation steps were divided into three parts:

- *Audits analysis and reclamation* – Additional audits and reclamation on the top levels of Mine A were scheduled for this step. Time was added for any delays encountered for both the stripping and the loading of the pumps identified for reclamation.

- *Pumps exchange and installation* – Co-ordination of the reclaimed pumps is required to establish how many of the reclaimed pumps are in a working condition and can be exchanged for new 15kW pumps in stock at the service exchange store. After co-ordination, the installation of the pumps available for exchange commenced. Delays were also accounted during this step.
- *Results analysis* – Audits of the installed pumps and logger measurements are scheduled for this step. The logger measurements will be used to establish the final results of the strategy in order for the comprehensive pump exchanges to be included in the budget cycle.

Ensure task responsibilities are allocated clearly – Tasks were allocated to engineering personnel situated on each of the lower mining levels. Teams were divided into three sections:

- Pump stripping – One boilermaker, one fitter and one electrician for each of the half levels.
- Pump loading – One loco driver, one rigger and one fitter for each of the half levels.
- Pump installation – One loco driver, one rigger, one fitter and one electrician.

The stripping of pumps consisting of little to no water demand was scheduled for the weekdays as no isolation was required. Pump loading was scheduled during mining activities, as a part of the team consisted of tramming personnel allocated to the mining crews. Pump installation was scheduled for off-weekends as isolation is required. All the teams were given a time limit in which to complete each job according to the initiative schedule.

Confirm labour availability to properly plan schedules – Unforeseen breakdowns are almost inevitable in deep-level mines. This usually means planned jobs are lower priority should these breakdowns occur, due to breakdown importance exceeding that of planned jobs. Each of the teams were given standby engineering personnel to ensure the scheduled jobs proceed as scheduled.

Arrange training sessions for all technical staff – All of the untrained staff, such as the personnel on standby, were also enrolled in training sessions to ensure **all** personnel within the teams are aware of their respective responsibilities.

Prepare the infrastructure and confirm logistics – The non-return valve operation of all the pumps indicated for reclamation should be operational.

If non-return valves were not in a working condition, the boilermaker and the fitter allocated to each half level were instructed to repair/replace the non-return valve on the delivery side of the spindle pump. Logistics were confirmed with the vertical transport personnel as loading on each of the levels occurred.

Monitor the implementation budget – Some of the reclaimed pumps were in a worse condition than others and required extensive refurbishing. These pumps could not be included in the direct trade with new 15kW pumps. Arrangements with the exchange store were made to examine all reclaimed pumps and establish how many pumps would be equivalent to one new, discounted 15kW pump. The examination was comprehensively tracked to ensure the monthly engineering budget for each level was not surpassed. Additionally required parts were indicated before replacement or refurbishment occurred. Replacement activities took place according to the available budget for each month of the phased implementation period.

Monitor work quality – Sufficient time was included for quality assurance audits after each of the indicated activities. Quality audits ensure minor problems are identified and rectified before transitioning into major, uncontrollable problems.

Monitor system performance – As pumps were stripped, loaded and installed on the target levels, the spindle pump return system performance was monitored. The replacement of pumps with the highest water demands noted were scheduled to be replaced last.

Results analysis

At the time of writing, Mine A exchanged **ten** 45kW pumps for 15kW pumps on the lower mine levels using the strategy of reclamation pump exchange. Most pumps identified for reclamation on the top mining levels were not running. **Six** of the top mine pumps (45kW) identified for reclamation had been running and were recommended to be switched off and reclaimed based on zero water demand into the sumps. Non-return valves on **two** of the top mine pumps (45kW) were in a non-working condition. This led to the inability to switch the pumps off as water would divert to the path of least resistance and flood the haulage through entering the delivery column of the spindle pumps.

The non-return valves were repaired, and the pumps were switched off and reclaimed. Targets and KPIs were determined according to the quantity of pumps that were exchanged and switched off during the implementation of the project.

Monitoring

Translation of objectives into KPIs and targets

The **main** objective of the study is to develop a simulation-based horizontal water management strategy which can be followed to obtain electricity cost savings. Secondary objectives were also identified to ensure a comprehensive strategy is developed. The objectives specified in Chapter 1 are discussed below.

- *Integrate current and future water demands through simulations to reduce OPEX costs* - Alternative pumps were suggested for installation on the targeted production levels. According to the analysis, a total of **43** pumps were identified for potential exchange with smaller sized pumps. The currently installed pumps **not recommended** for exchange (after further analysis) are the bullnose spindle pumps located at the development ends. These pumps account for the last XC's water demand as well as the service water used for development activities. At the time of writing, a total of **23%** of the suggested 45kW pumps for exchange have been replaced with 15kW pumps. An additional **six** pumps were identified to be switched off through the extended top mine audits, which increases the electrical cost savings.
- *Increasing water demands forecasting accuracy leading to better capital allocation* - Future water demands were determined by integrating the planned ore tonnes for each section. This was done by using the water intensity calculated from the actual tonnes hoisted originating from each production section. Water demands were forecasted for the following two quarters of the financial year and will be revised as the actual water demands change. Sections where mining will scale down significantly will be re-evaluated to determine the quantity and size of pumps needed.
- *Provision of a platform to test scenarios of horizontal water management improvement prior to implementation* – The simulation models developed provide an integrated overview of the entire spindle pump system. Various water demand scenarios can be trialed and tested to ensure the spindle pump configuration on each level is correctly allocated to the current and future demands. Unrelated projects applied to the same operating system tend to influence the performance of one or both projects at hand. These influences tend to be overlooked and may cause underperformance (or even failure) of the projects.

The strategy integrated the effects of both projects and established that the projects complimented one another and no adjustments to the primary strategy were required.

- *Adding a system monitoring aspect to a previously unmonitored and under-equipped system* – The previously unmonitored spindle pump return system was added to the integrated digital twin monitoring system. Each operational level consists of allocated limits with linked corresponding actions should system performance exceed or operate below set limits. Awareness was created amongst mining personnel which increased the focus placed on the operation of spindle pumps.

Routine data collection on new configurations

Data loggers were installed on the exchanged 15kW pumps. Due to the smaller pump size installed, some of the pump suctions were left partially submerged when increased water demands were noted. The 45kW pumps' suction side was rarely left submerged during normal operation and the pump was left idling most of the time. Focus was, therefore, placed on the water demands of the exchanged pumps to ensure the effects of the demands into the sumps were noted.

Three pumps with variable water demands into the sump were chosen to be measured to ensure the results were analysed comprehensively. The demands into the sumps were classified into high (120L 38XC), medium (120L 48 XC), and low (120L 45XC). The analysis of the demands entailed documentation of the water quantity from footwalls and the open-end pipe into the sumps during weekdays and weekend periods. Loggers were installed to cover a weekday and weekend period. The remaining exchanged pumps on 123L and 126L were divided into the **high demand** classification due to current water demands noted. Figure 54 shows the graphs of the 15kW exchanged pumps' performance.

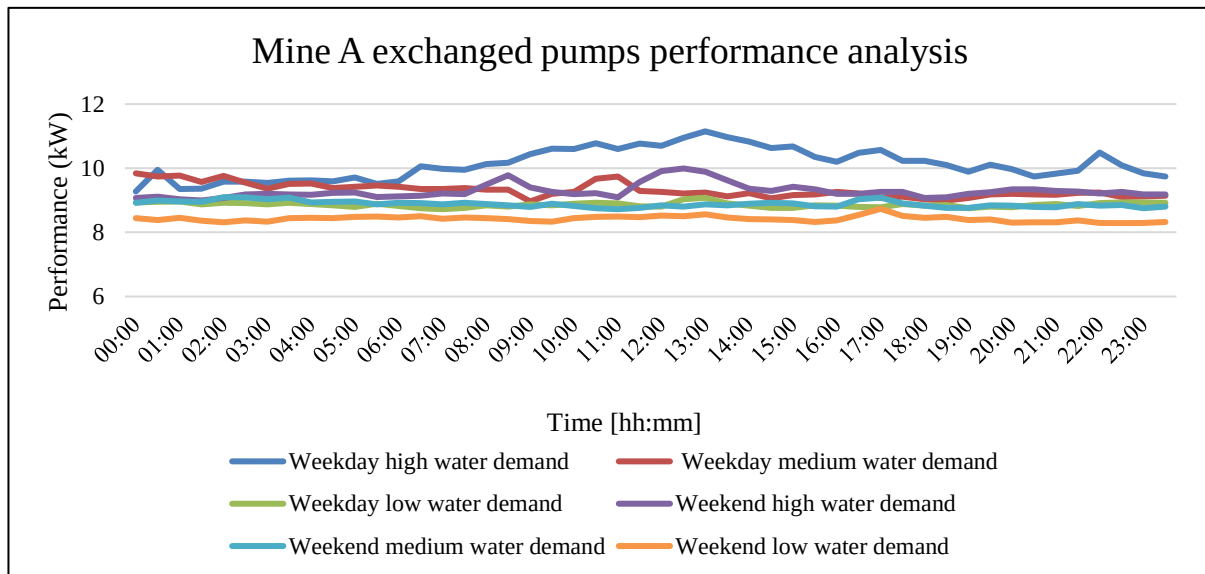


Figure 54: Consumption of exchanged 15kW pumps compared to water demands into sump

Figure 54 illustrates a small difference in consumption when considering the different water demands into the sumps. Weekend periods, when demands are lower, also show a reduction in electrical consumption. Table 38 shows the parameter averages of the measured pumps.

Table 38: Exchanged 15kW spindle pumps logger results

Spindle pump parameter averages			
Weekday			
	Average kW	Average Amps	Average Volts
120L 38 XC	10.13	11.92	516.35
120L 48 XC	9.31	11.01	513.94
120L 45 XC	8.86	10.49	513.14
Weekend			
	Average kW	Average Amps	Average Volts
120L 38 XC	9.29	11.14	506.73
120L 48 XC	8.88	10.76	501.93
120L 45 XC	8.42	10.03	510.34

The parameter averages indicated in Table 38 will be used to establish the potential savings according to the current spindle pump configuration.

Data processing

Analysis from predicted results

The sequentially exchanged pumps **already exchanged or switched off** throughout **all** of the levels were evaluated. The results can be extrapolated based on the sample size determination method developed in Step 1 of Chapter 2 [86].

Comparisons of 15kW and 45kW pump performances were made to indicate the difference when also considering the water demand influence on the 15kW pump suction. Figure 55 shows the comparisons of the 15kW pumps' performances compared to the 45kW pump's performance.



Figure 55: Weekday and weekend performance of exchanged spindle pumps

Figure 55 shows slight deviation from the initially measured 15kW pumps. It is, therefore, necessary to analyse the replaced pumps with the appropriate water demand based on the logger measurements.

The weighted average consumption of the replaced pumps is required to accurately determine the savings of the configurations as it currently stands according to the demands. This is done by using Equation 26.

$$\text{Weighted ave high demand} = 10.13 \times \frac{259}{365} + 9.29 \times \frac{106}{365}$$

$$\text{Weighted ave high demand} = 9.89 \text{ kW}$$

$$\text{Weighted ave medium demand} = 9.31 \times \frac{259}{365} + 8.88 \times \frac{106}{365}$$

$$\text{Weighted ave medium demand} = 9.19 \text{ kW}$$

$$\text{Weighted ave low demand} = 8.86 \times \frac{259}{365} + 8.42 \times \frac{106}{365}$$

$$\text{Weighted ave low demand} = 8.73 \text{ kW}$$

Individual logger measurements are used to establish consumption until enough pumps are replaced to note the reduction in energy consumption on the individual levels' mine feeders without being offset by variable energy load throughout the day.

Savings analysis derived from processed data

The calculated weighted averages of the replaced pumps were used to calculate the savings **potential** of the exchanged pumps. The additional pumps switched off through the audits conducted on the top mine levels will be allocated the weighted average of the normal operation of the 45kW pump. Due to the replacement of only 10 constantly operating pumps thus far, Equation 22 was adapted to determine the electrical cost savings.

$$\text{Cost savings} = \text{Weighted average diff} \times \text{pumps replaced} \times \text{Avge Eskom tariff} \times \text{running hours}$$

Where:

Weighted average diff = Difference between the weighted average of a water demand classified 15kW pumps compared to the weighted average of a 45kW pump (kW)

Pumps replaced = Quantity of pumps replaced within the demand classification

Avge Eskom tariff = Average Eskom tariff (R/kWh)

Running hours = Running hours of the newly installed pumps (or running hours avoided for pumps that were switched off)

$$15kW \text{ high demand savings} = 6 \times 10.84 \times 8760 \times 1.165$$

$$\mathbf{15kW \text{ high demand savings} = R663\,759}$$

$$15kW \text{ medium demand savings} = 2 \times 11.54 \times 8760 \times 1.165$$

$$\mathbf{15kW \text{ medium demand savings} = R235\,540}$$

$$15kW \text{ low demand savings} = 2 \times 12 \times 8760 \times 1.165$$

$$\mathbf{15kW \text{ low demand savings} = R244\,930}$$

$$\text{Total exchanged pumps kWh avoidance} = \mathbf{982\,171 \text{ kWh}}$$

$$\text{Total exchanged pumps savings} = \mathbf{R1\,144\,229}$$

The additional pumps that were switched off contribute significantly to the savings realised.

$$\text{Running pumps costs avoidance} = 6 \times 20.73 \times 8760 \times 1.165$$

$$\mathbf{\text{Running pumps kWh avoidance} = 1\,089\,569 \text{ kWh}}$$

$$\mathbf{\text{Running pumps costs avoidance} = R1\,269\,348}$$

$$\mathbf{\text{Total current project savings p.a.} = R2\,413\,577 \text{ (2\,071\,740 kWh)}}$$

The current annual predicted savings, based on already exchanged pumps, deviates from the initially predicted savings potential if **all** the pumps are exchanged for 15kW pumps. The accumulated savings will increase throughout the next financial year as the 45kW installations are phased out.

BEP conclusions on new installations

One of the **secondary goals** of the spindle pump configuration changes was to analyse the pump performance in relation to its BEP and resulting energy efficiency. Flows out of the spindle pumps were measured for the new installations to establish pump operation in relation to its BEP. The three demand scenarios were measured at normal operation. Water flows for the demand scenarios were as follows:

- High demand – 16.5 l/s, Medium demand – 12.8 l/s, Low demand – 8.9 l/s

Figure 56 displays the pump operational performance in relation to the BEP of a 15kW spindle pump.

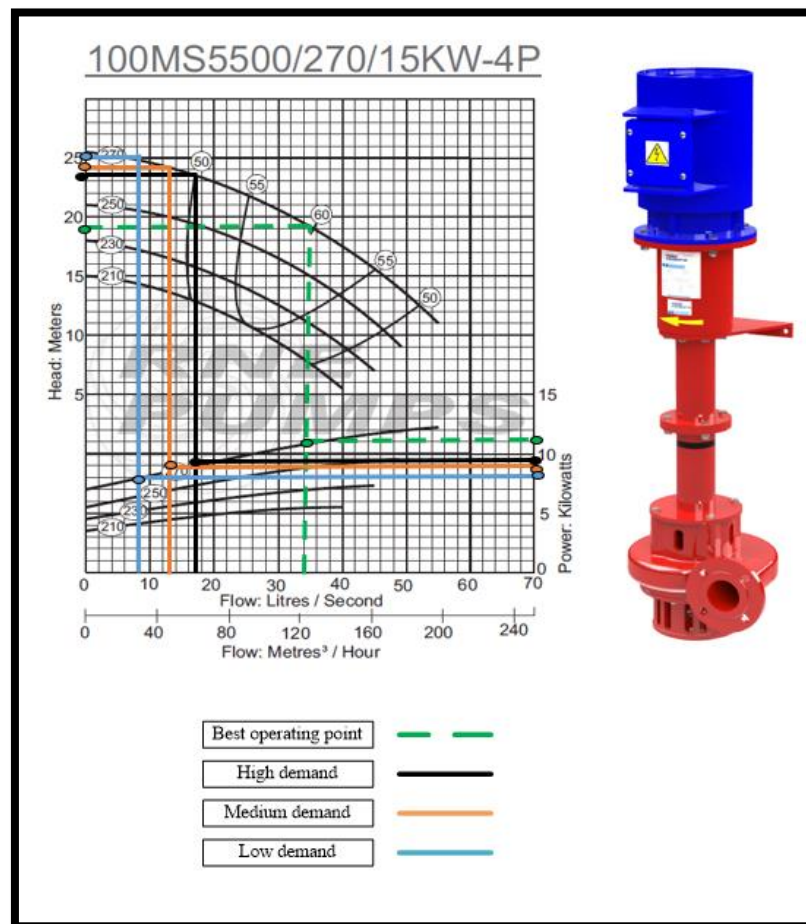


Figure 56: Exchanged 15kW pumping performance comparison (performance curve)

The pump performance in relation to its BEP is summarised in Table 39.

Table 39: 15kW exchanged pumps performance in relation to its operating BEP

15kW BEP pressure deviation calculation				
Operation type	Head (m)	Flow (L/s)	Power (kW)	Deviation (%)
BEP	20	34	11	-
High demand	24	17	10	17.4%
Medium demand	24	13	9	19.1%
Low demand	25	8	8	21.7%

At the various demand scenarios, it is seen that the high water demand performed the best in relation to the 15kW pumps' BEP. This indicates that there is still some room for improvement in relation to the BEP should the water demands increase in the various sections where the replacements have been done.

Evaluation

Analysis on results deviating from predictions

The simulation models were used as a base to establish a better suited pump size for the flows on the various target levels. According to the latest service water return demands, the pump best suited for the application, **without operating near maximum system limits**, was established as the 15kW pump. It was noted, however, that the newly installed pump performance differed from the initial 15kW measurements taken. This is due to the water demands varying on each level dependent on the activities within the XCs. Levels where mining activities have already been scaled down significantly from the previous financial year, such as 120L, would inevitably consist of a lower service water demand. Development on 123L is near completion and mining activities remain in full force in the XCs nearing the development ends. Development on 126L is taking place at a rapid rate and is set to continue for the next few financial years after which mining activities will remain. Monitoring measures and corresponding actions for the main production levels are in place should an increase or decrease in water demand be noted.

One of the major deviations to the savings prediction model was the inclusion of the top mine audits for the primary objective of pump reclamation. Information received prior to conducting the UG audits indicated that most of the bullnose spindle pumps on the top mine levels were switched off when mining activities concluded. The audits revealed that there was significant scope to further improve the system by switching off the pumps that were running

unnecessarily due to negligence and faulty non-return valves. This, in turn, indicated the lack of monitoring and focus placed on the spindle pump system.

Implementation evaluation

The implementation step of the project consisted of additionally developed steps compared to the usual implementation methods. The training of staff, labour confirmation, delays anticipation and constant monitoring of budget and system performance assisted greatly in keeping the initiative on track. The main challenge regarding the pump replacements were the budget allocations. Budgets at Mine A are set up before the start of each financial year (July – June). The budgets usually cannot be changed unless breakdowns or labour issues result in forced budgets changes. The project was identified after the start of the 2022 financial year and a phased implementation approach, together with pump reclamation exchange, was developed to adapt to the FY22 budget cycle. This resulted in **10 out of a possible suggested 43** pump replacements (development end pumps to remain) to occur before July 2022. The following budget cycle will account for pump replacement with the exchange strategy in force for each of the targeted production levels.

Future improvement recommendations

Contrary to past belief, the spindle pump return system requires monitoring to maintain an adequate degree of performance. The methodology steps developed addressed all the necessary steps required to investigate, assess, develop and analyse sustainable solutions to maintain improved spindle pump system performance. Improvements for **sustained** future performance entails the continuous and timeous rollout of the stope SCADA monitoring system. Monitoring each XC individually assists to classify each XC as an individual business unit. Budget limits, over/underperformance and fault finding can, therefore, be narrowed down to each individual XC rather than conducting time-consuming audits to identify the complication within the system.

As stated in Figure 13, adjustments to the developed strategy can be made if deemed necessary. It is also recommended to expand the strategy to lower ore-producing levels to ensure spindle pumps are not running necessarily due to faulty infrastructure or lack of monitoring. The project results can be used as the motivation to properly equip low-priority service systems if it is deemed feasible.

3.7 Summary

Initial configuration audits were conducted at Mine A to establish the current operation of the spindle pumps system and determine the operational parameters needed for simulation integration. The developed simulations were used to establish a better suited pump size using scientific principles for the current water demands on the main production levels. The simulation model was integrated with the SCADA monitoring system to dynamically assess the performance of each level's spindle pump system. Initial measurements were also obtained to establish an energy consumption baseline which was used to determine potential electricity cost savings.

The lack of horizontal water transport system management in literature added challenges in the methodology development of the study. The studies analysed within the state of art matrix did, however, provide solid bases on important focus points to include on the study. Influential aspects which contributed greatly to the success of previously listed studies could be replicated and applied to ensure the successful implementation, monitoring and analysis of the initiative in the study.

The methodology consisted of an adjusted implementation strategy which minimised project costs and constraints which previously led to time delays and project failure. Involved personnel were properly trained and labour schedules were comprehensively analysed to ensure availability on the scheduled days. The sequential approach followed led to the replacement of ten (**10**) 45kW pumps with 15kW pumps. The additionally conducted audits on the top mine levels revealed a further **six pumps** can be turned off due to the absence of water demand into the sumps of the identified pumps. Lower priority production levels should be included in the preliminary audits to ensure cost avoidance of unnecessary running infrastructure is also considered.

Manual pump performance measurements were conducted after pump replacements to evaluate the effect of the configuration changes. The electrical cost savings due to the configuration changes made currently amounts to **R2 413 577 p.a. (2 071 740 kWh)** with the potential to reach an annual saving of R4 821 131 or 4 039 148 kWh avoidance if all suggested pumps are exchanged.

The study provides a new water management strategy driven by placing focus on system performance, energy consumption, water demands forecasting and monitoring of the less energy-intensive horizontal water transport system. The study highlights the importance of including **all contributing sub-systems** to a main system to realise savings potential that would otherwise be unassessed. It was, therefore, validated that it is viable to **analyse system requirements** before installation rather than following outdated, standardised mining procedures.

CHAPTER 4

CONCLUSION

“Reasoning draws a conclusion, but does not make the conclusion certain, unless the mind discovers it by the path of experience.”

— Roger Bacon

4 CONCLUSION

The final section aims to conclude the primary findings of the study and place focus on the novel contributions discussed in Chapter 1.

4.1 Preamble

Water system improvement strategies developed for deep-level mines largely focused on the energy-intensive dewatering pumps used to pump water out of the mine. Implementation of the case study methodology provided measurable results from which clear conclusions could be made. Research indicated that focus has yet to be placed on the horizontal water transport system primarily used to move used service water from the production sections towards the annex holes/ holding dams on the respective levels. This study provided a new water management strategy focused on the system performance, energy consumption, water demands forecasting and monitoring of the less energy-intensive horizontal water transport system. The methodology was used to create awareness of the important role horizontal water transport pumps have in deep-level mines. Integrated simulation techniques were used as part of the methodology to incorporate the digitised mining approach into the existing mining infrastructure. This provides a valuable foundation to the industry of the importance of including **all** contributing entities relating to energy-consuming systems.

4.2 Review of the novel contributions and objectives

- ***S&M of horizontal water transport systems in a deep-level gold mine to obtain improved operation leading to electrical cost savings***

The analysis of the results in Chapter 3 revealed that through use of the developed simulations, better suited pump sizes could be established by using the obtained flows as an indication of performance. Pumping performance curves were also used and compared to the flows currently measured to ensure an additional measure of efficiency is added. The simulations revealed the operational limits of each pump's size and proved the inefficiency of the current operation. Established limits provide a good indication of actions required when measured flows surpass the set limits.

The contributing audits conducted on both the top and main production levels, primarily for data collection for simulation development, revealed scope to improve the system even further. This was done by using redundant spindle pumps for exchange and switch off pumps that are running unnecessarily (little to no water demand). Infrastructure such as non-return valves was repaired where needed and contributed to the reduction of running spindle pumps.

The data collected on the 45kW and 15kW pumps was used to establish whether electricity cost savings were achieved by replacing the over-specified pumps with better suited pumps. The results showed that the 15kW pumps consumed less energy than the 45kW pumps at the current water demands. The main novelty is addressed in **Step 3** of **Chapter 3**. The integration of future and current water demands with the simulation to reduce OPEX costs was done, which also firmly addresses **Objective 1** derived in Chapter 1.

The developed approach can be applied to any deep-level mine, keeping in mind that more extensive manual measurements may be required should other mines consist of less monitoring infrastructure than Mine A.

- ***Continuous horizontal water system simulation integration used as a means of mine development planning (without additionally installed condition monitoring infrastructure)***

Future service water flows were forecasted to establish timelines when the re-evaluation of the spindle pump system may be necessary. Planned tonnes for the following financial year were used to establish the XCs where mining activities will be the main focus. Baseline water demands were determined through tests conducted at Mine A to more accurately depict the demands of the foreseeable future. Mining intensity values formed an important part of the demand calculation as this was added to the baseline flows to obtain the total water demands of the different sections. The novelty was addressed in **Step 4** of Chapter 3 (sustainable development). The 2nd **objective** of an improved water demand forecast was addressed along with the indicated novelty in **Step 4** of **Chapter 3**.

The demand calculation assists with future planning as cooling requirements can be calculated to counteract the used service water quantities ending up in the footwalls of XCs and in the haulage. As the developments on the production levels progress, water demands can be

established, and the system performance can be simulated to ensure the most suitable pumps are used. Efficiently using the demand forecasts for the spindle pump system adds to the success of the project's sustainability.

The developed forecasting method is a useful means to ensure mines punctually prepare the necessary infrastructure required for future mining. It should be noted that forecasting should not be done too far ahead in the future, as ore production planning may deviate from the original mine planning schedule.

- ***Integrated horizontal water management strategy using simulation techniques to establish resulting water demands***

The influence of projects on the same system are often neglected and may cause underperformance of one or both projects. The influence of the isolation control project on the chilled water line was integrated with the current and future demands to establish if the pump sizes suggested would be viable upon implementation of the isolation control project. The simulation can be used to determine the pumping system performance should changes be necessary.

The developed novelty was addressed in **Step 4** of Chapter 3 (dynamic adaptability). It was found that the two coinciding projects would not negatively impact performance of either initiative. **Objective 3**, devised to ensure various scenarios of water demand, can be calculated using the integrated simulation. This was achieved along with the novelty in **Chapter 3 Step 4**. This establishes the use of simulations to depict water demands before implementation of a project to ensure preparation.

- ***Integrated monitoring technique for low priority water transfer systems***

The lack of previous spindle pump system monitoring resulted in the neglect of the entire system. The monitoring aspect of the spindle pump system ensures the system is regularly checked for anomalies, and actions are taken should the demands of the monitored levels change. The inclusion of the system on the digital twin and the REMS monitoring system ensures the correct personnel have continuous access to the measured values and are alerted timeously through automated communication channels should system limits be exceeded. The novelty is addressed in **Step 4** of Chapter 3 (dynamic adaptability). **Objective 4** directly relates to the novelty and was also achieved in Step 4 of Chapter 3.

Monitoring the performance of the system at hand ensures changes can be made prior to breakdowns or other contributing complications. Regular calibration of the system is required if changes were made to ensure the established limits align with the correct configurations.

4.3 Recommendations for future work

The methodology was developed to serve as a comprehensive tool to ensure project execution is done properly when replicating. Throughout the project timeline, certain areas of improvement were identified:

- Include UG audits of the less ore-intensive levels in Step 1 of the methodology to establish the number of pumps running unnecessarily which can be switched off without additional maintenance required. This enables an immediate realisation of electrical cost savings prior to assessment of the main levels.
- Assemble teams to assess faulty non-return valves during the initial audit phase of the project to ensure **all** non-return valves are in a working condition prior to pump replacement.
- Ensure redundant tramming personnel allocated to the main production levels are fully utilised on the less productive levels with a much smaller labour force.
- Involve finance personnel from project start to establish if the project meets the criteria to conduct a budget scope change to obtain funding previously allocated elsewhere.
- Future spindle pump evaluation projects can be expanded to include the pumps situated in the XCs to evaluate whether operation can be improved.
- Involve the finance department at the start of the project to possibly include additional monthly contract purchased pumps into their respective budgets. This ensures that additional pumps are available upon project implementation.
- Use **preliminary** project results **throughout** the project lifetime to create awareness among the relevant personnel to motivate monitoring infrastructure purchases which can assist the study.

- The project should be used to create awareness relating to proper housekeeping of UG footwalls within in the XCs and in the haulages to decrease debris in the spindle pump sump resulting in a potentially increased pump life.
- For future studies conducted on systems transporting a fluid with a higher SG value, consider incorporating guidelines from CSA C502:21 Benchmark energy factor assessment of slurry pumping systems to assist with system quantification.
- For potential further study improvement, additionally consider incorporation of guidelines set out by CSA C504:20 Measuring and monitoring industrial and commercial pumping system energy performance.
- To ensure future work additionally contains the lesser seen effect of energy savings, analysis can be extended to the effect of energy savings on carbon emissions and the possible resulting 12L compensation it holds. Reducing carbon emissions is the ultimate goal to ensure a sustainable future.

4.4 Closing remarks

This study emphasised the importance of including all aspects of the water reticulation system when conducting improvement analysis. The developed methodology provides a validated, sustainable horizontal water transfer management strategy which can be implemented on deep-level mines. The strategy assists to obtain improved system operation through reduced electricity consumption and monitoring and provides a platform supplementing mine development planning through water demand forecast and variable scenario simulations.

The developed strategy, therefore, provides an accurate and practical approach to improving horizontal water transport systems.



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APPENDIX A – PIPELINE DESIGN AND SPECIFICATIONS

Friction and pipeline coefficients

Figure 57 displays the resistance of fittings along the pipeline.

Friction Losses in Pipe Fittings Resistance Coefficient K (use in formula $hf = Kv^2/2g$)													
Fitting	LD	Nominal Pipe Size											
		½	¾	1	1¼	1½	2	2½-3	4	6	8-10	12-16	18-24
		K Value											
Angle Valve	55	1.48	1.38	1.27	1.21	1.16	1.05	0.99	0.94	0.83	0.77	0.72	0.66
Angle Valve	150	4.05	3.75	3.45	3.30	3.15	2.85	2.70	2.55	2.25	2.10	1.95	1.80
Ball Valve	3	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04
Butterfly Valve							0.86	0.81	0.77	0.68	0.63	0.35	0.30
Gate Valve	8	0.22	0.20	0.18	0.18	0.15	0.15	0.14	0.14	0.12	0.11	0.10	0.10
Globe Valve	340	9.2	8.5	7.8	7.5	7.1	6.5	6.1	5.8	5.1	4.8	4.4	4.1
Plug Valve Branch Flow	90	2.43	2.25	2.07	1.98	1.89	1.71	1.62	1.53	1.35	1.26	1.17	1.08
Plug Valve Straightaway	18	0.48	0.45	0.41	0.40	0.38	0.34	0.32	0.31	0.27	0.25	0.23	0.22
Plug Valve 3-Way Thru-Flow	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
Standard Elbow	90°	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39
	45°	16	0.43	0.40	0.37	0.35	0.34	0.30	0.29	0.27	0.24	0.22	0.21
	long radius 90°	16	0.43	0.40	0.37	0.35	0.34	0.30	0.29	0.27	0.24	0.22	0.21
Close Return Bend	50	1.35	1.25	1.15	1.10	1.05	0.95	0.90	0.85	0.75	0.70	0.65	0.60
Standard Tee	Thru-Flow	20	0.54	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.28	0.24
	Thru-	60	1.62	1.50	1.38	1.32	1.26	1.14	1.08	1.02	0.90	0.84	0.72
90 Bends, Pipe Bends, Flanged Elbows, Butt-Welded Elbows	r/d=1	20	0.54	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.28	0.24
	r/d=2	12	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.17	0.14
	r/d=3	12	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.17	0.14
	r/d=4	14	0.38	0.35	0.32	0.31	0.29	0.27	0.25	0.24	0.21	0.20	0.17
	r/d=6	17	0.46	0.43	0.39	0.37	0.36	0.32	0.31	0.29	0.26	0.24	0.20
	r/d=8	24	0.65	0.60	0.55	0.53	0.50	0.46	0.43	0.41	0.36	0.34	0.29
	r/d=10	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39
	r/d=12	34	0.92	0.85	0.78	0.75	0.71	0.65	0.61	0.58	0.51	0.48	0.41
	r/d=14	38	1.03	0.95	0.87	0.84	0.80	0.72	0.68	0.65	0.57	0.53	0.46
	r/d=16	42	1.13	1.05	0.97	0.92	0.88	0.80	0.76	0.71	0.63	0.59	0.50
	r/d=18	45	1.24	1.15	1.06	1.01	0.97	0.87	0.83	0.78	0.69	0.64	0.55
Mitre Bends	a=0°	2	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.02
	a=15°	4	0.11	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05
	a=30°	8	0.22	0.20	0.18	0.18	0.17	0.15	0.14	0.14	0.12	0.11	0.10
	a=45°	15	0.41	0.38	0.35	0.33	0.32	0.29	0.27	0.26	0.23	0.21	0.20
	a=60°	25	0.68	0.63	0.58	0.55	0.53	0.48	0.45	0.43	0.38	0.35	0.30
	a=75°	40	1.09	1.00	0.92	0.88	0.84	0.76	0.72	0.68	0.60	0.56	0.48
	a=90°	60	1.62	1.50	1.38	1.32	1.26	1.14	1.08	1.02	0.90	0.84	0.72

Note: Fittings are standard with full openings.

Figure 57: Friction loss and pipe coefficients

Figure 58 displays the loss of head due to pipe fittings exerted on water in a pipeline.

Friction Loss of Water in Pipe Fittings in Terms of Equivalent Length - Feet of Straight Pipe																
Nominal pipe size	Actual inside diameter inches d	Friction factor f	Gate valve - full open	90° elbow	Long radius 90° or 45° std elbow	Std tee - thru flow	Std tee - branch flow	Close return bend	Swing check valve - full open	Angle valve - full open	Globe valve - full valve	Butter-fly valve	90°Welding elbow		Mitre bend	
													r/d =	r/d =	45°	90°
½	.622	.027	.41	1.55	.83	1.04	3.11	2.59	5.18	7.78	17.6					
¾	.824	.025	.55	2.06	1.10	1.37	4.12	3.43	6.86	10.3	23.3					
1	1.049	.023	.70	2.62	1.40	1.75	5.25	4.37	8.74	13.1	29.7					
1¼	1.380	.022	.92	3.45	1.84	2.30	6.90	5.75	11.5	17.3	39.1					
1½	1.610	.021	1.07	4.03	2.15	2.68	8.05	6.71	13.4	20.1	45.6					
2	2.067	.019	1.38	5.17	2.76	3.45	10.3	8.61	17.2	25.8	58.6	7.75	3.45	2.07	2.58	10.3
2½	2.469	.018	1.65	6.17	3.29	4.12	12.3	10.3	20.6	30.9	70.0	9.26	4.12	2.47	3.08	12.3
3	3.068	.018	2.04	7.67	4.09	5.11	15.3	12.8	25.5	38.4	86.9	11.5	5.11	3.07	3.84	15.3
4	4.026	.017	2.68	10.1	5.37	6.71	20.1	16.8	33.6	50.3	114	15.1	6.71	4.03	5.03	20.1
5	5.047	.016	3.36	12.6	6.73	8.41	25.2	21.0	42.1	63.1	143	18.9	8.41	5.05	6.31	25.2
6	6.065	.015	4.04	15.2	8.09	10.1	30.3	25.3	50.5	75.8	172	22.7	10.1	6.07	7.58	30.3
8	7.981	.014	5.32	20.0	10.6	13.3	39.9	33.3	66.6	99.8	226	29.9	13.3	7.98	9.98	39.9
10	10.02	.014	6.68	25.1	13.4	16.7	50.1	41.8	83.3	125	284	29.2	16.7	10.0	12.5	50.1
12	11.938	.013	7.96	29.8	15.9	19.9	59.7	49.7	99.7	149	338	34.8	19.9	11.9	14.9	59.7
14	13.124	.013	8.75	32.8	17.5	21.8	65.6	54.7	109.7	164	372	38.3	21.8	13.1	16.4	65.6
16	15.00	.013	10.0	37.5	20.0	25.0	75.0	62.5	125.0	188	425	31.3	25.0	15.0	18.8	75.0
18	16.876	.012	16.9	42.2	22.5	28.1	84.4	70.3	140.6	210	478	35.2	28.1	16.9	21.1	84.4
20	18.814	.012	12.5	47.0	25.1	31.4	94.1	78.4	156.8	235	533	39.2	31.4	18.8	23.5	94.1
24	22.628	0.12	15.1	56.6	30.2	37.7	113	94.3	188.6	283	641	47.1	37.7	22.6	28.3	113
30	28	.011	18.7	70	37.3	46.7	140	117	233.6				46.7	28	35	140
36	34	.011	22.7	85	45.3	56.7	170	142					56.7	34	43	170
42	40	.010	26.7	100	53.3	66.7	200	167					66.7	40	50	200
48	46	.010	30.7	115	61.3	76.7	230	192					76.7	46	58	230
L/D			8	30	16	20	60	50	½ to 6 = 100 24 to 48 =50	150	340		20	12	15	60

Figure 58: Friction loss due to pipe fittings

Figure 59 shows pipeline roughness coefficients of the most used materials.

Pipe Material Roughness Coefficients			
Pipe Material	Specific Roughness Factor, ϵ , mm (ft)	Hazen-Williams Coefficient, C	Manning Factor, n
Steel, welded and seamless	0.061 (0.0002)	140	-
Steel, Sheet metal, new	5×10^{-2} (1.6×10^{-4})		
Commercial, new	4.6×10^{-2} (1.5×10^{-4})		
Steel, Riveted	3.0 (1×10^{-2})		
Steel, Rusted	2.0 (7×10^{-3})		
Stainless	2×10^{-3} (7×10^{-6})		
Ductile Iron	0.061 (0.0002)	130	-
Iron, Cast new	2.6×10^{-1} (8.5×10^{-4})		
Iron, Wrough, new	4.6×10^{-2} (1.5×10^{-4})		
Iron, Galvanized, new	1.5×10^{-1} (5×10^{-4})		
Iron, Asphalted, cast	1.2×10^{-1} (4×10^{-4})		
Ductile Iron, asphalt coated	0.12 (0.0004)	130	0.013
Copper and Brass	0.61 (0.002)	140	0.010
Brass, new	2×10^{-3} (7×10^{-6})		
Glass	0.0015 (0.000005)	140	-
Thermoplastics	0.0015 (0.000005)	140	-
Drawn Tubing	0.0015 (0.000005)	-	-
Concrete, smoothed	4×10^{-2} (1.3×10^{-4})		
Concrete, Rough	2.0 (7×10^{-3})		
Rubber, Smoothed	1×10^{-2} (3.3×10^{-5})		
Wood, Stave	5×10^{-1} (1.6×10^{-3})		

Figure 59: Pipe material roughness coefficients

Water flow meter instrumentation

Permanently installed water flowmeters used are installed on the pipeline and connected to the SCADA monitoring system for documentation. The flowmeter is shown in Figure 60.



Figure 60: Permanently installed water flow meter on mining operations

Manual required water flow measurements can be done by using a portable, regularly calibrated, ultrasonic water clamp on meter. The flow meter can be programmed to log over a period of time and store the data for later use. The clamp-on ultrasonic flowmeter is shown in Figure 61.



Figure 61: Portable ultrasonic clamp on water flow meter

Slurry volumes correction factor

Service water quantities on deep-level mining operations consist of solid particles. Slurry volumes with a solids content of $> 15\%$ should be adjusted by factors found in Figure 62.

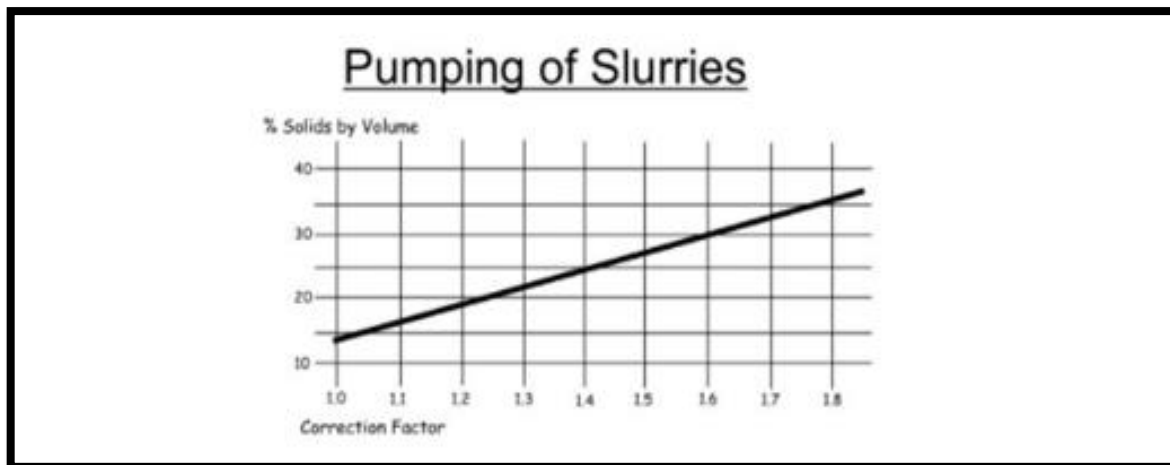


Figure 62: Graph of slurry volume correction factors

Alternative pumping performance curves

Alternative pumping curves can provide additional information regarding certain pumps. Figure 63 and Figure 64 are examples of performance curves comparing power factor, current, speed, head, power and efficiency.

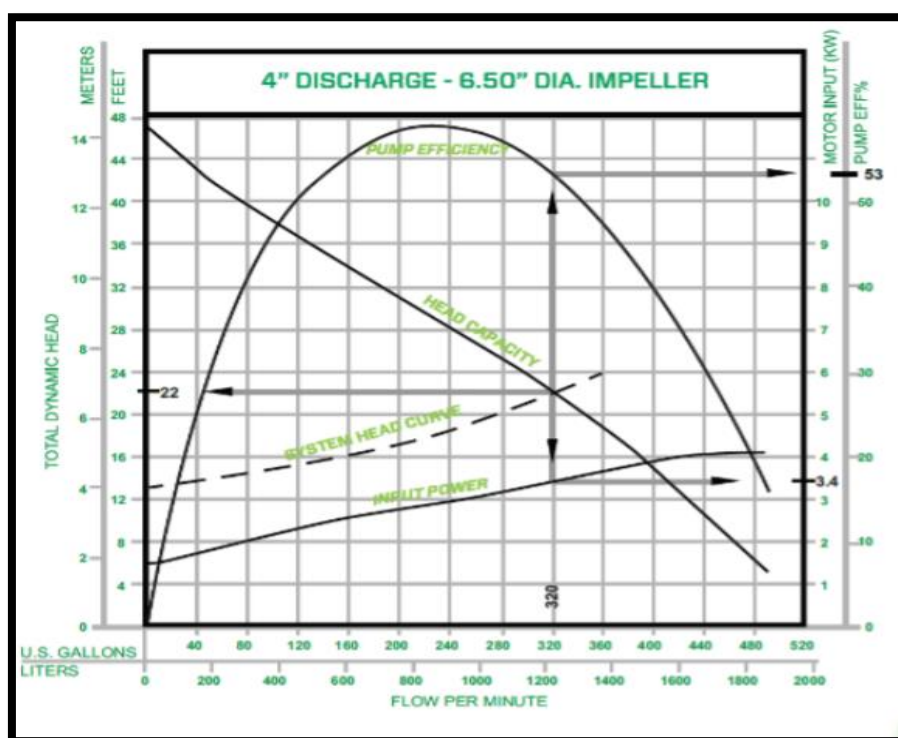


Figure 63: Pump performance curve comparing flow, efficiency and power

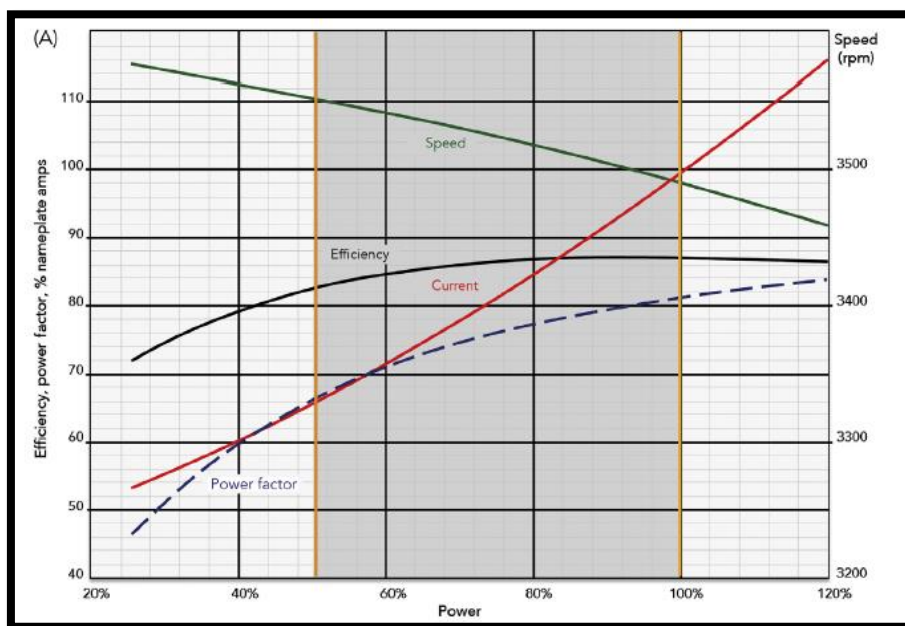


Figure 64: Pump performance curve comparing efficiency, power, speed and current

Portable DENT logger measuring instruments

The DENT logger measuring device will be used to determine the individual electrical consumption of the spindle pumps. The spindle pumps are connected to a main mining feeder that supplies power to the different sections of levels. The actual effect of the spindle pump replacement might not initially be picked up on the main mining feeder but may display a difference in energy consumption as more of the spindle pump configurations change. Individual pump measurement is, therefore, important in order to establish the baseline energy consumption of each pump size. A DENT logger measuring instrument is shown in Figure 65.



Figure 65: DENT logger measuring instrument

Portable power meter setup

Installation of the portable DENT logger instrument is crucial to obtain accurate measurements. The three-phase four-wire setup is most commonly used and is displayed in Figure 66.

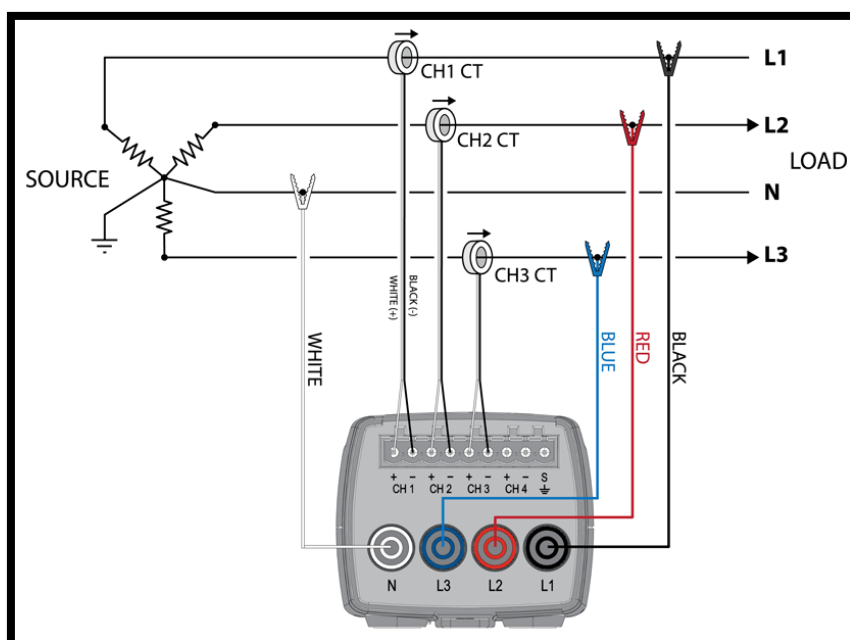


Figure 66: Three-phase four-wire setup

Holding dam distance determination

Figure 67 represents the distances measured from the last spindle pump on 120L until the holding dams according to current operating configuration. To ensure the total quantity of return water per level reaches the annex holes, the split spindle pumps will be included in the simulation.



Figure 67: Distance from last spindle pump towards the annex hole on 120L

With current system operation, the return water easily reaches the holding dams. The distance from the last 45kW spindle pump until the holding dams is measured as 335m (rounded up), whereas distance between the last 45kW pump and the East/West split is measured as 939m.

The lowest operating levels, 123L and 126L, do not consist of an extended haulage such as 120L. The holding dams are located much closer to the East/West split and simplifies operation as well as any potential operational suggestions. Figure 68– Figure 69 displays the distances from the East/West split on 123L and 126L, respectively.

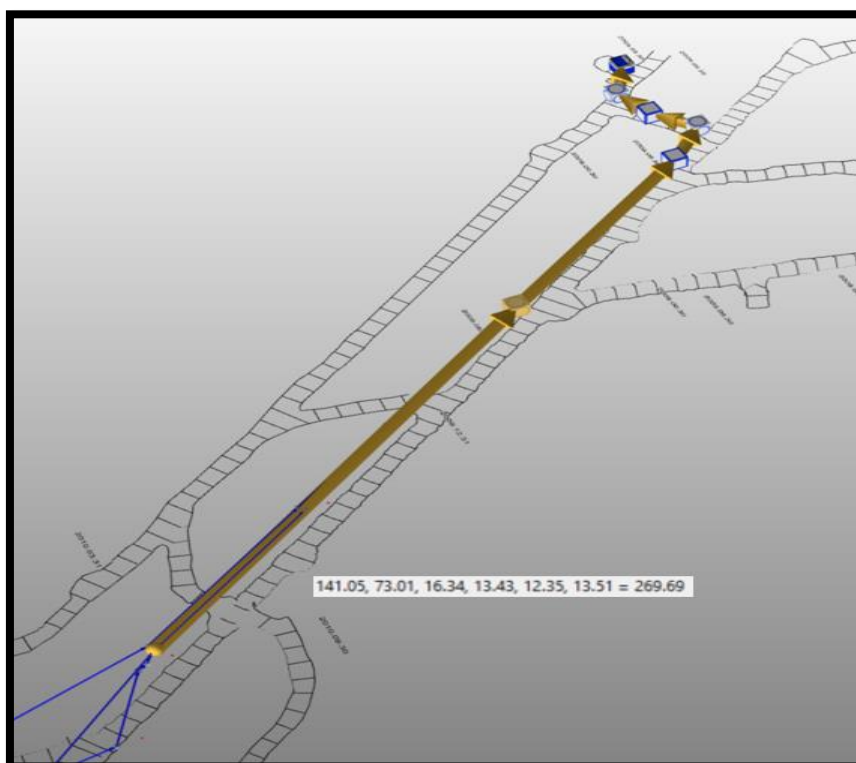


Figure 68: Distance from last spindle pump towards annex hole on 123L

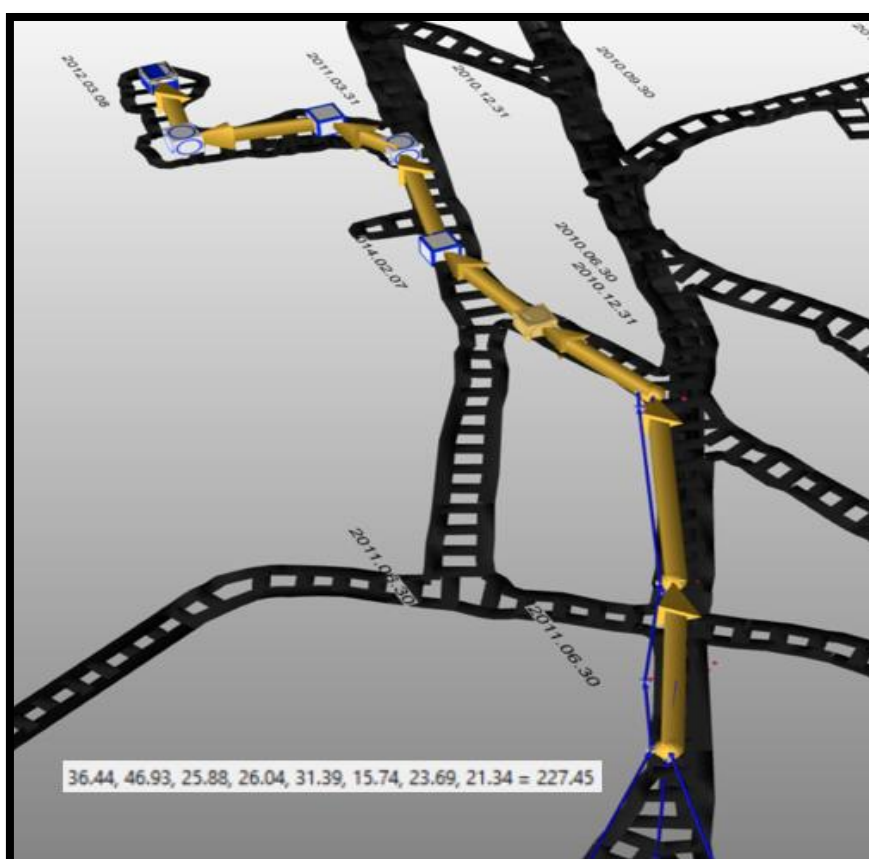


Figure 69: Distance from last spindle pump towards the annex hole on 126L

Pipe sizes and configurations

The simulation environment requires the knowledge of the piping configuration used to represent the system as accurately as possible. This entails specifying the distance from the pipe to the haulage and XC floor to assist with fluid head calculations. Figure 70 – Figure 71 displays the return pipe sizes and configuration in the haulages and XCs on 123L and 126L.

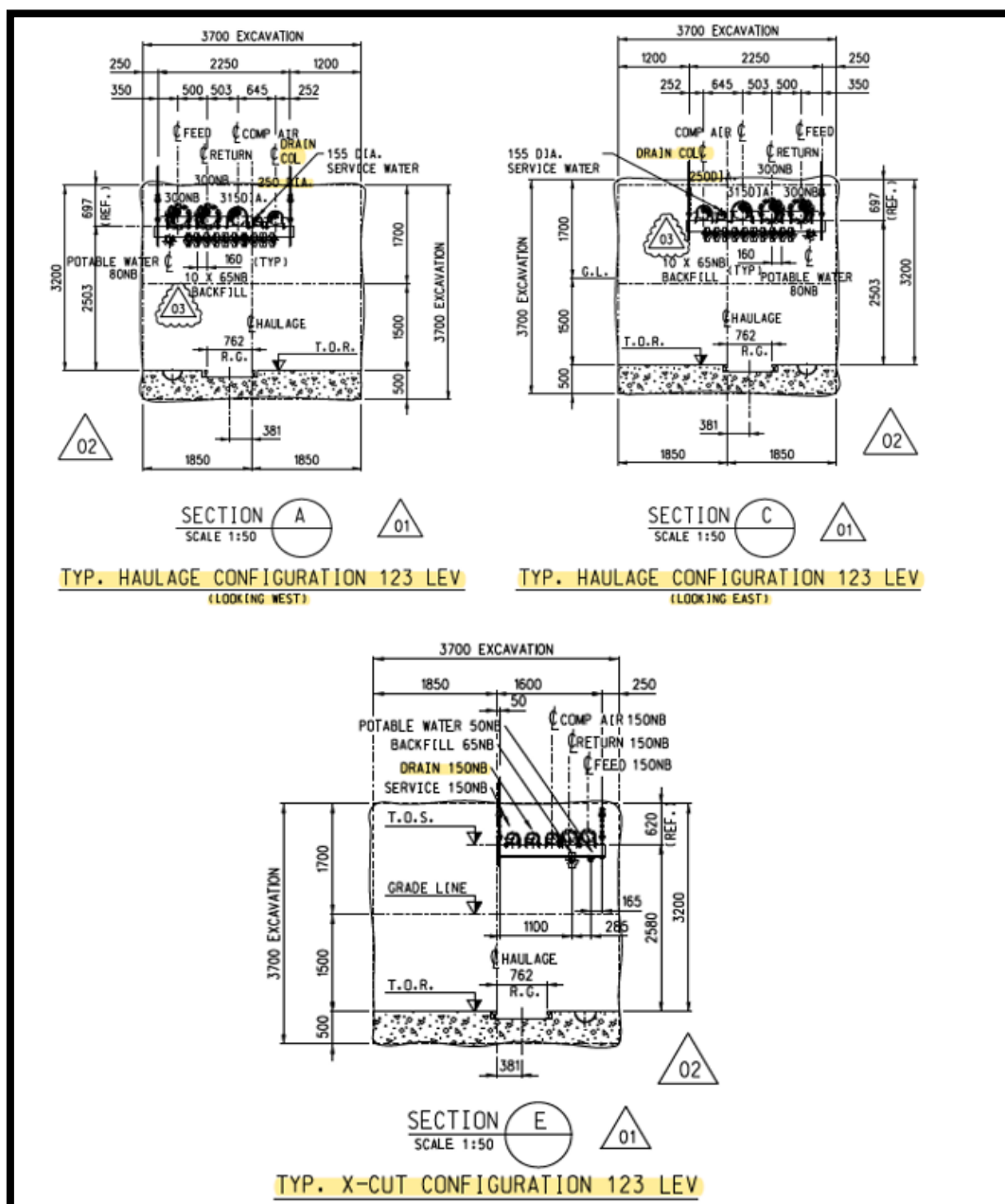


Figure 70: 123L Haulage and XC water pipe specifications



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The pipe sizes for 120L were identified as 200NB in the haulage and 150NB in the XC sections. The pipe height from the ground is specified as 2.950m for both the haulage and XC sections. This is shown in Figure 72.

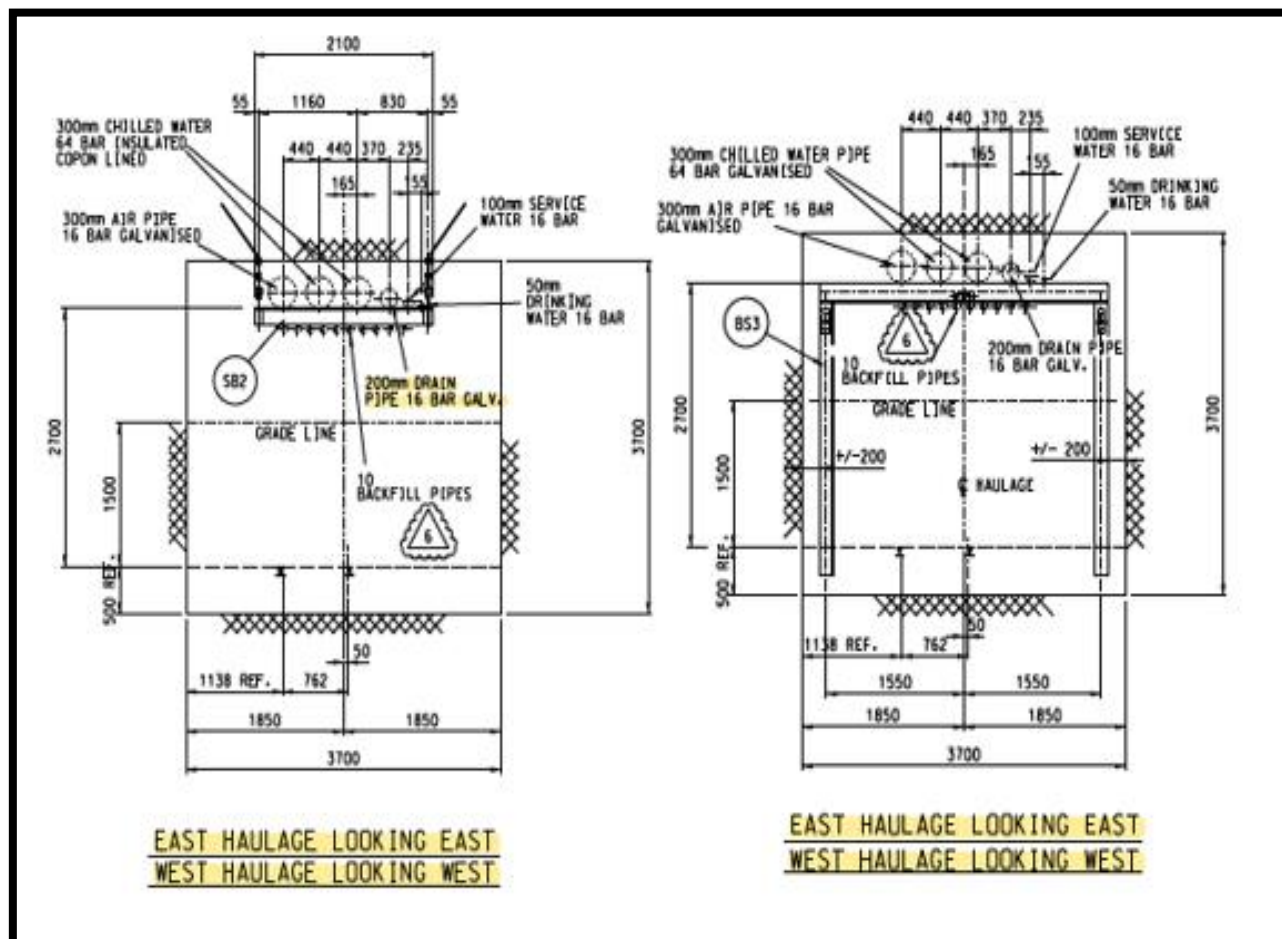


Figure 72: 120L haulage and XC water pipe specifications

The low pressure UPVC pipe used for the application (due to potential corrosive materials in the return water) is designed for 16bar pressure in the haulage sections, and 10bar in the XC sections of all the production levels.

APPENDIX B – PTB3D FUNDAMENTAL CALCULATIONS

Process toolbox (PTB3D) is classified as a one-dimensional Computational Fluid Dynamics (CFD) code platform solving complex thermo-hydraulic distribution and reticulation systems. The code was devised to include incompressible water, compressible air and two-phase fluid (steams) systems. Semi-empirical models are designed to link to pressure boundaries and nodes to represent system boundary start or end (pressure boundaries) and conduct complex flow network calculations throughout the designed system (nodes) [96] [137]. PTB3D consists of an easy-to-use interface where components can be dragged into the 3D Graphical User Interface (GUI) simulation environment according to scale. Figure 73 represents some of the pre-configured simulation components primarily used [96].

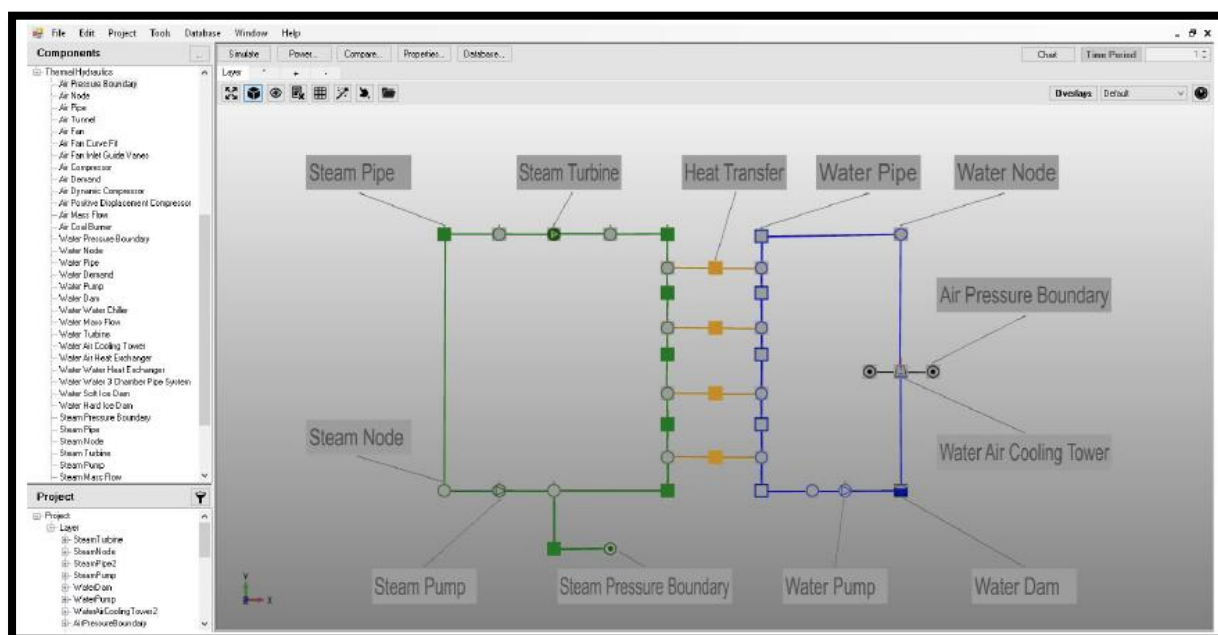


Figure 73: PTB3D simulation components representation

The developed code provides time-step-based results for energy, mass, and momentum for steady-state and transient solutions. All thermo-hydraulic properties such as pressure, temperature and enthalpy are calculated in the pressure boundaries and nodes. All other supplementary components are responsible for flow resistance, heat and mass transfer and work calculations on the fluids. Upstream nodes provide downstream components of inlet conditions and enables the downstream component to provide accurate outlet parameter conditions.

A component-specific user interface is allocated to each component type. Each of the components specified in Table 23 consists of certain hydraulic calculation principles.

Water Pipe

4.1.13 Water Pipe

4.1.13.1 Description

The flow network pressure losses are calculated in the pipe component. The pipe component includes a variable valve fraction for flow or pressure control.

4.1.13.2 Theory

Assumptions:

- The thermal dynamic conditions stay constant throughout the length of the pipe.

Inputs:

P_{up} Upstream node water total pressure (kPa)

P_{down} Downstream node water total pressure (kPa)

T_{up} Upstream node water temperature (°C)

T_{down} Downstream node water temperature (°C)

Interface Inputs:

P_{inlet} Water inlet pressure (kPa)

P_{outlet} Water outlet pressure (kPa)

m Water mass flow rate (kg/s)

k_v Valve fraction

Outputs:

m_w Water mass flow rate (kg/s)

Internal Variables:

k_w Flow admittance ($\text{kg}^2/\text{s}/\text{m}^3/\text{kPa}$)

ρ_w Water inlet density (kg/m^3)

Equations:

$$\rho_w = 1000$$

$$k_w = m^2 / (\rho_w (P_{inlet} - P_{outlet})) k_v$$

$$m_w = (k_w \rho_w (P_{up} - P_{down}))^{0.5}$$

Figure 74: PTB3D water pipe theory and empirical equations

Water node

4.1.12 Water Node

4.1.12.1 Description

Water height (change in network elevation) and water volume are specified in water nodes. All the water network properties, pressure, temperature, enthalpy, etc. are calculated in the water nodes.

4.1.12.2 Theory

Assumptions:

- It is assumed that 100% mixing occurs and that no stratification takes place.

Inputs:

h_{wI}^j	Water inlet enthalpy of link j (kJ/kg)
m_{wI}^j	Water inlet mass flow of link j (kg/s)
m_{wO}^j	Water outlet mass flow of link j (kg/s)
P_{wO}	Water pressure (kPa)

Interface Inputs:

V_w	Water node volume (m^3)
UA	Heat transfer coefficient (kW/°C)
T_{amb}	Ambient air temperature (°C)
Heat	External heat load (kW)

Outputs:

h_{wO}	Water outlet enthalpy (kJ/kg)
ρ_w	Water density (kg/m ³)
T_{wO}	Water outlet temperature (°C)

Internal Variables:

M_w	Node water mass (kg)
M_w^o	Node water mass previous time step (kg)
Q_s	Sensible heat (kW)
Q_{scomp}	Sensible heat generated by upstream components (kW)

Equations:

$$Q_s = Q_{scomp} + UA(T_{amb} - T_{wO}) + Heat$$

$$h_{wO} = ((\sum_{j=1}^n (m_{wI}^j h_{wI}^j dt) + M_w^o h_{wO} + Q_s) / (M_w + \sum_{j=1}^n (m_{wO}^j dt))$$

$$T_{wO} = (h_{wO} - 0.14399 - 0.0009843694 * P_{wO}) / (4.18537 - 0.0000023832 * P_{wO})$$

$$\rho_w = 1000$$

$$M_w = \rho_w V_w$$

Figure 75: PTB3D water node theory and empirical equations

Water pressure boundary

4.1.11 Water Pressure Boundary

4.1.11.1 Description

The water pressure boundary has constant user specified pressures and temperatures for every time period. This component is used where the network connects to other systems or sources.

4.1.11.2 Theory

Assumptions:

- All the conditions are constant for each time period.

Inputs:

None

Interface Inputs:

P_w Water pressure (kPa)

T_w Water temperature (°C)

Outputs:

h_{wo} Water outlet enthalpy (kJ/kg)

P_{wo} Water outlet pressure (kPa)

ρ_{wo} Water outlet density (kg/m³)

T_{wo} Water outlet temperature (°C)

Internal Variables:

None

Equations:

$$h_{wo} = (-0.0000023832 * T_w + 0.0009843694) P_w + 4.18537 T_w + 0.14399$$

$$T_{wo} = T_w$$

$$P_{wo} = P_w$$

$$\rho_{wo} = 1000$$

Figure 76: PTB3D water pressure boundary theory and empirical equations

Water dam

4.1.14 Water Dam

4.1.14.1 Description

The dam component is a thermal hydraulic system break with variable thermal storage where the inlet and outlet flows are not functions of each other.

4.1.14.2 Theory

Assumptions:

- It is assumed that 100% mixing occurs and that no stratification takes place.
- The water density is 1000 kg/m³ throughout.
- The dam cross sectional area is constant throughout the height of the dam.

Inputs:

h_{in}^j Water inlet enthalpy of link j (kJ/kg)

m_{in}^j Water inlet mass flow of link j (kg/s)

m_{wo}^j Water outlet mass flow of link j (kg/s)

Interface Inputs:

P_{wo} Water pressure (kPa)

UA Heat transfer coefficient (kW/°C)

T_{amb} Ambient air temperature (°C)

$Heat$ External heat load (kW)

V_w Dam volume (m³)

Outputs:

h_{wo} Water outlet enthalpy (kJ/kg)

ρ_w Water density (kg/m³)

T_{wo} Water outlet temperature (°C)

L Dam water level (%)

Internal Variables:

M_w Node water mass (kg)

M_w^o Node water mass previous time step (kg)

Q_s Sensible heat (kW)

Q_{scomp} Sensible heat generated by upstream components (kW)

Equations:

$$Q_s = Q_{scomp} + UA(T_{amb} - T_{wo}) + Heat$$

$$h_{wo} = ((\sum_{j=1}^n (m_{wi}^j h_{wi}^j) dt) + M_w^o h_{wo} + Q_s) / (M_w + \sum_{j=1}^n (m_{wo}^j dt))$$

$$T_{wo} = (h_{wo} - 0.14399 - 0.0009843694 * P_{wo}) / (4.18537 - 0.0000023832 * P_{wo})$$

$$\rho_w = 1000$$

$$M_w = M_w^o + (\sum_{j=1}^n (m_{wi}^j dt) - \sum_{j=1}^n (m_{wo}^j dt))$$

$$L = M_w / (V_w \rho_w) * 100$$

Figure 77: PTB3D water dam theory and empirical equations

Water demand

4.1.20 Water Demand

4.1.20.1 Description

This component is used when a different demand of water mass flow at different pressures for each time period in a flow network is required. A unique flow resistance can therefore be specified for each time period.

4.1.20.2 Theory

Assumptions:

- The thermal dynamic conditions stay constant throughout the length of the component.

Inputs:

P_{up} Upstream node water total pressure (kPa)

P_{down} Downstream node water total pressure (kPa)

T_{up} Upstream node water temperature (°C)

T_{down} Downstream node water temperature (°C)

Interface Inputs:

P_{inlet} Water inlet pressure (kPa)

P_{outlet} Water outlet pressure (kPa)

m Water mass flow rate (kg/s)

k_v Valve fraction

Outputs:

m_w Water mass flow rate (kg/s)

Internal Variables:

k_w Flow admittance ($\text{kg}^2/\text{s}/\text{m}^3/\text{kPa}$)

ρ_w Water inlet density (kg/m^3)

Equations:

$$\rho_w = 1000$$

$$k_w = m^2 / (\rho_w (P_{inlet} - P_{outlet})) k_v$$

$$m_w = (k_w \rho_w (P_{up} - P_{down}))^{0.5}$$

Figure 78: PTB3D water demand theory and empirical equations

Water pump

4.1.17 Water Pump

4.1.17.1 Description

The pump component generates a pressure differences in the flow network to induce water flow through the network. The pump component generates heat in the fluid due to inefficiencies.

4.1.17.2 Theory

Assumptions:

- The pump motor efficiency stays constant at full and partial load.
- No heat transfer between the water inside the pump and the ambient air.

Inputs:

m_w Water mass flow rate (kg/s)

Interface Inputs:

a Pump pressure curve coefficients

b Pump efficiency curve coefficients

N Pump speed faction

ρ_w Water density (kg/m³)

E_m Motor efficiency

Outputs:

Pwr Pump motor electrical power (kW)

Internal Variables:

dP Pump water pressure difference (kPa)

E_p Pump efficiency

Equations:

$$dP = (a_2 m_w^2 + a_1 m_w + a_0) (N^2)$$

$$E_p = b_2 (m_w / N)^2 + b_1 (m_w / N) + b_0$$

$$Pwr = (m_w / \rho_w) dP / E_p / E_m$$

Figure 79: PTB3D water pump theory and empirical equations

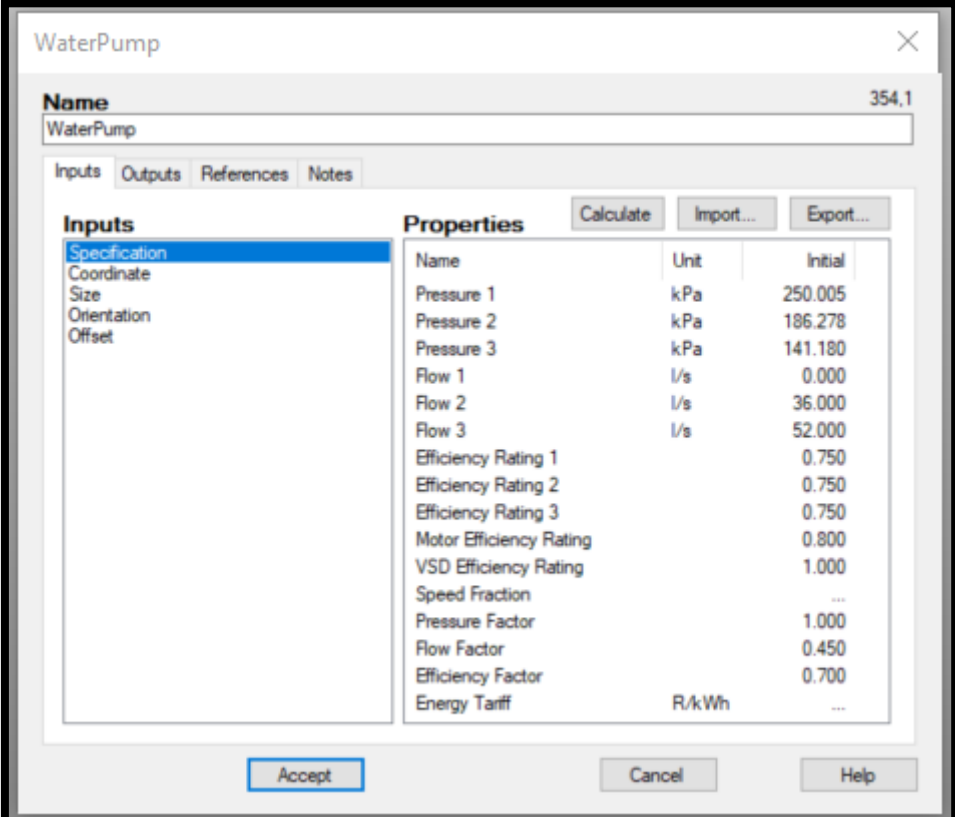
APPENDIX C – SIMULATION DEVELOPMENT

Known parameters are required to be completed within the interface to accurately model the system at hand. Each of the half-level pumps were configured according to the measured XC flows. Figure 80 represents one of the water pump user interfaces used to configure the **current** 123L West (according to the half-level flow measured) spindle pump system (**1st simulation**).

Name	Unit	Initial
Pressure 1	kPa	372.800
Pressure 2	kPa	274.680
Pressure 3	kPa	156.960
Flow 1	l/s	0.000
Flow 2	l/s	80.000
Flow 3	l/s	116.000
Efficiency Rating 1		0.750
Efficiency Rating 2		0.750
Efficiency Rating 3		0.750
Motor Efficiency Rating		0.800
VSD Efficiency Rating		1.000
Speed Fraction		...
Pressure Factor		1.000
Flow Factor		0.200
Efficiency Factor		0.500
Energy Tariff	R/kWh	...

Figure 80: 45kW spindle pump parameter interface within PTB3D

The 45kW pump used was specified by adding three flow and pressure values to obtain a pumping performance curve according to which the pump will operate. To imitate the current inefficient operation of the 45kW system, adjustments were made to the flow and efficiency factor parameters. These adjustments were required to simulate a **deviation** from the pumping performance curves as recorded with actual measured results (according to trial and error). The second simulation entailed representation of operation when 45kW pumps are exchanged for 15kW pumps. The interface specified for current demand performance for the 15kW spindle pump system is shown in Figure 81.



WaterPump 354,1

Name: WaterPump

Inputs Outputs References Notes

Inputs

- Specification
- Coordinate
- Size
- Orientation
- Offset

Properties

Name	Unit	Initial
Pressure 1	kPa	250.005
Pressure 2	kPa	186.278
Pressure 3	kPa	141.180
Flow 1	l/s	0.000
Flow 2	l/s	36.000
Flow 3	l/s	52.000
Efficiency Rating 1		0.750
Efficiency Rating 2		0.750
Efficiency Rating 3		0.750
Motor Efficiency Rating		0.800
VSD Efficiency Rating		1.000
Speed Fraction		...
Pressure Factor		1.000
Flow Factor		0.450
Efficiency Factor		0.700
Energy Tariff	R/kWh	...

Calculate Import... Export...

Accept Cancel Help

Figure 81: 15kW spindle pump parameter interface within PTB3D

Adjustments were also made to the flow and efficiency factors of the 15kW system to imitate performance with current water demands. The values obtained also deviated from the pumping performance curve, but to a much lesser extent than the 45kW pumps. Flow, efficiency and pressure factor values were kept at a value of 1 when simulating the **maximum demand** scenarios for both systems. Pipe sizes were inserted into the simulation as specified by the design department using the correct pipe roughness as calculated by the simulation software. Figure 82 represent the pipe specification interface in PTB3D as done for the corresponding main haulage.

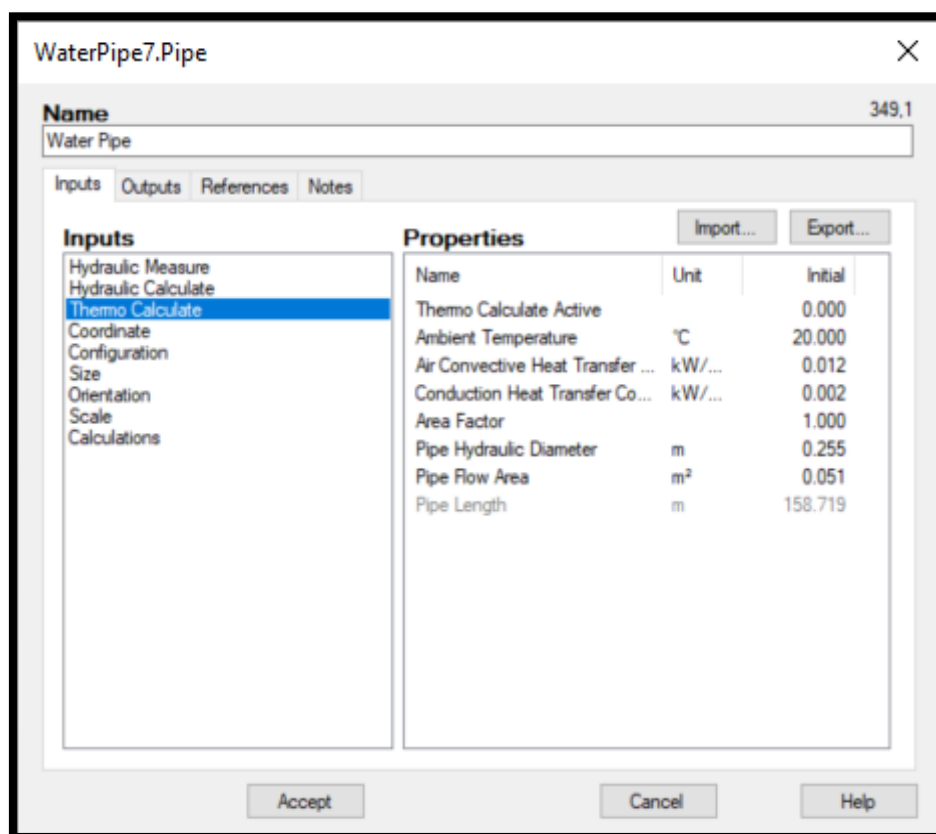


Figure 82: Piping parameter interface within PTB3D

Current system calibration results (1st simulation)

Current system calibration entails altering specifications of the individual pumps within the simulation environment to operate according to the measurements obtained. Due to the pumps not running on the specified curve, adjustments were made to parameters to ensure the actual **current** configuration is represented as accurately as possible. Some of the parameters to be altered include:

- Flow and efficiency factor, and
- pressure factor and speed fraction.

Calibration is done to obtain the correct relation of each of these factors according to current operation. These parameters were altered to best suit the current system operation after which it was compared to the measured return water flows. A summation of each half-level flow value was chosen to illustrate the difference between measured and simulated values. This comparison is seen in Figure 83 - Figure 85.

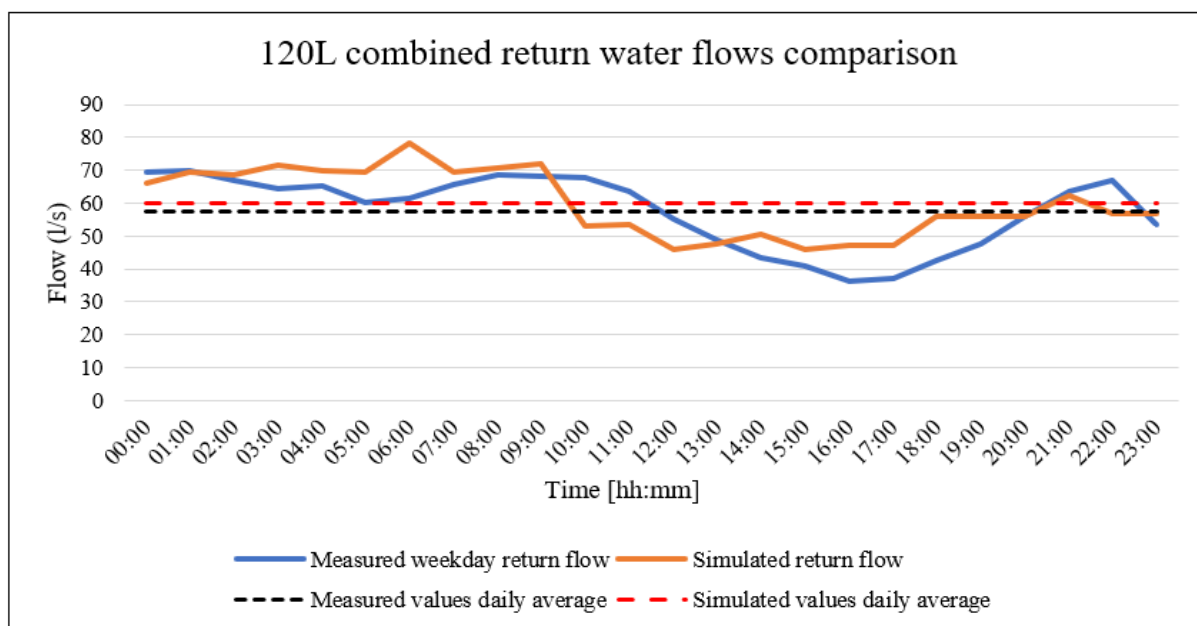


Figure 83: 120L Combined return water flows comparison

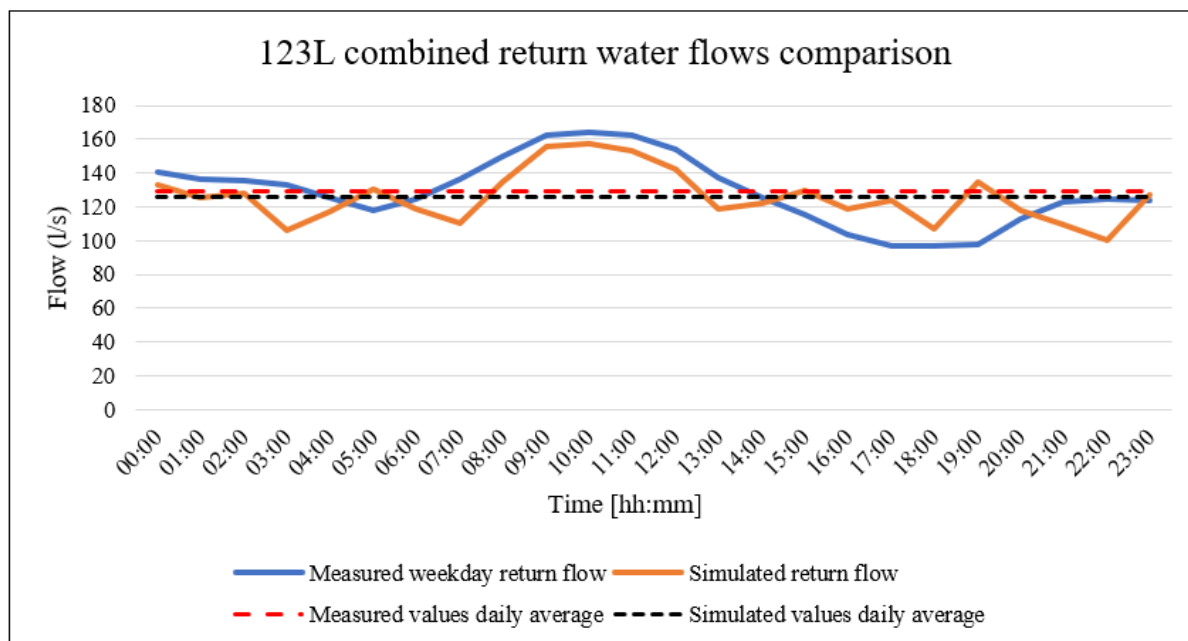


Figure 84: 123L combined return water flows comparison

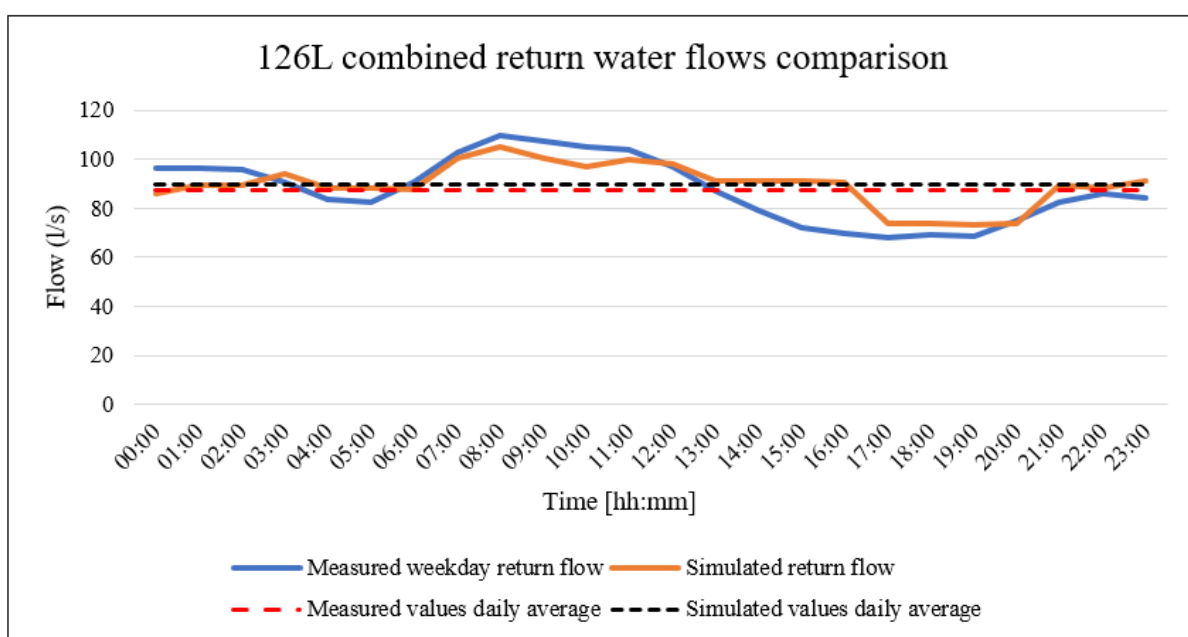


Figure 85: 126L combined return water flows comparison

Calibration of the current system simulation yielded a 4.1%, 2.5% and 2.2% difference between the measured and simulated values for 120L, 123L and 126L, respectively. Establishing that the current, inefficient system can be modelled within a cumulative average error of 3% adds validity to the use of PTB3D for the development of additional configuration scenarios.

Current system maximum water demand scenario (2nd simulation)

The maximum demand scenario illustrates the inefficiency of the current configuration by comparing the current flow demand with the maximum allowable demand determined through simulation. The maximum demand represents the total water flow that can be pumped to the holding dams by the current installed configuration. This is shown in Figure 86 - Figure 88.

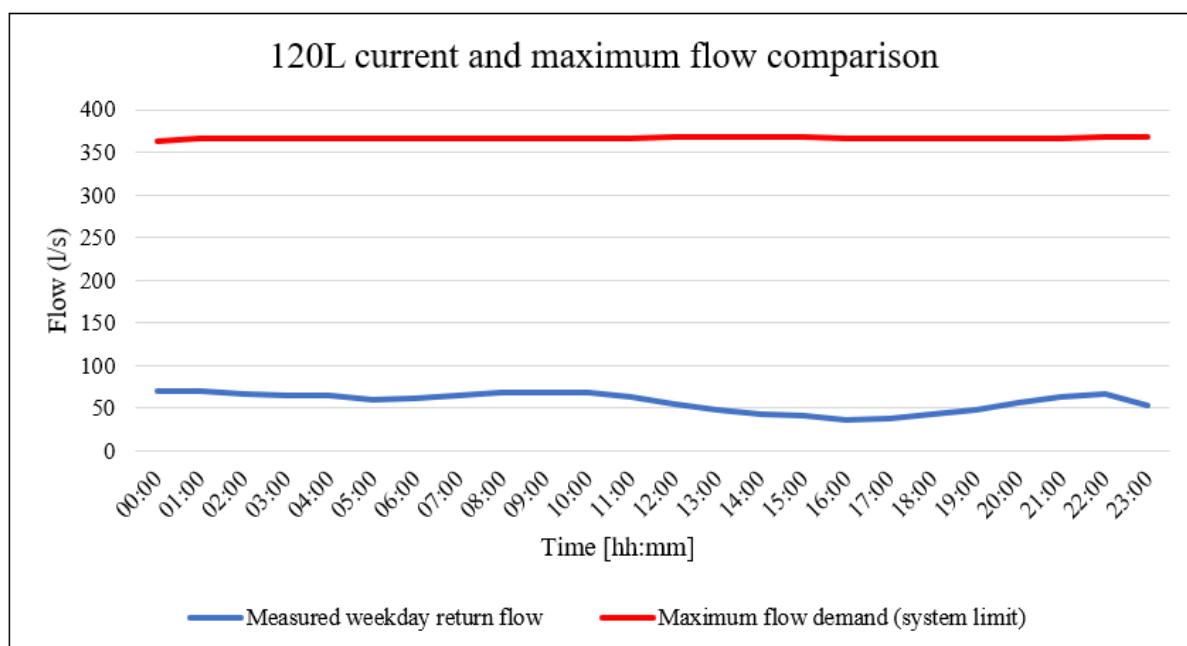


Figure 86: 120L maximum flow capacity comparison with currently installed pump sizes

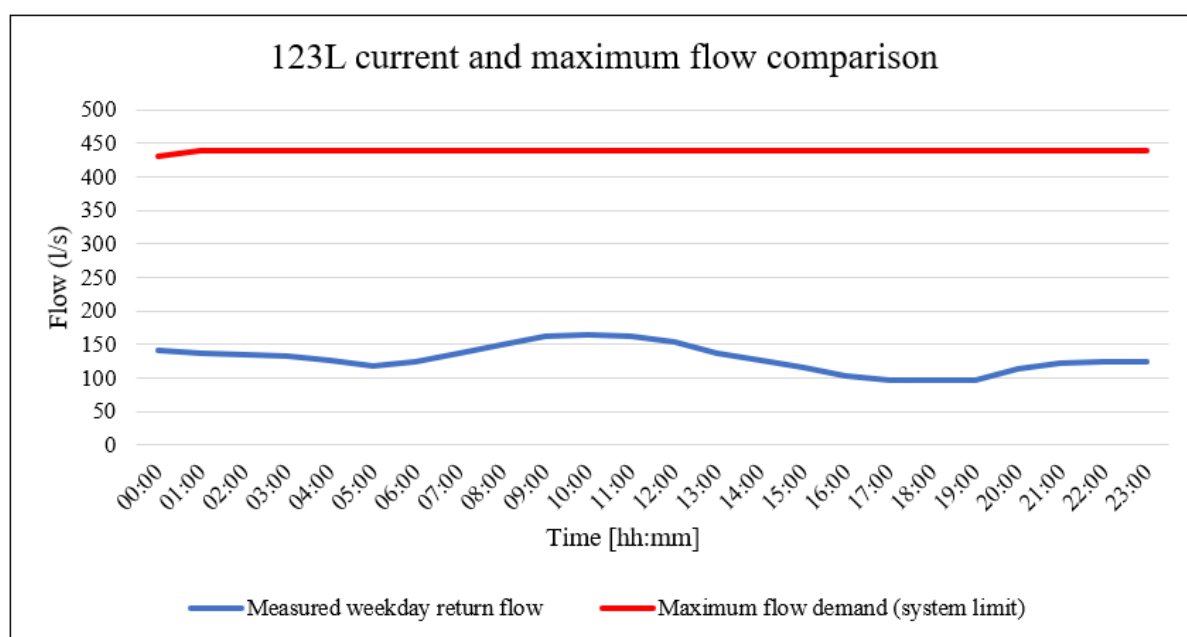


Figure 87: 123L maximum flow capacity comparison with currently installed pump sizes

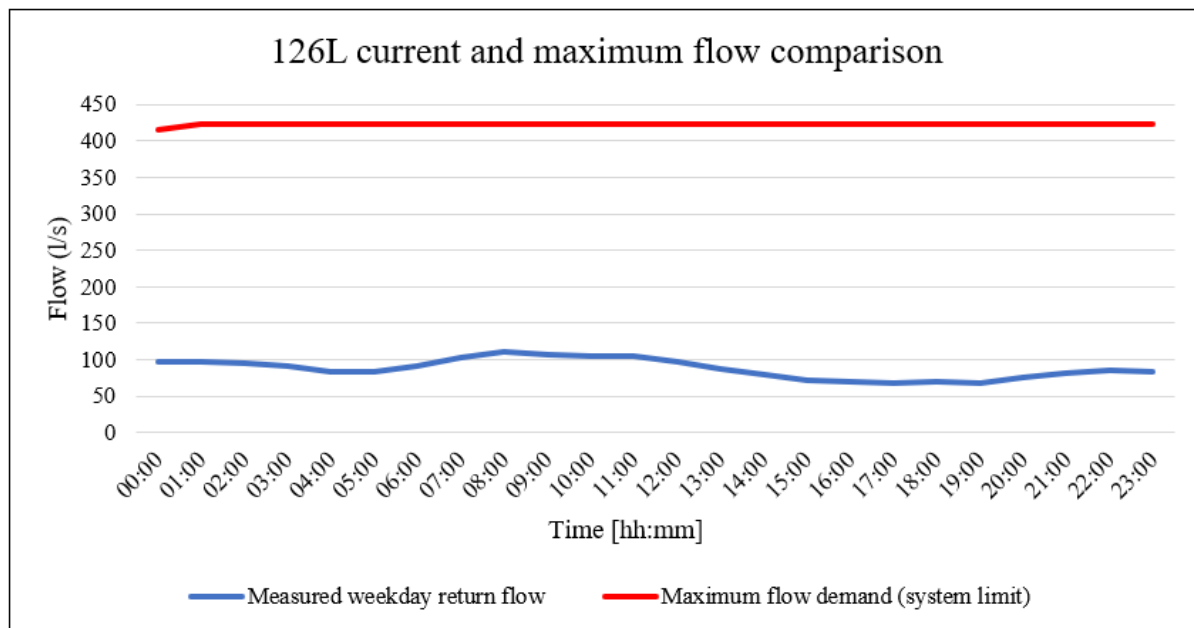


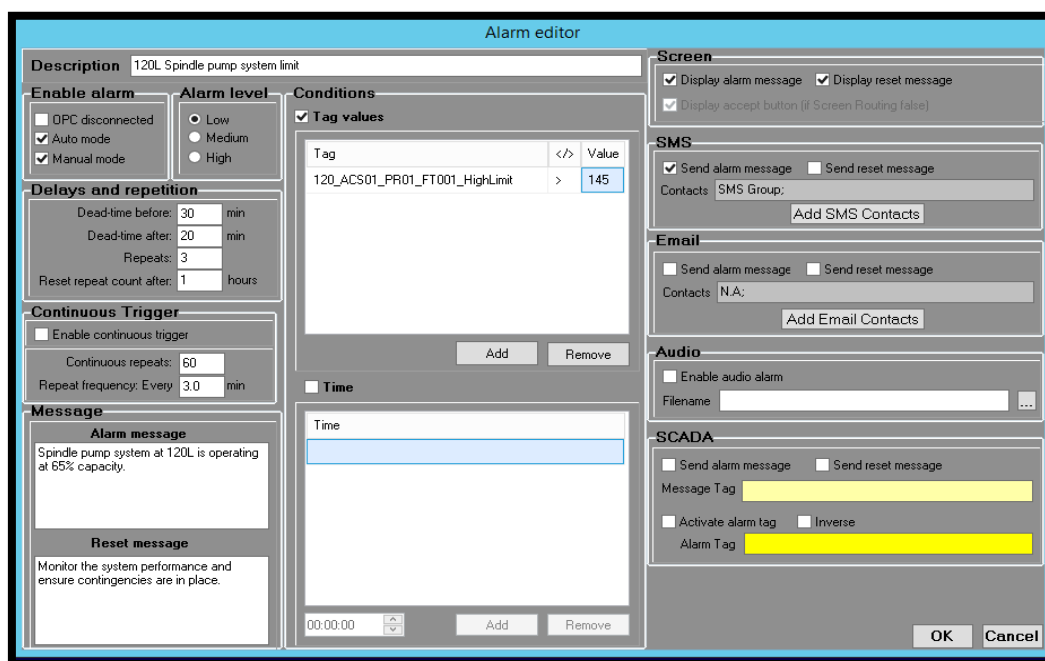
Figure 88: 126L maximum flow capacity comparison with currently installed pump sizes

As seen from the comparison graphs above, the maximum flow limit is well above the current flow demands of the spindle pump system on each level. This shows that the pump size is over specified for the system. The levels are currently operating on 15%, 28% and 20% of its available water capacity for 120L, 123L and 126L, respectively. The analysis reveals that there is scope for changes to be made to the current system configuration based on the operation relating to its actual system capacity.

APPENDIX D – RESULTS AND VALIDATION

Monitoring and alerts

Alarm limits can be linked to tags monitoring the return flows on each level from the SCADA. Each operating regime requiring action can be included and an SMS/email can be sent to the relevant parties required to act. Implementing a dynamic alert system enables actions to be taken quickly after distribution. Figure 89 shows the setup for the 120L alarm limits available on the integrated REMS platform.



The screenshot displays the 'Alarm editor' window for a '120L Spindle pump system limit'. The configuration is as follows:

- Description:** 120L Spindle pump system limit
- Enable alarm:**
 - ☐ OPC disconnected
 - ☒ Auto mode
 - ☒ Manual mode
- Alarm level:**
 - ☒ Low
 - ☐ Medium
 - ☐ High
- Conditions:**
 - ☒ Tag values

Tag	</>	Value
120_ACS01_PR01_FT001_HighLimit	>	145
- Delays and repetition:**
 - Dead-time before: 30 min
 - Dead-time after: 20 min
 - Repeats: 3
 - Reset repeat count after: 1 hours
- Continuous Trigger:**
 - ☐ Enable continuous trigger
 - Continuous repeats: 60
 - Repeat frequency: Every 3.0 min
- Message:**
 - Alarm message:** Spindle pump system at 120L is operating at 65% capacity.
 - Reset message:** Monitor the system performance and ensure contingencies are in place.
- Screen:**
 - ☒ Display alarm message
 - ☒ Display reset message
 - ☒ Display accept button (if Screen Routing false)
- SMS:**
 - ☒ Send alarm message
 - ☐ Send reset message
 - Contacts: SMS Group: [Add SMS Contacts]
- Email:**
 - ☐ Send alarm message
 - ☐ Send reset message
 - Contacts: N/A: [Add Email Contacts]
- Audio:**
 - ☐ Enable audio alarm
 - Filename: []
- SCADA:**
 - ☐ Send alarm message
 - ☐ Send reset message
 - Message Tag: []
 - ☐ Activate alarm tag
 - ☐ Inverse
 - Alarm Tag: []

Figure 89: Real-time alarm alert system integration of the 15kW spindle pump system

The simulation can also be viewed on a digital twin smart view on MTB. The real-time tags are obtained from the SCADA monitoring system and are stored on a historian for further viewing if needed. The different return flow tags can be linked to data boxes on the simulation and be viewed accordingly on the digitized smart view displayed on a large and accessible monitoring screen. Figure 90 shows the smart view interface and monitoring screen at Mine A.

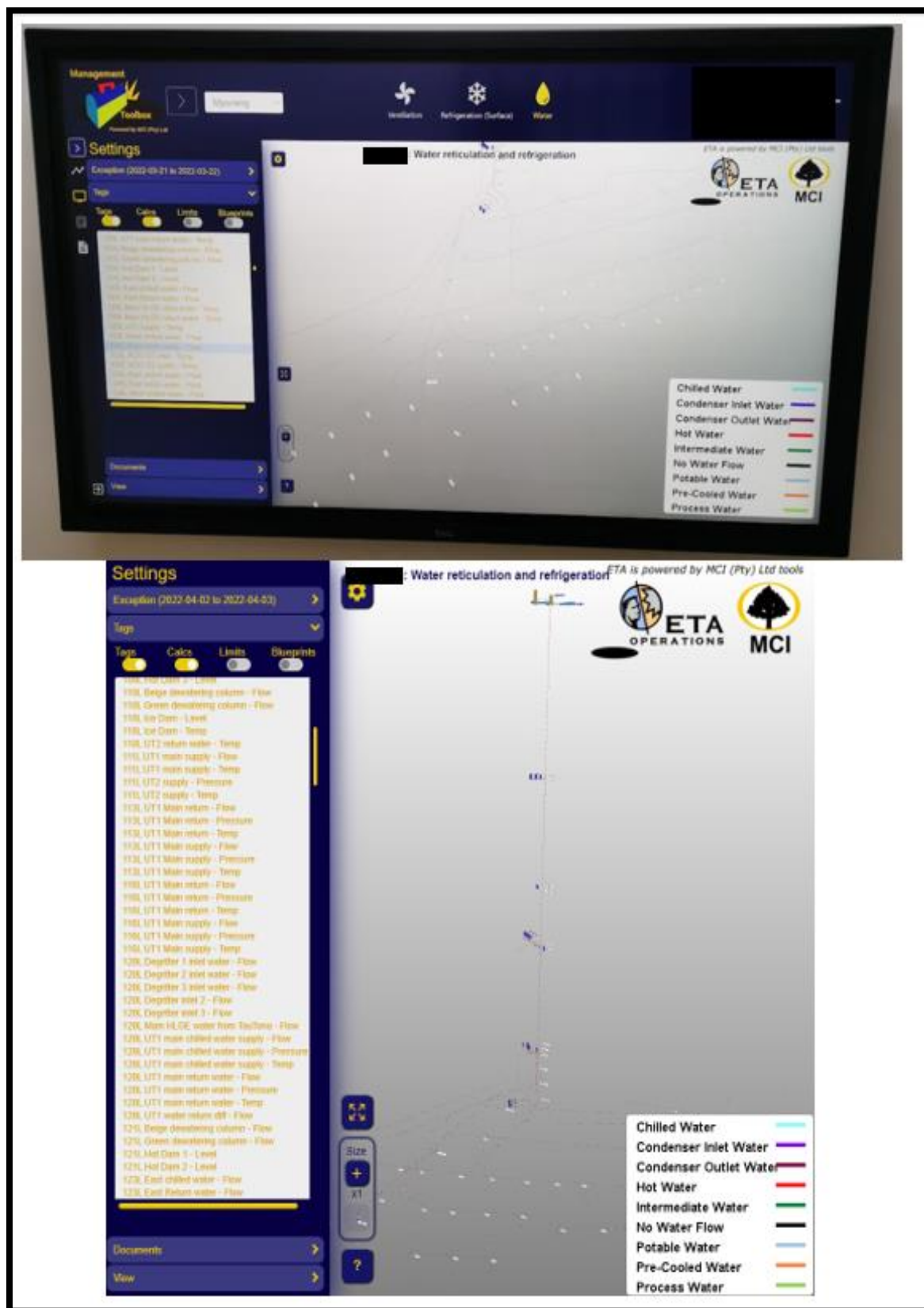


Figure 90: Real-time smart view integration at Mine A

Stope isolation controls and monitoring

One of the initiatives implemented on the production levels was identified as the stope isolations controls. This minimises water wastage in the stopes during off-peak mining times by ensuring the valves are closed, which minimises chilled water wastage. The water flow avoidance to the stopes effectively decreases the quantity of return water in each XC.

These valves are required to be installed on the low-pressure side of the chilled water pipe after the PRV. This will ensure the chilled water is still utilised at the cooling car but does not proceed to the stopes where a water demand is still present due to inefficiencies. A visual representation of the valve location (AUMA actuator and valve) is shown in Figure 91.

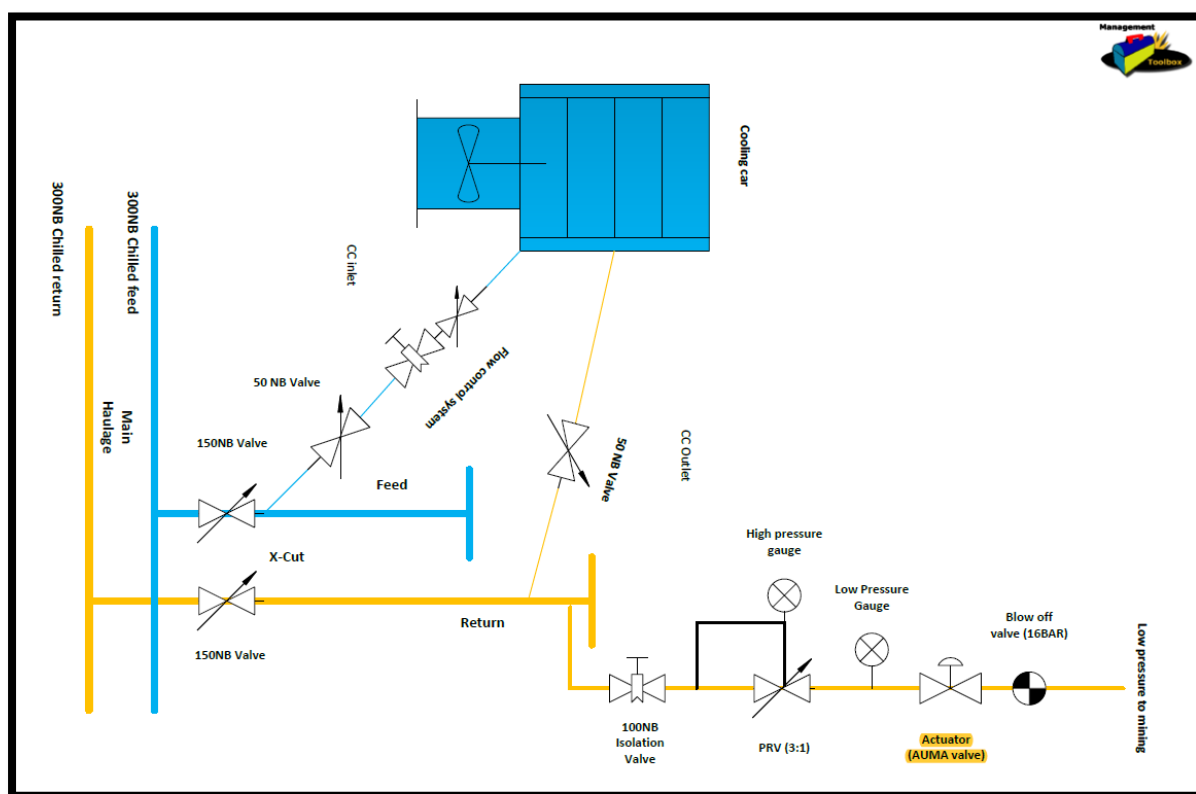


Figure 91: Stope Isolation Valve (SIV) location diagram on the chilled water return line

Tracking of the stope isolation valves was accompanied by the installation of a stope SCADA monitoring system. The system enables the monitoring of water flow sent to the stopes, water temperature and total water quantity for the day. This enables simplification of project savings tracking and the influence on the spindle pump return system. The interface is shown in Figure 92.

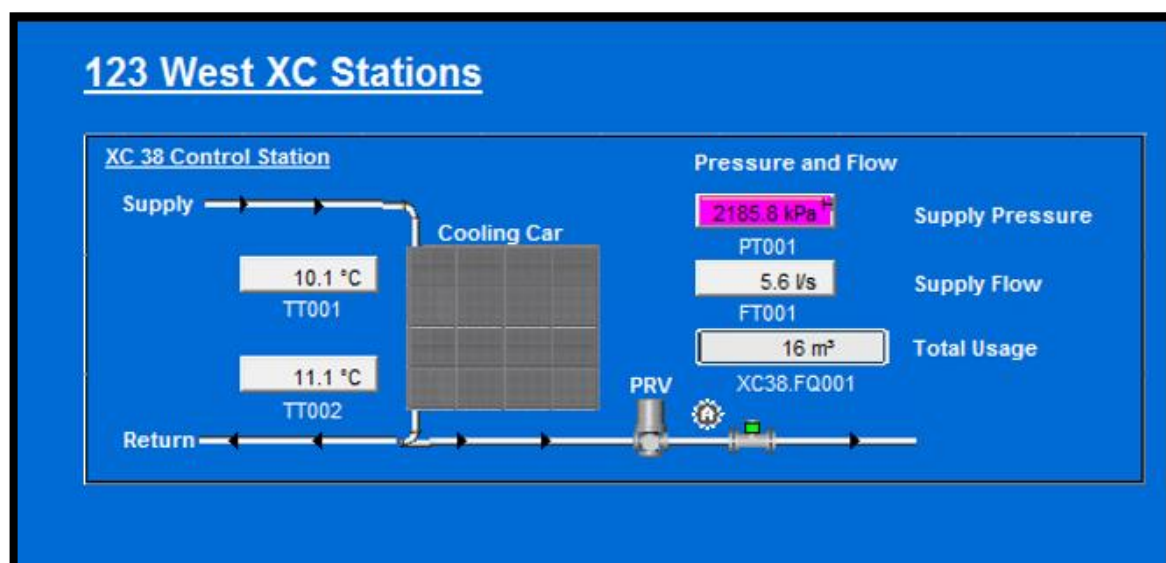


Figure 92: Stope SCADA monitoring system at Mine A

Mine ore production planning

Ore-producing scheduling is important to easily identify non-productive XCs on production levels. This assists with flow forecasting and spindle pump configurations for the foreseeable future. Mine planning for 120L is shown in Figure 93.

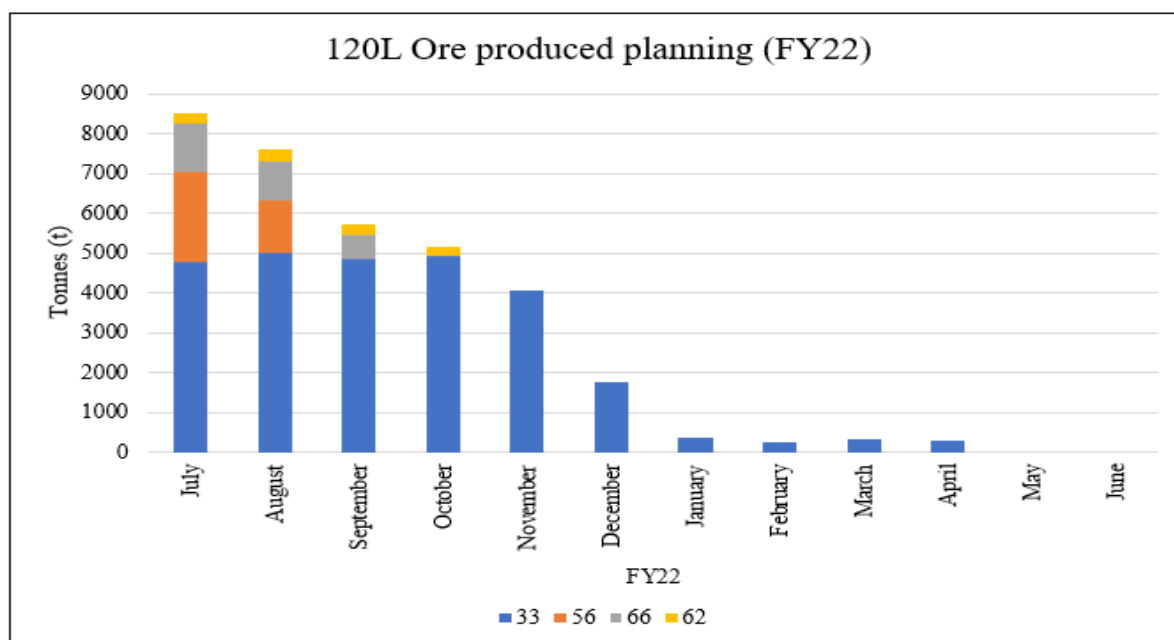


Figure 93: 120L ore planning schedule

Mine planning on 120L shows a steady decline until April 2022 due to depleted reserves. At the time of writing, all the XCs included in the graph above are still used as top holing entrances for 123L and consist of reclamation activities which require services such as water and compressed air. Scope does exist to evaluate the 120L spindle pump configuration in July 2022 due to some reclamation activities which are scheduled to conclude.

Figure 94 – Figure 95 indicate mining is set to continue well into FY24 on 123L with more XCs currently being developed. Several XCs, where mining activities are scheduled to stop, are also seen on the graphs. Evaluation of these XCs can be aligned with the mine planning schedule to optimise the spindle pump configuration on 123L.

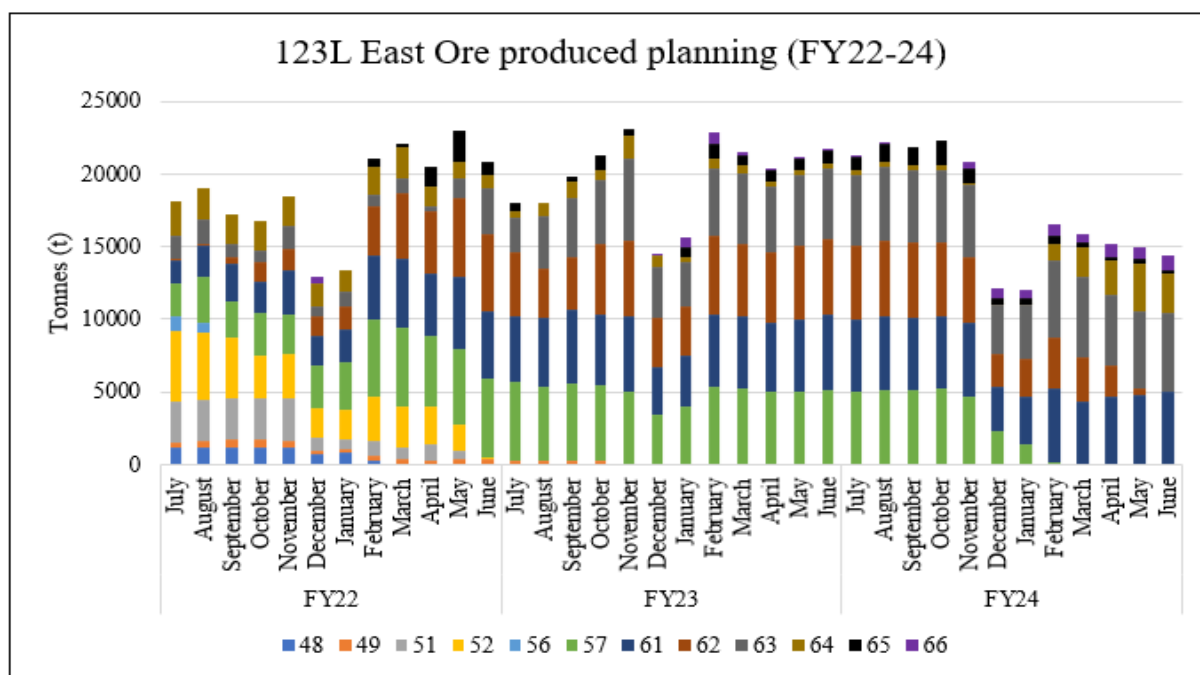


Figure 94: 123L East ore planning schedule

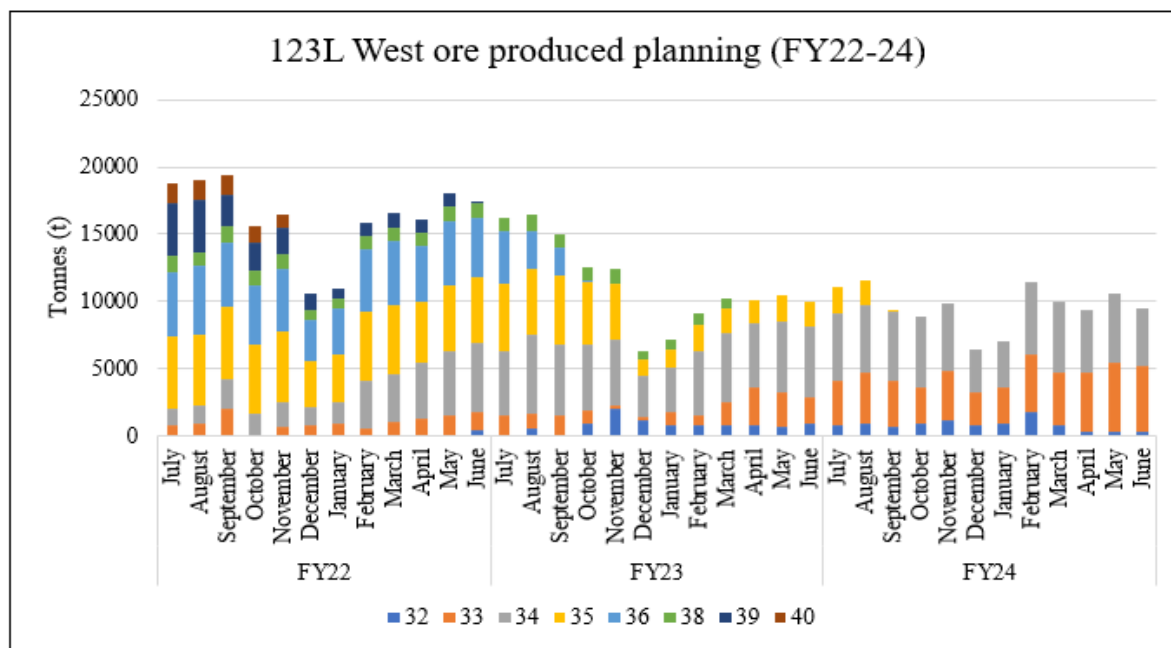


Figure 95: 123L West ore planning schedule

Most development activities at Mine A are currently focused on 126L (Figure 96 – Figure 97) as this is the deepest and most recently opened operating production level. Several additional XCs are still to be developed on 126L and the water demand is likely to increase rather than decrease in upcoming financial years. According to the current simulation results, the water demand needs to increase significantly before exceeding the 15kW spindle pump limit.

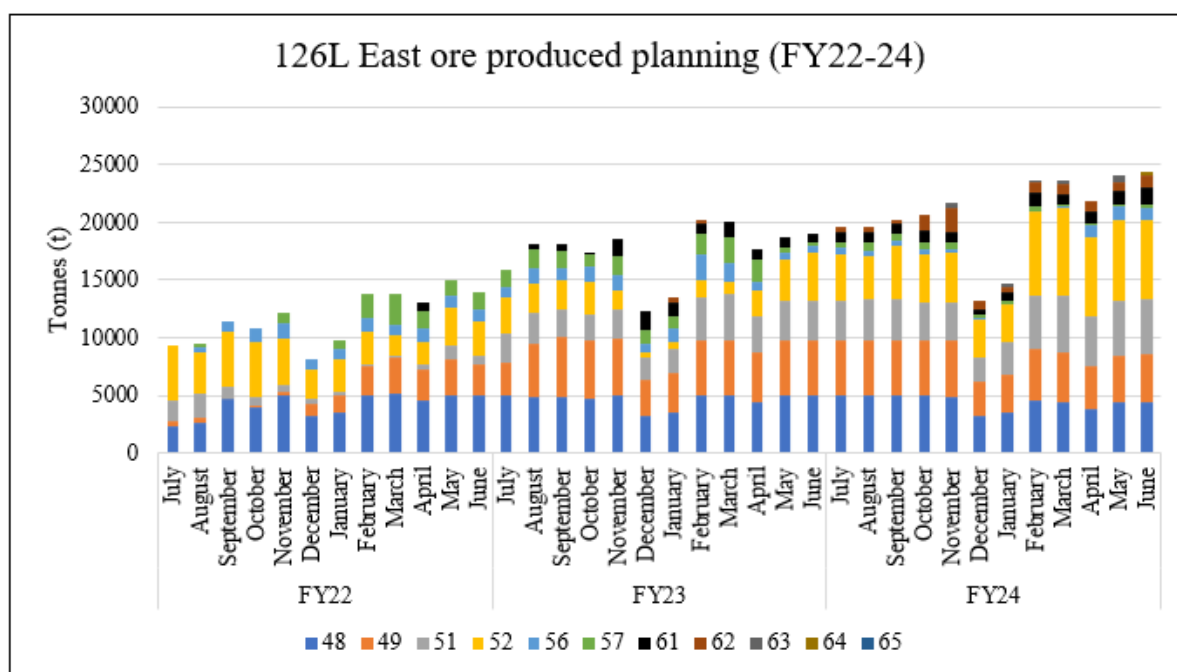


Figure 96: 126L East ore planning schedule

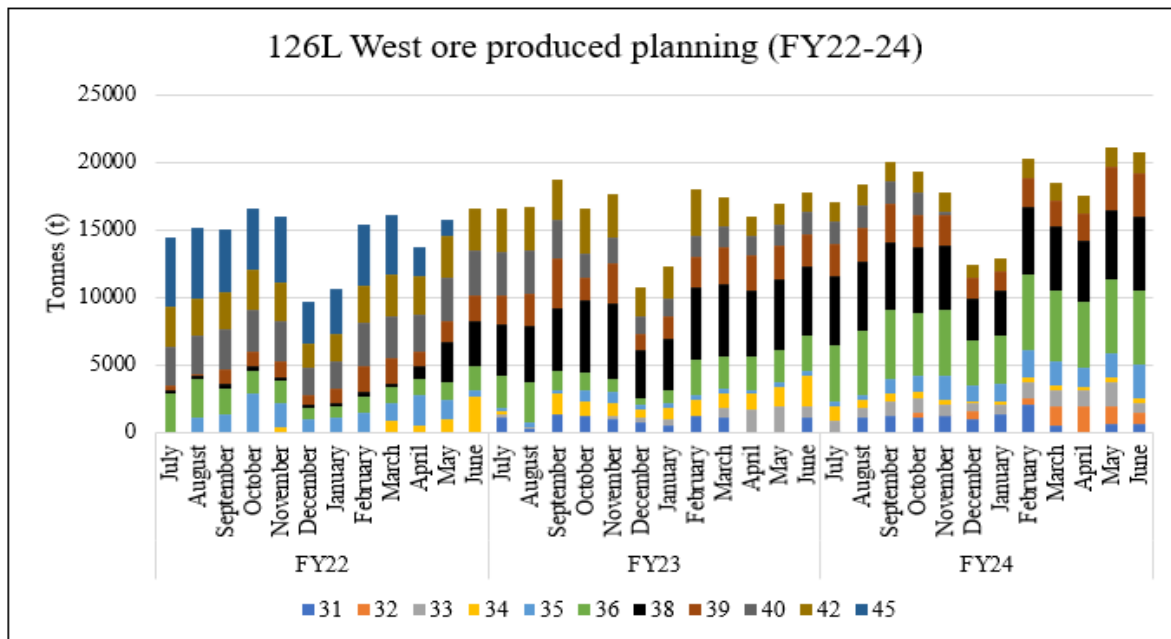


Figure 97: 126L West ore planning schedule

A total of 18 XCs on the lower mine production levels are scheduled to stop mining activities before FY24 ends. A summary of the XCs to be closed is shown in Table 40.

Table 40: Mine A mining activities end dates

Mining activities end dates (before FY24)		
	XC location	End date
120L	33	Jun-22
	56	Sep-21
	66	Oct-21
	62	Nov-21
123L	48	Mar-22
	49	Nov-22
	51	Jun-22
	52	Jul-22
	56	Sep-21
	61	Mar-24
	62	Jun-24
	35	Oct-23
	36	Nov-22
	38	Apr-23
	39	Jul-22
	40	Dec-21
126L	40	Dec-23
	45	Jun-22

System limits monitoring interface

The system limits developed according to the seven-step interval system in Chapter 3 was added to the monitoring interface and can be viewed as a trend in real-time. The interface is easily accessible to involved personnel to ensure action is taken when necessary. Figure 98 portrays the system performance of 126L.

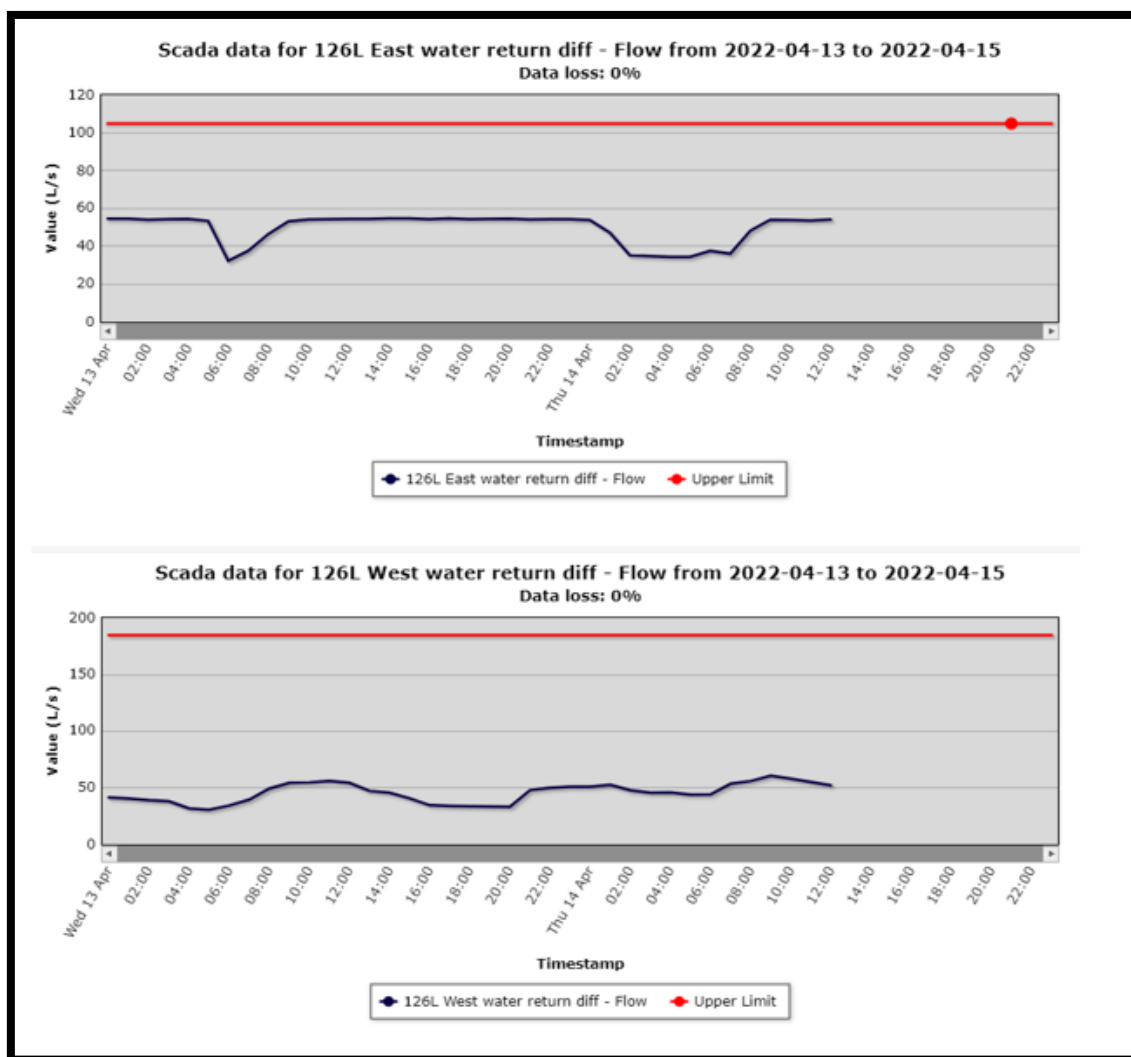


Figure 98: Real-time monitoring system limit addition for 126L

Project delays identification

Delays are inevitable occurrences during any project. The anticipation of delays prior to project implementation enables proactive solution formulation before they occur.

The majority of delays encountered during each step of the study are:

- Potential annual leave and unconfirmed absence,
- unexpected priority breakdowns or jobs requiring involved personnel,
- industry and manufacturer delay due to pandemics or other related issues,
- information required from specialised personnel,
- re-allocation of project funds, and
- production and logistical related issues.

The delays for all the methodology steps are shown below:

Step 1- The first step took place during the first quarter of FY22, which was still susceptible to recurring waves of the Covid-19 pandemic. Personnel conducting the initial audits were placed on a flexible rotation schedule to avoid any delays to scheduled audits due to positive Covid-19 cases.

Step 2 – Building the simulation entailed lots of specification identification for underground infrastructure. Designers at Mine A were tasked with providing essential information to complete the simulation of the underground spindle pump system. Most of the simulation design was done in the second quarter of FY22. It is very common for mining personnel to take yearly leave during this period of a year. The specialised designers were, therefore, asked to provide their respective leave schedules to obtain the required information before annual leave is taken. Priority tasks assigned to the designers were also identified and critical meetings relating to spindle pump specifications were scheduled around the priority tasks.

Step 3 – During the second quarter of the financial year, a mine aims to hoist vigorously in order to make target before the December break.

Due to the increased mining activities for this period, any underground audits relating to the specific solutions development of the spindle pumps system considered the increased mining activities for this short timeframe before normal mining times and water demand quantities returned to normal.

Step 4 – Mines are prone to experience equipment breakdowns after the start-up of a December break period during the third quarter of FY22, when most of the equipment was either running at a reduced load or switched off completely. Unexpected labour tasks during this period were prominent and increased the challenges to project scheduling.

Step 5 – The fourth quarter of a financial year focuses on mining areas which are prioritised in terms of labour. The preparation of mining intensive production areas requires increased personnel allocation to ensure the production section is ready at the start of the new financial year. Activities relating to audits conducted on the less mining-intensive levels were dependent on certain personnel which were moved in order complete the preparations of the prioritised mining sections. This delay was partially mitigated through senior personnel backing, which identified the spindle pump audits and reclamation as priority.

APPENDIX E – SAIIE 33 SUBMISSION

Dear Jamie du Preez,

Congratulations, after a careful review of your submission, your submission has been accepted for presentation at SAIIE33.

Please upload a final, camera-ready version onto the conference paper management system before 6 September 2022. When you upload your revised version, you may now include your final author and affiliation information. Please upload as the FINAL paper. If you already uploaded a file under FINAL paper, you can replace it.

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Also please note that conference papers are not sent for language editing and as a result, if papers are submitted where there are extensive errors, we will have no choice but to decline the paper.

Please also ensure that you are registered for the conference and one of the authors is able to attend and present, in-person, in Durban. Further information regarding sessions and presentations will follow soon. To register, please visit our website:

<https://saiee.glueup.com/event/saiee33-annual-conference-47603/>

Watch out for exciting news regarding the line-up of fantastic workshops, keynote speakers and networking events.

In the interim if you have any questions, please do not hesitate to contact us.

We are really looking forward to seeing everyone at SAIIE33 in Durban!

Teresa Hattingh

SAIIE33 Editorial Team



Figure 99: SAIIE33 Certification

*The article was kept in its original format as submitted to the SAIIE editorial team

A SIMULATION-BASED HORIZONTAL WATER TRANSPORT MANAGEMENT STRATEGY IN DEEP-LEVEL MINES

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ABSTRACT

Dewatering and water transfer pumping is one of the main electricity consumers in the South African mining industry. It is important to consider all possible angles to ensure maximum possible savings and efficiency when investigating industrial water reticulation systems. Horizontal pumping systems, however, was previously excluded from optimisation techniques. In this study, a scientifically derived water management strategy is developed for horizontal water pumping in deep-level mines through simulation of current and future mining activities.

System simulations of the current system was based on the most recent return flows on each level. Additional simulations were done to establish maximum demand limits for installed spindle pumps. Results revealed the system is over-specified for the application. Scope exists to exchange numerous of the current 49 spindle pumps with better suited pumps based on current and future water demand requirements. Implementation will result in electrical cost saving of R4 821 131 p.a.

Keywords: Integrated, Simulation-based, Horizontal water transport

* Corresponding Author

1. INTRODUCTION

Deep-level mines in South Africa use process water in large quantities for various applications on surface operations and underground [1]. Underground applications mainly include cooling, drilling- and mining activities, dust suppression, energy recovery, backfilling, and water jet cleaning [1] [2] [3] [4].

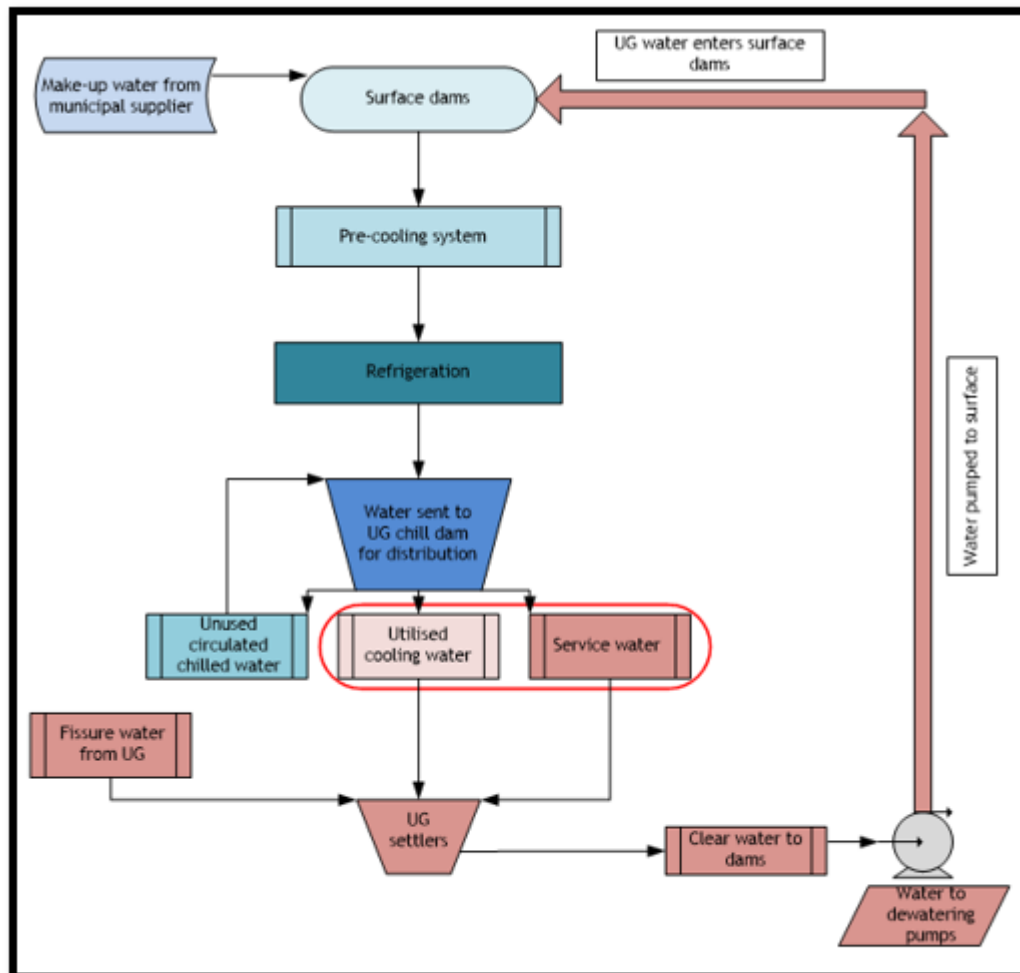


Figure 1: A typical deep-level mine water reticulation network

Water is distributed from surface after it exits the refrigeration system. For deeper mines, there are usually dams situated strategically on descending levels as water moves through the shaft column [2]. This is also done to ensure there is enough storage capacity for the water being sent underground.

As the water moves down, it usually accumulates at a central location with a large dam capacity where it is distributed to the various mining levels. Most mines feed the production levels through gravity feed and make use of booster pumps situated on the production levels to ensure the chilled water reaches end users at a sufficient pressure [2] [3].

The most common underground chilled water end users include cooling cars, Bulk Air Coolers (BACs), winders, drills, ore face cleaning and fridge plants [2] [4]. Chilled water is first used for cooling entities after which a portion of water in each cross-cut (XC) is sent to the stopes according to demand required at specific hours of the day.

To mitigate pumping cost, some mines consist of a chilled water return system. This ensures most utilised chilled water (not used for drilling) returns to a central chilled water accumulation point and correspondingly, mitigating pumping cost on the dewatering pumps [5]. A typical representation of an underground chilled water return system is shown in Figure 2.

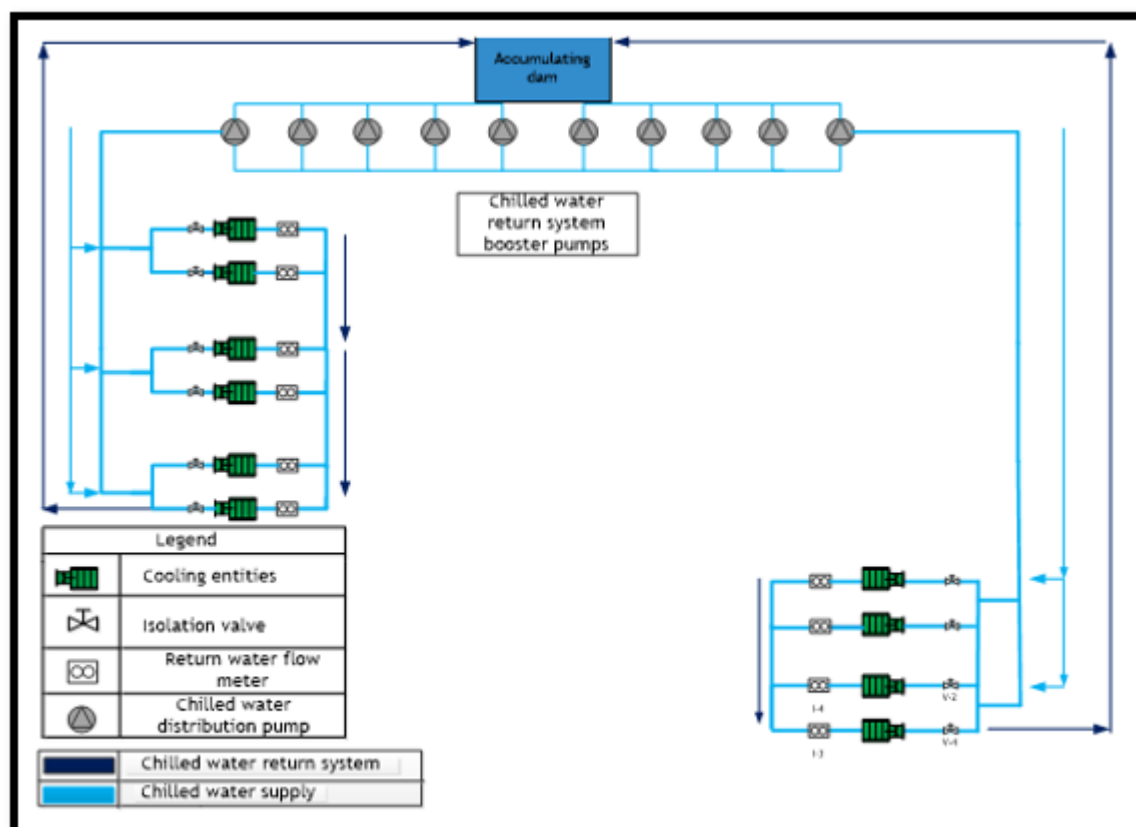


Figure 2: Typical chilled water return system

Water sent to the stopes (used for mining activities) does not remain in the chilled water system. Mining activities adds significant heat to the water and would render a large temperature gradient should it return via the chilled water system. These quantities of water are transported by the spindle pump return system (Horizontal Water Transport System, HWTS) towards annex holes/ holding dams on respective levels after which it enters the dewatering system.

Horizontal Water Transport System

Used mining water drains from the stopes by means of footwalls and service water pipes. Service water return pipes are suspended from the rock face within a XC directing the water to the front of the section. Water accumulated along the footwalls of a XC is transported through a series of submersible spindle pumps towards the front of the section where the return service water is dumped into a sump.

Each XC contains a sump at the bullnose (entrance) of the XC where the service water accumulates and is pumped into the main service water return line suspended in the main haulage of the level. Figure 3 is a visual representation of the spindle pump return water system currently in use at the active XCs.

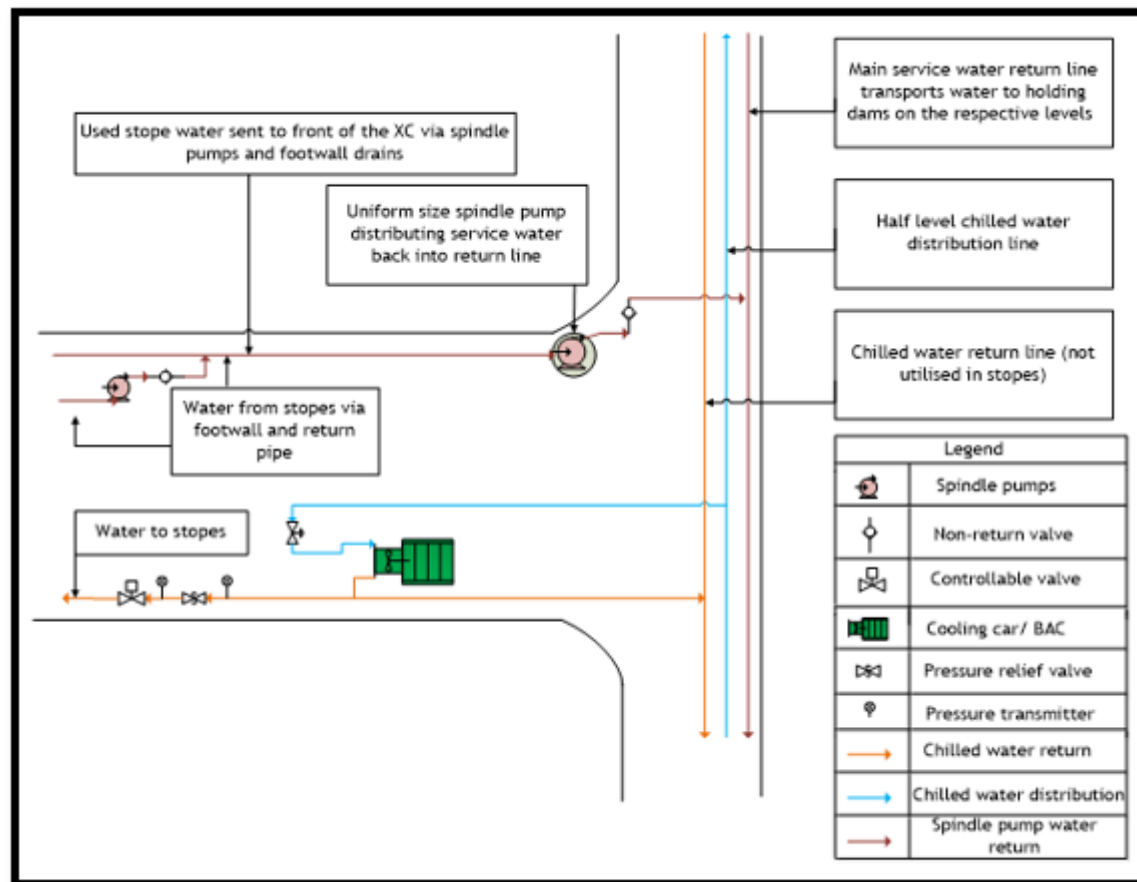


Figure 3: Bullnose spindle pump XC configuration

Research was done on the operation of the HWTS in deep-level mines. It was found that according to mining standards and procedures set out for deep-level mining, the bullnose spindle pumps are of a uniform size for each operation regardless of the water demands present on the levels of installation [6].

Aim and objectives

Due to the lack of engineering principle integration concerning bullnose pumps within the HWTS, a need exists to develop, implement and validate a simulation-based water management strategy to improve operation of the HWTS in deep-level mines. To successfully evaluate the HWTS, an objective list was constructed to establish the specific focus points of horizontal water system improvement. Objectives will aim to address the shortcomings within current literature and be used to develop a strategy to properly research, evaluate and improve existing spindle pump return systems.

These objectives are:

- Integration of current and future water demands through simulations to reduce OPEX costs.
- Increase water demands forecasting accuracy for better capital allocation.
- Test scenarios of horizontal water management improvement and the effects on water demand prior to implementation.
- Add a system monitoring aspect to previously unmonitored and under-equipped systems

Literature review

Various water management strategies have been researched to reduce the Operational Expenditure (OPEX) cost of the larger dewatering pumps in deep-level mines. The HWTS contributes significantly less to electrical load and is therefore regarded as a lower priority energy system [7]. Literature studies were chosen to illustrate the **types** of water management strategies researched and implemented on deep-level mines.

This includes basic control strategies, electrical load shifting, pump specification improvement, reconfiguration of water systems, service delivery improvement, failure analysis and management relating to electrical cost savings. As far as can be ascertained, an extensive review of literature relating to water reticulation systems revealed that **no focus** has been placed on HWTS management. To illustrate the gap identified in literature, a state of art matrix was constructed in Table 1.

Table 1: Literature review matrix summary

A simulation based horizontal water transport management strategy in deep-level mines										
Study	Year	Ref	Underground horizontal water management inclusion	Pump specification optimisation	Simulation	Electrical cost savings	System monitoring tool with minimum infrastructure	Sustainable	Water demand management & forecast	Dynamic adaptability
Vosloo	2008	[8]		X	X	X		X		X
Botha	2010	[9]				X			X	
Rautenbach et.al	2008	[10]			X	X		X		
Stephenson	1983	[1]		X						
Bridgwood et.al	1983	[11]		X						
Murray	2000	[2]		X	X	X		X		X
Venter	2020	[12]				X		X	X	
van Niekerk	2017	[13]			X	X	X		X	
du Plessis et.al	2015	[14]			X	X		X	X	X
Conradie	2018	[15]			X	X			X	
van Staden	2018	[16]				X			X	
van Rooyen	2019	[17]					X	X		
Ashmead	2019	[18]				X				X
Taljaard	2012	[19]			X	X		X		X
Zhang	2011	[20]		X		X		X		X
Cilliers	2014	[21]			X	X		X		X
Jacobs	2021	[22]					X	X		
Jerling	2019	[23]				X	X		X	
Peach et.al	2018	[24]				X		X	X	X
Mare'	2016	[25]			X	X		X	X	X

**The state of art matrix compares the focus of the different water management strategies and assessed whether any of the studies extended the strategy development to the HWTS.*

The literature review of water system improvement techniques reveals that a gap in literature exists through the lack of focus placed on improvement of the HWTS in deep-level mines. Although the HWTS typically contributes 6% of total pumping expenditure, the size of modern day deep-level mines more than motivates the need for improvement. This study aims to address the exclusion to ensure a strategy for horizontal water system improvement is established.

2. Methodology

The methodology was developed to establish a **dynamic and sustainable** horizontal water transport management strategy and address the objectives through use of simulation software.

Step 1 - Performing a pumping system audit

The first process step entails a preliminary pumping system audit from which certain conclusions, limitations and design specifications can be determined. Secondly, a detailed investigation regarding the pumping system should be conducted to establish usable operational parameters and more efficient operating configurations [26] [27] [28]. This is shown in Figure 4.

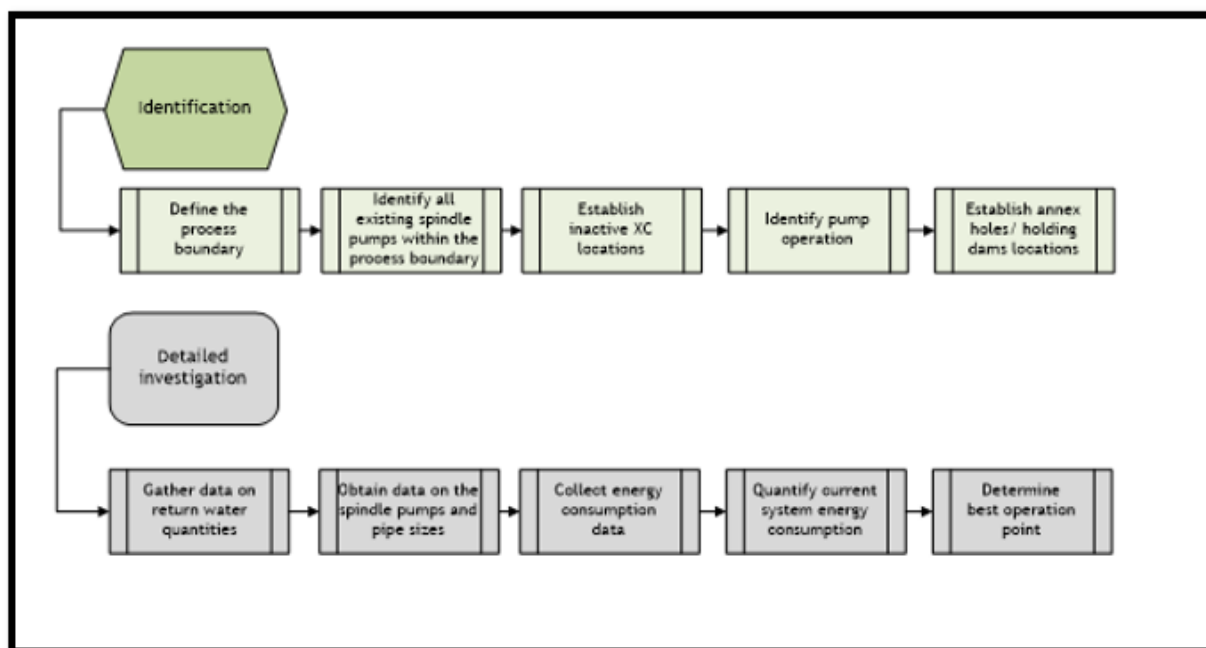


Figure 4: Pumping system audit and investigation flowchart

Step 2 - Modelling the current system configuration through simulation

Simulation software adds the benefit of validation after initial measurements and calculations have been done. Detailed simulations additionally assist in providing valuable information while considering a vast number of network constraints allowing both a localised and holistic overview of an entire modelled system [29].

Various simulation software systems have been in use in the mining industry over the past few decades. Certain mining companies prefer specific simulation software, mostly due to familiarity. It was seen upon comparison however, that there are some shortcomings to some of the most used software entities.

The construction of the horizontal water transfer pumping system will be done using Process Toolbox (PTB3D). PTB3D is a transient thermal flow solver which enables the solving of complex systems using a wide array of contributing parameters [29] [30]. The simulation will be used as an integrated verification evaluation to assist in establishing accurate parameters by using the data collected in Step 1 of the methodology.

Step 3 - Improve the system energy consumption and configuration

After proper calibration and verification of the model is completed, potential changes to the system can be considered [31]. Measured and simulated performance results of the current system should be used as a baseline for the potential changes to the system.

Step 4 - Dynamic adaptability and sustainable solutions incorporation

Dynamic adaptability and sustainable solutions are key elements to the success of any given project. Past identified projects, which delivered promising initial results, have failed miserably due to a lack of dynamic adaptability and sustainable solutions integration [32].

According to Mvudi [33], the main attributing factors to project failure are the following:

1. Project scope change,
2. Internal conflicts between project and departmental tasks,
3. Lack of resource and project performance tracking,
4. Deviation from, or lack of project management methodologies,
5. Lack of a defined software project management methodology framework,
6. Unrealistic project expectation and lack of future change planning.

All factors need to be considered to ensure a dynamically adaptable and sustainable solution.

Step 5 - Implementation tracking and results analysis

Project implementation can be a challenging task on a deep-level mine, often due to mismanagement of resources and lack of communication between departments. The key to project implementation comprises of comprehensive planning prior to actual implementation [34]. A proper plan aids to streamline the implementation process and ensures project completion within the allocated timeframe and budget if followed correctly.

After project implementation, the performance of the newly implemented system needs to be assessed to determine the benefit of the project. Analysis forms an essential part of the final project stages and can be loosely described as the benchmark for project success [35]. It is recommended, if applicable, that results analysis should be conducted as a continuous process throughout implementation and should not be left until project completion [36]. A flowchart of the project implementation and results analysis is shown in Figure 5.

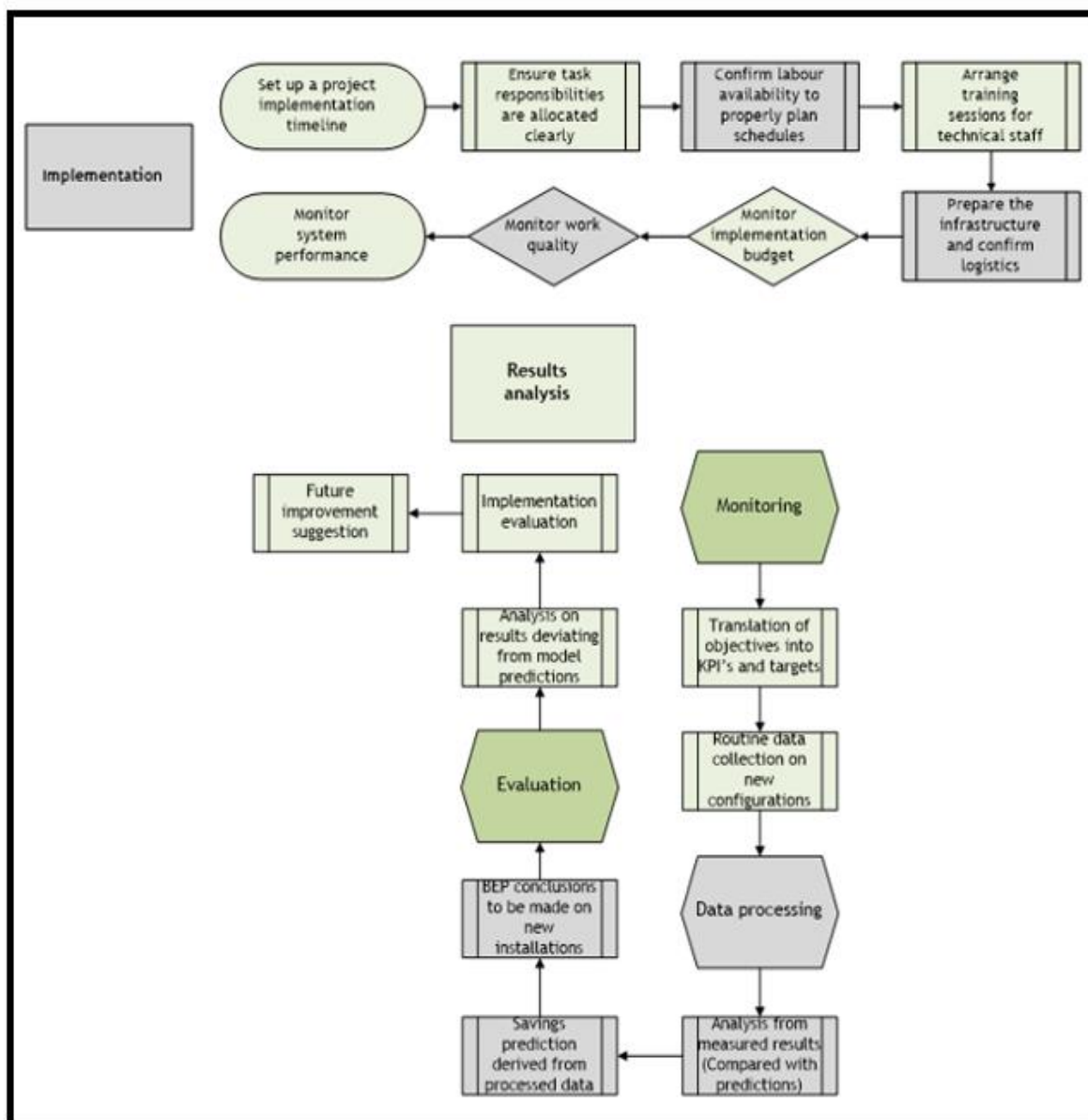


Figure 5: Implementation and results analysis flowchart

A summary of the methodology is shown in Figure 6.

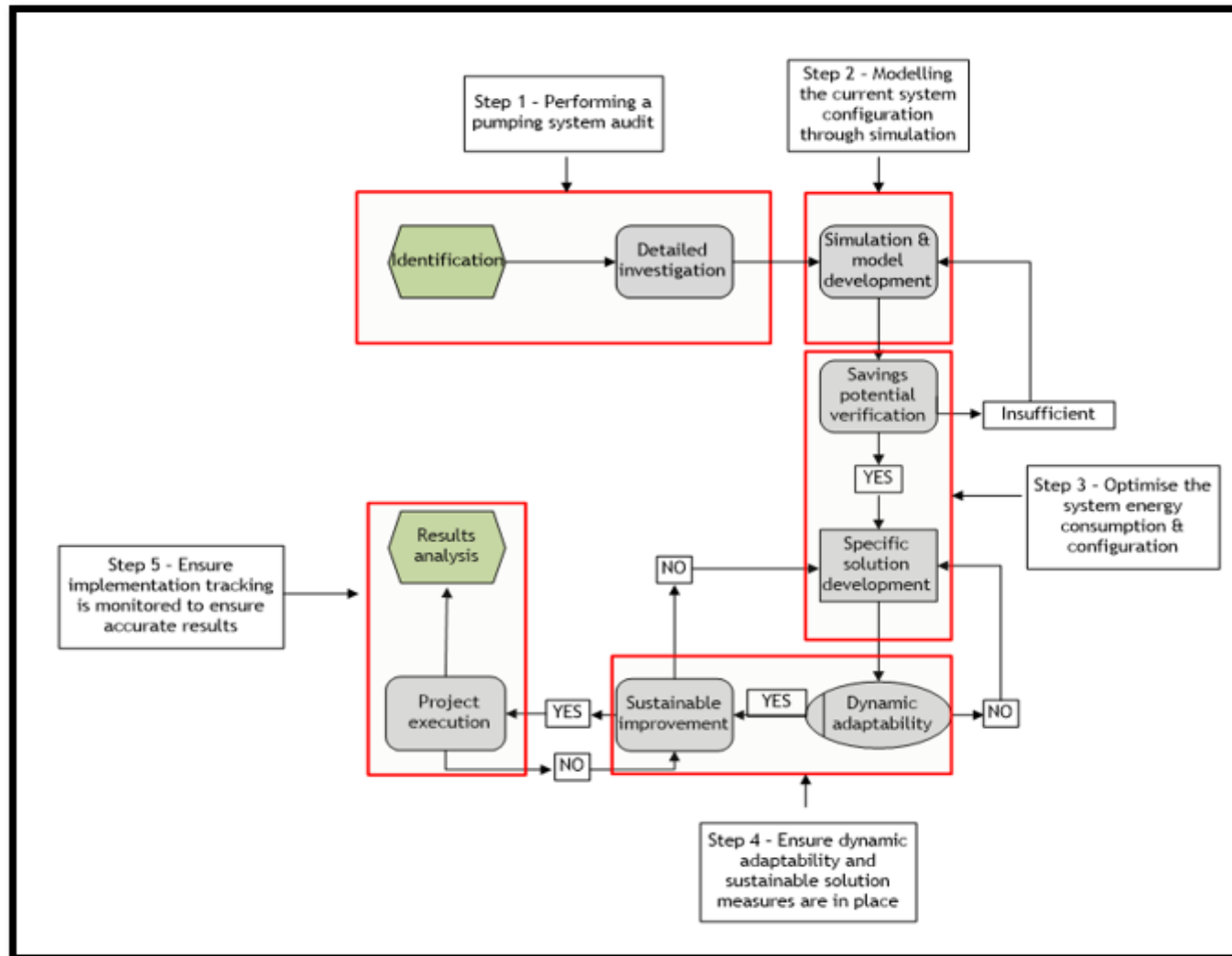


Figure 6: Methodology for horizontal water transport management strategies

3. Results and discussion

The developed methodology steps will be applied to a case study on Mine A, situated in South Africa. Mine A follows the standardized mining procedures set out for deep-level operations and use one uniform size pump at the XC entrances. The water demands will be assessed through measurements and simulation after which a conclusion on the pumping configuration will be made. The results of the case study will be evaluated and be presented in the same order as the five-step methodology developed in Figure 6.

Step 1 - Identification and investigation

Data was gathered through manual measurements and SCADA (Supervisory Control and Data Acquisition) historian analysis of the pumps identified within the process boundary. The process boundary on Mine A is shown in Figure 7.

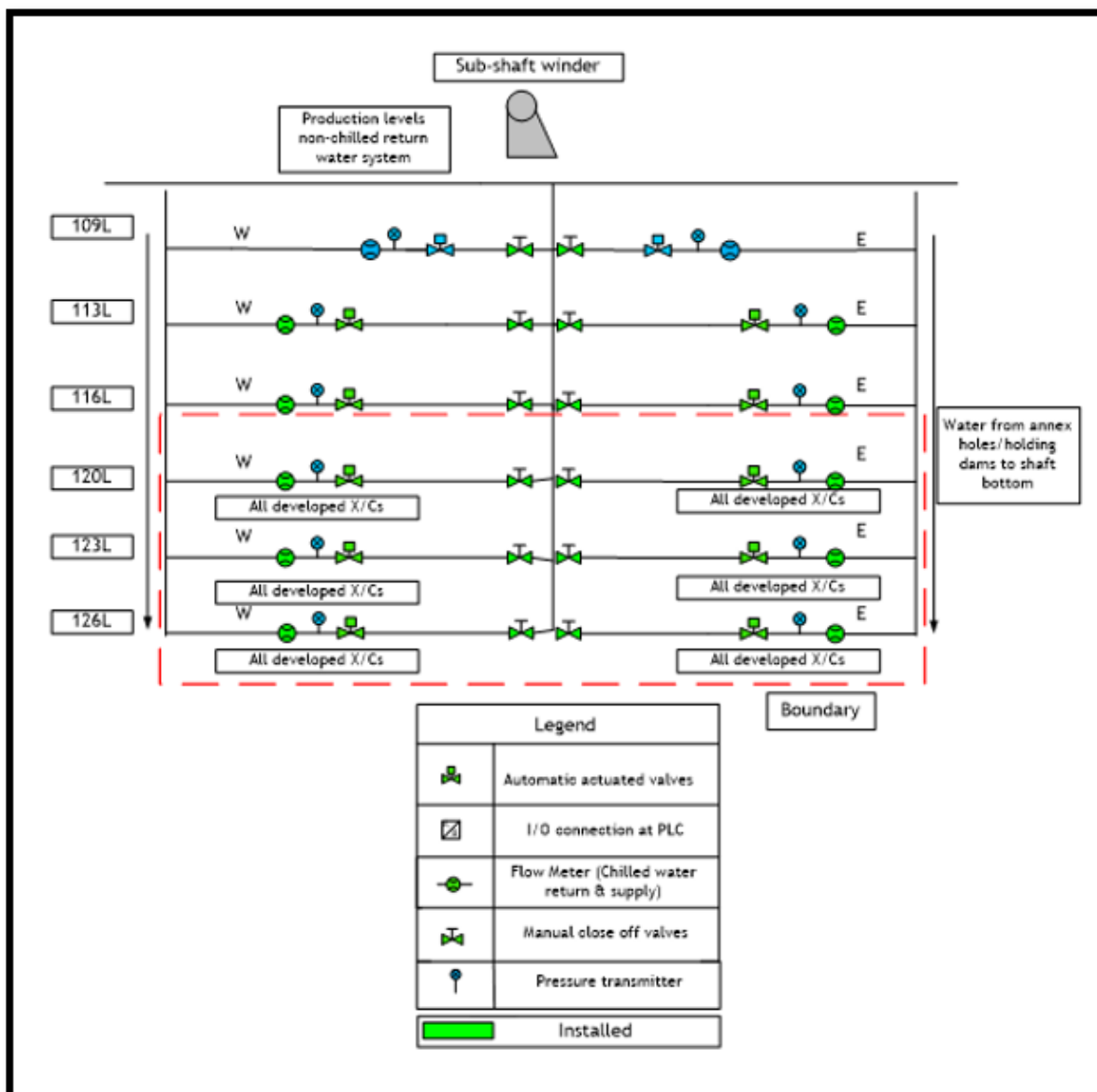


Figure 7: Mine A process boundary

Initial manual logger measurements of the installed bullnose spindle pump system (45kW spindle pumps) revealed consumption of 20.73 kW based on a weighted average calculation and operated on a permanent basis. Logger measurements comparison to performance curves are important due to the HWTs forming part of larger mining feeders which restricts proper assessment unless done through measurements.

Figure 8 shows the current pump performance of the 45kW pumps based on logger measurements and current observed water demands.

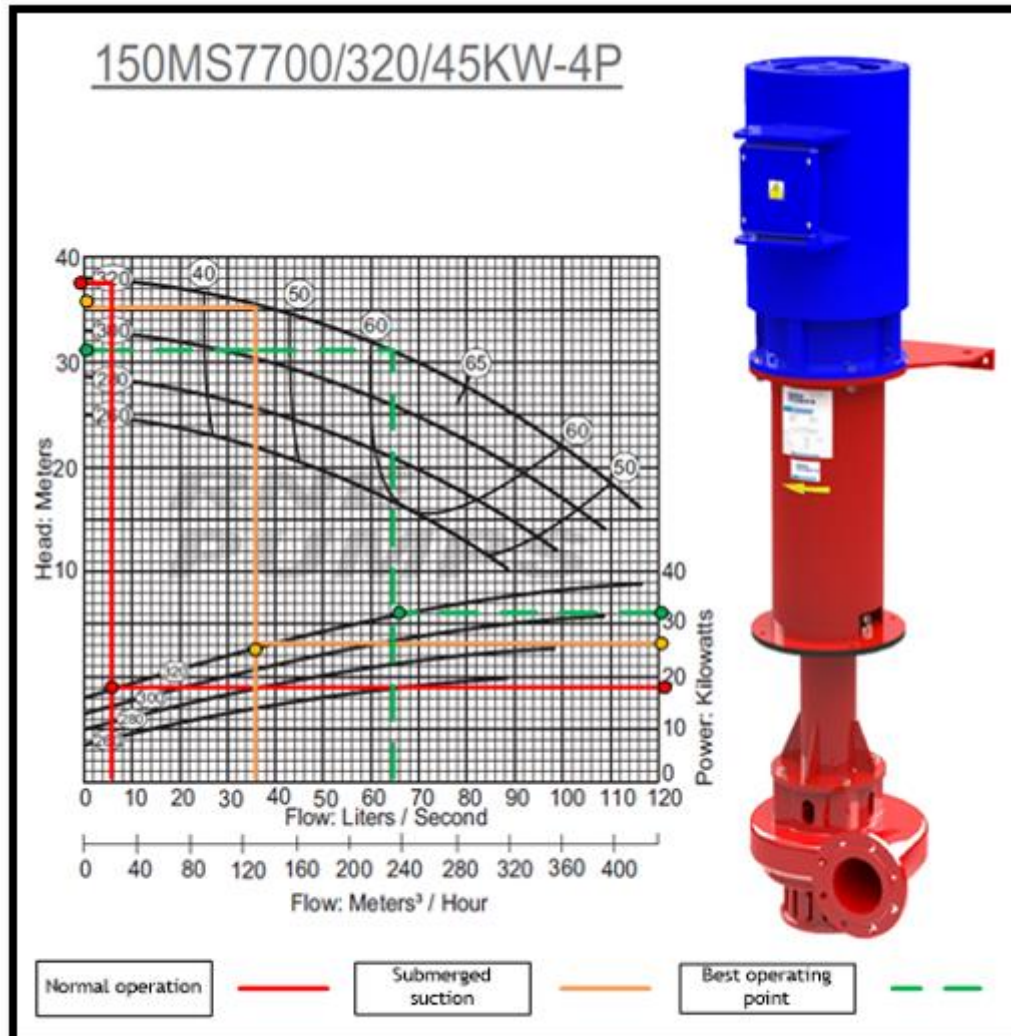


Figure 8: 45kW pump performance based on current demands

Cumulative cost of spindle pump consumption within the process boundary amounted to R10.48 million p.a based on the measured deviation of 17.74% (head calculation) from the pumps Best Efficiency Point (BEP) during normal operation [7][37]. Operation closer to a pump's BEP would result in improved performance. Simulation development, based on the data collected from the initial audits, will be used to identify better suited pumps for improved system operation.

Step 2 - Modelling the current system configuration through simulation

The simulation models were developed by using PTB3D, which was specifically designed for large-scale applications in the mining industry. It was seen that the current system operates at 15, 28 and 20% of its available capacity on 120, 123 and 126L respectively. Results of the current, inefficient system was used to establish the maximum operational demands each of the identified pump sizes will be able to transfer to the annex holes/ holding dams on each level. Additionally, pump performances relating to BEPs was established.

Step 3 - Improving system energy consumption and configuration

Three simulations scenarios were compared to the **current** system demand to illustrate the available water transfer capacity should demand requirements increase. This ensures limits are clearly identified to invoke action after exchange when needed. Critical evaluation of level results revealed significant scope to install better suited pump sizes on **all** the production levels. The maximum demand flows of a spindle system comprising of 45, 15 and 7.5kW pumps, compared to the current water demands are seen in Figures 9 - 11.

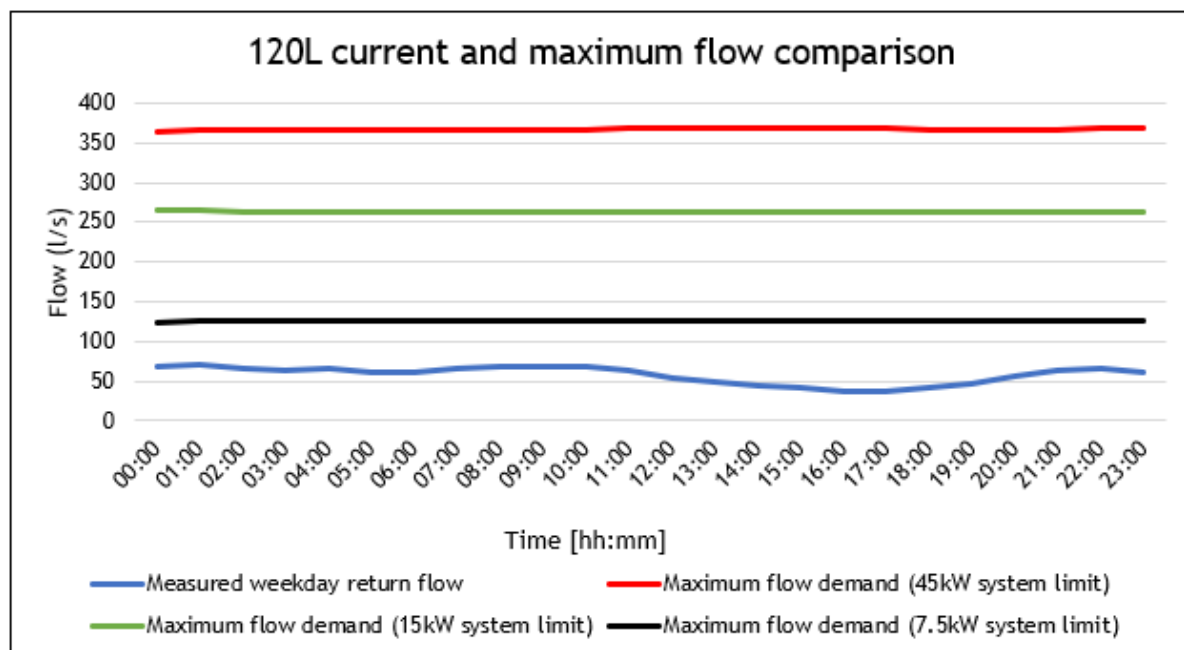


Figure 9: Maximum demand capacities on 120L

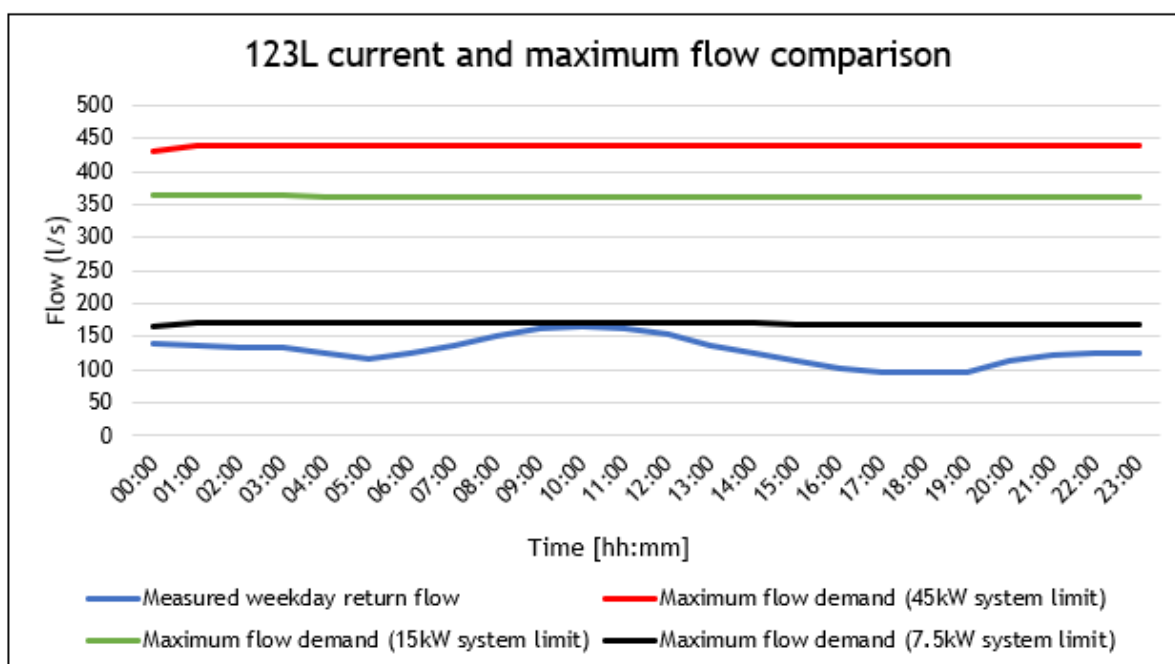


Figure 10: Maximum demand capacities on 123L

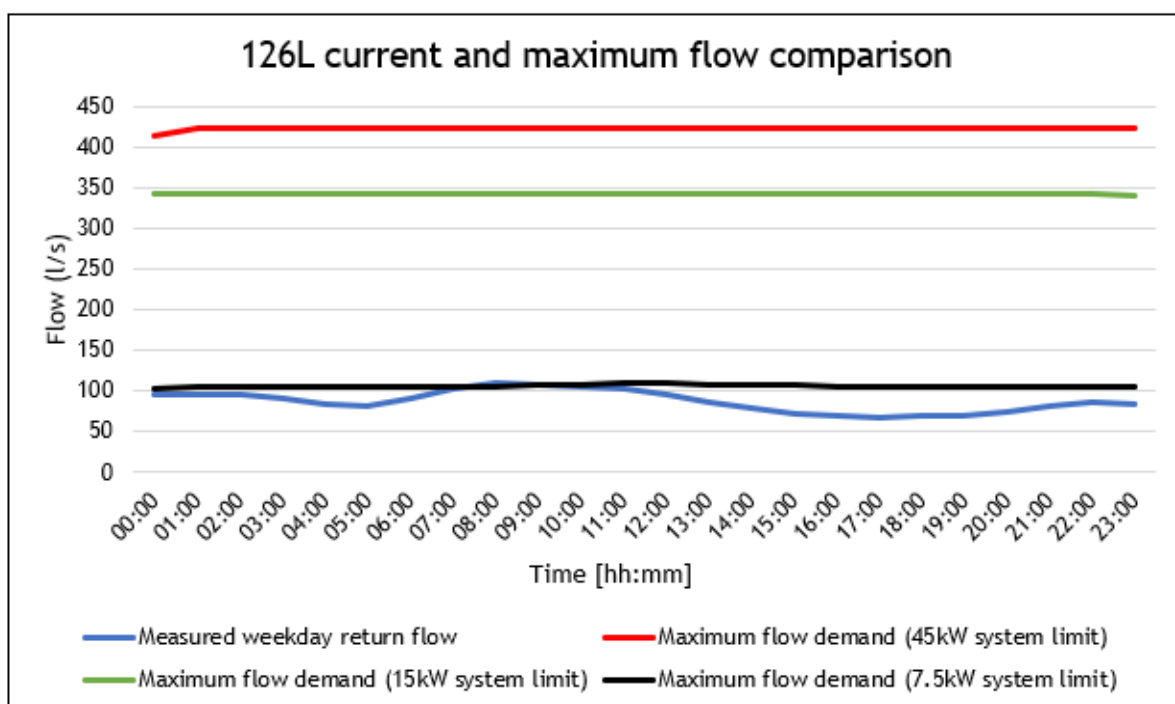


Figure 11: Maximum demand capacities on 126L

As seen on the figures above, the maximum water demand limits for both the 15- and 45kW systems remain well clear of the current demands on the production levels. The 7.5kW system's maximum capacity still operates above the current demand during certain times of the day but operates close to the maximum limit during peak drilling times. Table 2 provides a summary of the operational point of each evaluated spindle pump system at current flows.

Table 2: Production levels operational point comparison

Mine A average operational horizontal water transport capacity comparisons			
Level	45kW operating point (i.r.t. maximum capacity)	15kW operating point (i.r.t. maximum capacity)	7.5kW operating point (i.r.t. maximum capacity)
120	15%	21%	46%
123	28%	36%	76%
126	20%	26%	82%

The results reveal the 7.5kW spindle pump system would not be sufficient to transport the current water demand out of the respective sections during peak drilling time and is therefore not a suitable replacement for the 45kW. Levels scaling down on mining activities may be considered for configuration changes with the 7.5kW pump. The 15kW system operates closer to maximum capacity than the 45kW system, but remains well within the capacity boundaries. This allows for a buffer should sudden influxes of water occur.

The 15kW pump is currently chosen as the **replacement** for the 45kW pump on all the levels **considering the water demands present**. Logger measurements were done for the 15kW pump and revealed a weighted average consumption of 11.32 kW with current water demands. Continuous analysis is recommended for areas significantly scaling down on mining activities. If **all recommended** pumps within the process boundary are replaced with 15kW pumps, the expected electrical cost savings amounts to R4.82 million p.a.

Step 4 - Dynamic adaptability and sustainable solutions development

Real-time monitoring of the spindle pump system was established without additionally installed infrastructure through simulation integration with the operating SCADA system. System limits were established and incorporated into the software. Corresponding actions, based on the system limits (for the 15kW application), were developed to certify necessary steps are in place at various flow intervals to ensure mining personnel are prepared should changes to the system be required. Personnel will be alerted through automated communication channels should these limits be surpassed.

To ensure sustainability of the project, influence of implemented initiatives on the water demands are noted and corresponding demands for the foreseeable future are predicted. Water demand predictions are done using the mine ore planning schedule and the current mining intensity (kL/tonne) on the focused levels.

The predicted water demands are used to identify sections where mining activities will scale down and predict the installed system performance based on the new water demands. It is recommended to not extrapolate predictions too far ahead due to inevitable mining changes. Figure 12 shows the demand predictions for the Q3 of FY23.

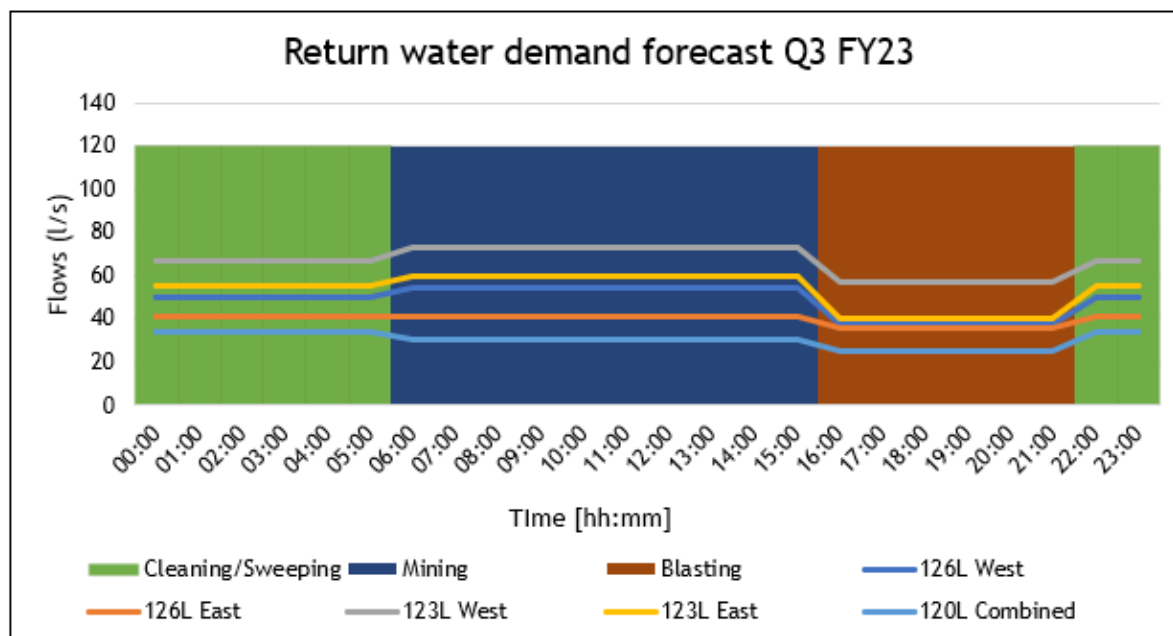


Figure 12: Water demand predictions for FY23 Q3

Each level's water demand is displayed according to the time period of each mining activity. Flow forecasts should be evaluated during each quarter to ensure forecasts remain up to date if changes occur. Flow prediction models is an effective way to ensure the most applicable pump sizes are used on levels where mining activities predominantly take place.

Step 5 - Implementation tracking and results analysis

Project implementation revealed scope for additional pumps' removal due to inactive mining sections. The additionally conducted audits were done as part of the sequential pump exchange roll out agreed upon by Mine A.

Unrequired pumps on lower ore producing levels were identified, removed and exchanged for new 15kW pumps (at a reduced cost) to be installed on the main production levels. Audits revealed pumps running with no water demand towards the sump in addition to faulty non-return valves. These pumps were switched off and removed. Personnel involved with pumps exchange were trained to ensure all parties are aware of the various responsibilities.

At time of writing, Mine A exchanged **ten** 45kW pumps for 15kW pumps on the lower production levels. Most reclamation pumps on the lower priority levels were not running, but **six** 45kW pumps could be additionally switched off and reclaimed for exchange. Logger measurements were conducted after pump replacement to establish pumping performance and savings potential.

Initial objectives set out for the study were addressed in the following steps:

1. Integration of current and future water demands through simulations to reduce OPEX costs - Steps 2 and 3.
2. Increase water demands forecasting accuracy for better capital allocation - Step 4
3. Test scenarios of horizontal water management improvement and the effects on water demand prior to implementation - Steps 3 and 4.
4. Add a system monitoring aspect to previously unmonitored and under-equipped systems - Step 4.

The achieved objectives substantiate the validity of the study and highlights the importance of analysing and monitoring lower energy-intensive systems to improve operations' efficiency.

Figures 13 and 14 show the comparison between the 45-and 15kW pump power consumption and the 15kW pump performance relating to new installations.

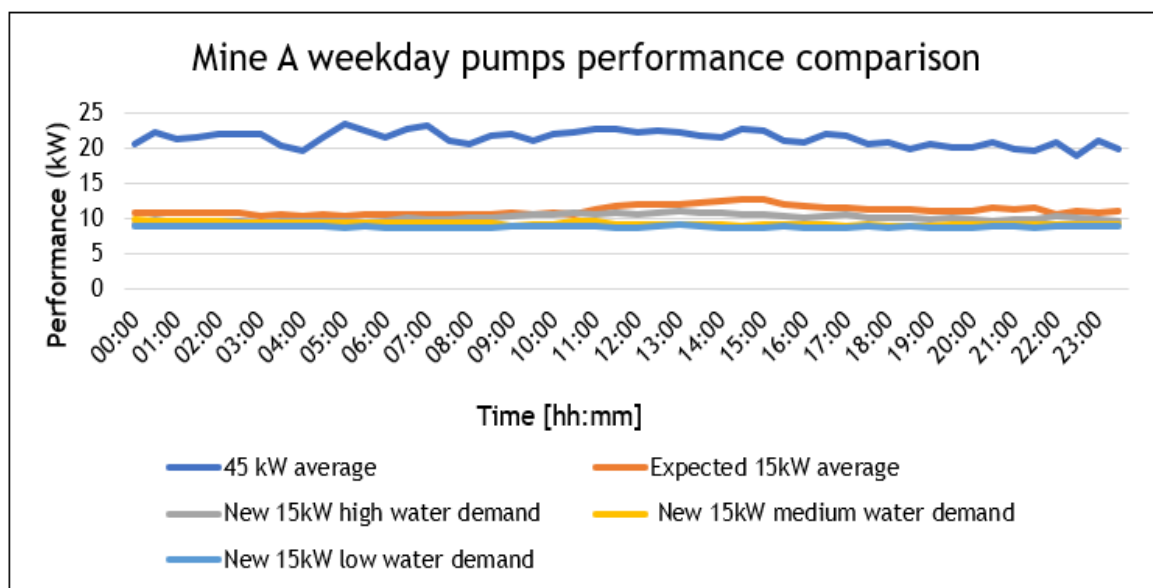


Figure 13: Spindle pump consumption comparison

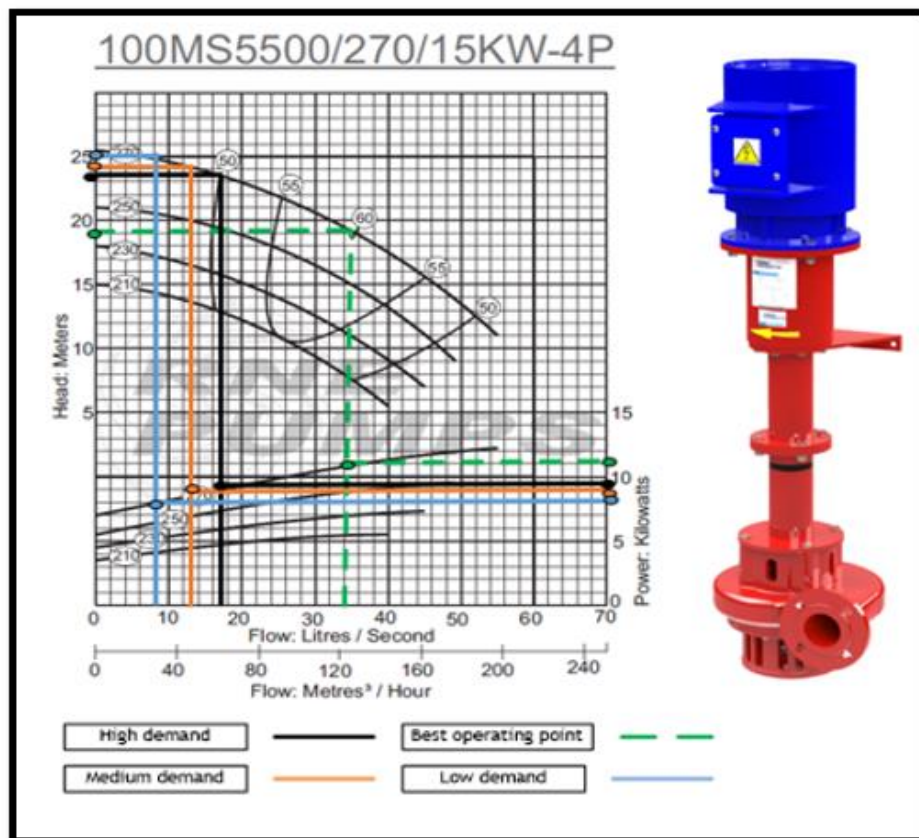


Figure 14: 15kW spindle pump performance (new installations)

Based on the **current** changes and replacements, the 15kW pump deviates 22.4%, 18.4% and 14.5% from its BEP (based on head calculations) for the low, medium and high demands, respectively. This amounts to an electrical cost saving of **R2.36 million p.a.**

4. Conclusion

Water system improvement strategies developed for deep-level mines largely focused on the energy-intensive dewatering pumps used to pump water out of deep-level mines. Research indicated that past improvement has not yet focused on the horizontal water transport system used to move used service water from the production sections towards the annex holes/holding dams on the respective levels. This is primarily due to outdated mining standards and procedures being followed and failure to analyse the potential of improving lower energy-intensive systems

This study provided a new water management strategy driven by placing focus on the system performance, energy consumption, water demands forecasting and monitoring of the less energy-intensive HWTs. All the set-out objectives were addressed through implementation of the methodology and discussed in the results and discussion Chapter. The strategy enabled the exchange and removal of inefficiently operated pumps resulting in an electrical cost saving of **R2.36 million p.a.**

The developed strategy therefore provides an accurate and practical approach to improving horizontal transport systems and highlights the importance of analysing smaller energy-contributing systems to improve pumping operation and obtain potential electrical cost savings.

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