An integrated simulation-based method for deep-level mine dewatering planning

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ABSTRACT

Title:	An integrated simulation-based method for deep-level mine dewatering planning
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The South African gold mining industry has declined rapidly over the last decades. The main contributors are rising operational costs and fluctuating gold prices. Due to increased electricity costs and increased mining depths, operational costs have increased steadily as shallow ore reserves are being depleted. Further aggravating the situation is the reducing ore grade at these deeper depths, which reduces the profitability per tonne ore mined.

A change in commodity prices can either extend a mine's LOM or shorten it. For example, multiple mining operations extended their life expectancy throughout 2020 due to an increase in mineral prices, making it more profitable to mine lower-grade ore. The rise in mineral prices was caused by the Covid-19 pandemic scoring the mining sector.

Capital is re-invested into a mine to ensure it remains profitable and operational. These capital investments include implementing planning projects to ensure that the mine has the required infrastructure for further expansion and development. It further entails avoiding unnecessary expenditures of capital on infrastructure that will not be utilised accordingly. In addition, energy-saving projects are included in these capital investments to reduce the power consumption and energy wastage of mining operations.

Various studies have shown the success of using a simulation model to replicate mining dewatering systems. After a simulation model has been verified according to the parameters and conditions of the existing system, it can be used to simulate configuration changes without physically installing pipes or pumps. However, previous studies have not considered using these models to assist with LOM planning. The simulation can be applied during the planning of future configurations to evaluate the feasibility of the recommended changes. This will ensure that suitable reconfigurations are implemented to reduce the risk of unnecessary expenditure.

The objective of this study was to develop a simulation-based method to assist in mine dewatering planning to prevent these over-expenditures. The method was applied to a case study to

investigate the pre-feasibility of a large capital project. To reduce the cost over the LOM, Mining Company A considered closing one of their care and maintenance shafts used for pumping. The deep-level gold mine had multiple integrated shafts. The case study focused on investigating the pre-feasibility of closing the pump shaft and diverting the water to a neighbouring shaft. The pumping shaft removed approximately $\pm$40 megalitres (ML) of groundwater each day.

A simulation model was created to simulate the neighbouring shaft's dewatering capacity. After the simulation model was verified against the measured values, the model was expanded to include the diverted groundwater from the pump shaft. The model was used to identify the necessary infrastructure required on the neighbouring shaft to handle the additional capacity.

The results of the pre-feasibility study validated the recommendations of this study. The results indicated that it would be feasible to close the pumping shaft. It is important to note that the LOM is dependent on the stability of the gold price. Fluctuations in the gold price could reduce or extend the LOM, thus influencing the period over which the cost savings have been estimated. For the project to be feasible, the LOM should be at least six years. The payback period of this project is in Year six. The overall LOM-estimated cost savings that could be achieved over the 16-year LOM would exceed R1 300 million. Therefore, the study's objective of developing a simulation-based method to assist with mine dewatering planning and investigating the pre-feasibility of this project was met.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbol	Description	Units
ρ	Density	kg/m^3
g	Gravitational acceleration	m/s^2
H	Head	m
Q	Volume flow	kg/s
η	Efficiency factor	–
P	Power	W

LIST OF ABBREVIATIONS

Abbreviation, Acronym or Symbol	**Definition**
BAC	Bulk Air Cooler
C&M	Care and Maintenance
DXF	Drawing Exchange Format
kl	Kilolitre
kPa	Kilopascal
kW	Kilowatt
kWh	Kilowatt-hour
ℓ	Litre
L	Level
LOM	Life of Mine
m	Metre
M	Million
ML	Megalitre
mm	Millimetre
MW	Megawatt
MWh	Megawatt-hour
PLC	Programmable Logic Controller
PS	Pump Station
PTB	Process Toolbox
R	Rand
REMS	Real-Time Energy Management System
s	Second
SCADA	Supervisory Control and Data Acquisition
T	Tonne

Chapter 1: Introduction

View of a deep-level gold mine's vertical shaft[1]

The chapter will discuss the study's background, followed by the need and objective of this study.

[1] Photo adapted from Vosloo (2008) [32].

CHAPTER 1: INTRODUCTION

1.1 Preamble

The increasing depth of gold mines causes numerous engineering challenges to ensure profitability and a safe work environment [1]. These challenges include the provision of adequate cooling for workers underground to comply with safety regulations [2], [3]. Chilled water is mainly sent underground and used as a cooling medium [4]. In addition, the water sent underground needs to be pumped back to the surface to prevent flooding of the mine [5]. The profitability of gold mines is influenced by fluctuating gold prices [6]. As seen during the Covid-19 pandemic, the rise in gold prices caused numerous mining operations to extend their LOM.

The design of a dewatering system is seldomly reconfigured. The system is usually designed before the mine start-up and minor adjustments are made if needed [7]–[9]. Increased water usage during production or increased groundwater can cause the mine to reconfigure the existing dewatering system [10]. These increased water demand loads on the dewatering system were not necessarily accounted for in the initial design. The increased water usage can also be caused by inefficiencies or water leaks on the water supply system [11].

This chapter will investigate the water reticulation system on a deep-level mine. The focus of this chapter will be directed towards the design of a dewatering system and a review of how this was done in previous studies. Finally, the study will evaluate these findings to identify a research gap in the literature on the design of dewatering systems.

1.2 Background

The South African gold mining industry reached its all-time high production peak around 1970 [12]. Since then, gold mines have reached record depths in South Africa. The deepest operational gold mine in the world is in South Africa and exceeds 4 000 m [13]. Mining at these depths poses various challenges [14], including hot working conditions, increased distances to transport the ore to the surface, and flooding caused by chilled water or groundwater [15].

As a mine deepens, the dry-bulb temperature rises approximately 10℃ for every 1 000 m [2]. The temperature rise phenomenon is caused by auto-compression [2]. Further aggravating the situation is the expected virgin rock temperature of approximately 60℃ at depths of 4 000 m [16]. The combination of these factors causes the temperature in a mine to exceed the allowable working temperature set by the Department of Mineral Resources in the Mine Health and Safety Act [17]. Any working environment exceeding a dry-bulb temperature of 37℃ or a wet-bulb temperature of 32.5℃ is classified as a ‘hot environment’[17]. Working at these temperatures can cause various heat-related health effects [18]. Therefore, artificial cooling must be installed when the working temperature nears the permissible temperature limit [19].

A variety of artificial cooling methods are used in deep-level mines. Figure 1 illustrates most of the known cooling methods used for each depth [20]. The effectiveness of these cooling methods is, however, limited to specific depths. Surface bulk air coolers (BACs) are widely used for effective cooling at depths of up to 1 500 m. However, depths exceeding 2 500 m require underground refrigeration plants or surface ice plants to ensure the working conditions are safe [20]. Localised cooling methods are also used for warm areas in mines. Mobile cooling cars are often installed closer to the working stations in mines to provide adequate cooling [19], [21], [22].

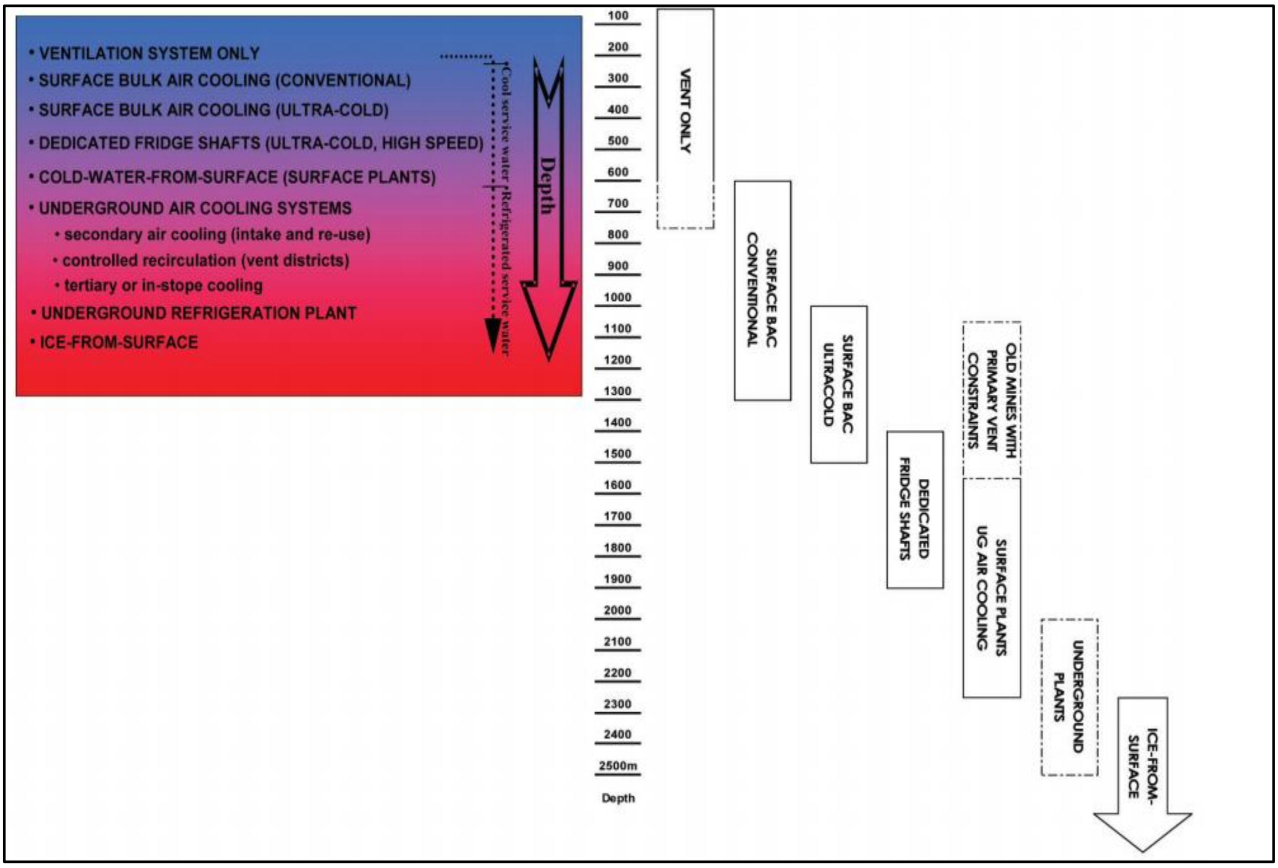

Figure 1: Cooling systems used at various depths [20]

After the chilled water has been used, it is returned to a closed-loop system or is sent to mining operations [16]. These mining operations include drilling, sweeping, cleaning, and dust suppression [21], [23]. The used water is usually ejected on the footwall of the mine, which slopes down to dams or draining pits. The water from the draining pits is pumped into hot dams for temporary storage before being pumped back to the surface for recirculation [10]. Figure 2 illustrates a typical deep-level mine reticulation system [5].

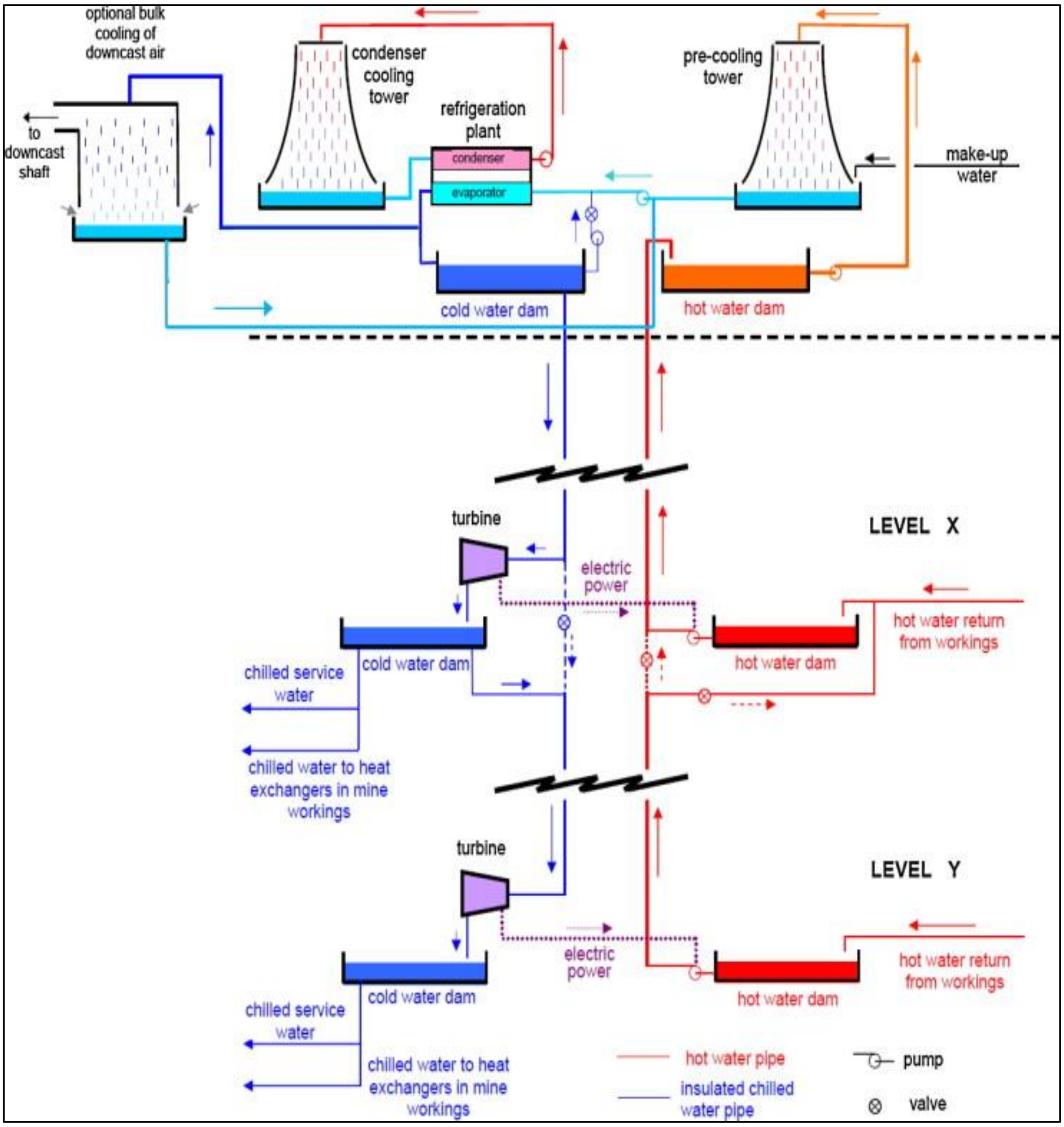

Figure 2: Typical water reticulation layout of a deep-level mine [5]

A dewatering system consists of a variety of pumps used to remove water from the mining operations. The water from these operations usually returns warm after being used and further contains ground particles. The return water from the operations is transferred to settlers, which separate the mud from the used mine water. The ground particles remain in the settler until it is removed to surface with a sludge pump [5], [24].

The separated water is stored temporarily in dams before being pumped to the surface or being recirculated into the underground refrigeration system after being filtered [5], [24]. Thereafter, the water is removed from the dams with multiple-stage centrifugal pumps. These pumps are widely used for their ability to transfer large quantities of water at high elevations, making them suitable for the mining environment [25].

An additional challenge is the presence of groundwater. As the mining operations expand, more groundwater is intersected [26]. When fractures are intersected, the exposed groundwater seeps into the mining operations. However, when dykes are intersected, they become a flow path for surface or groundwater into the mining operations [27]. Figure 3 demonstrates the concept thereof. Increased water ingress into mining operations can cause flooding [10].

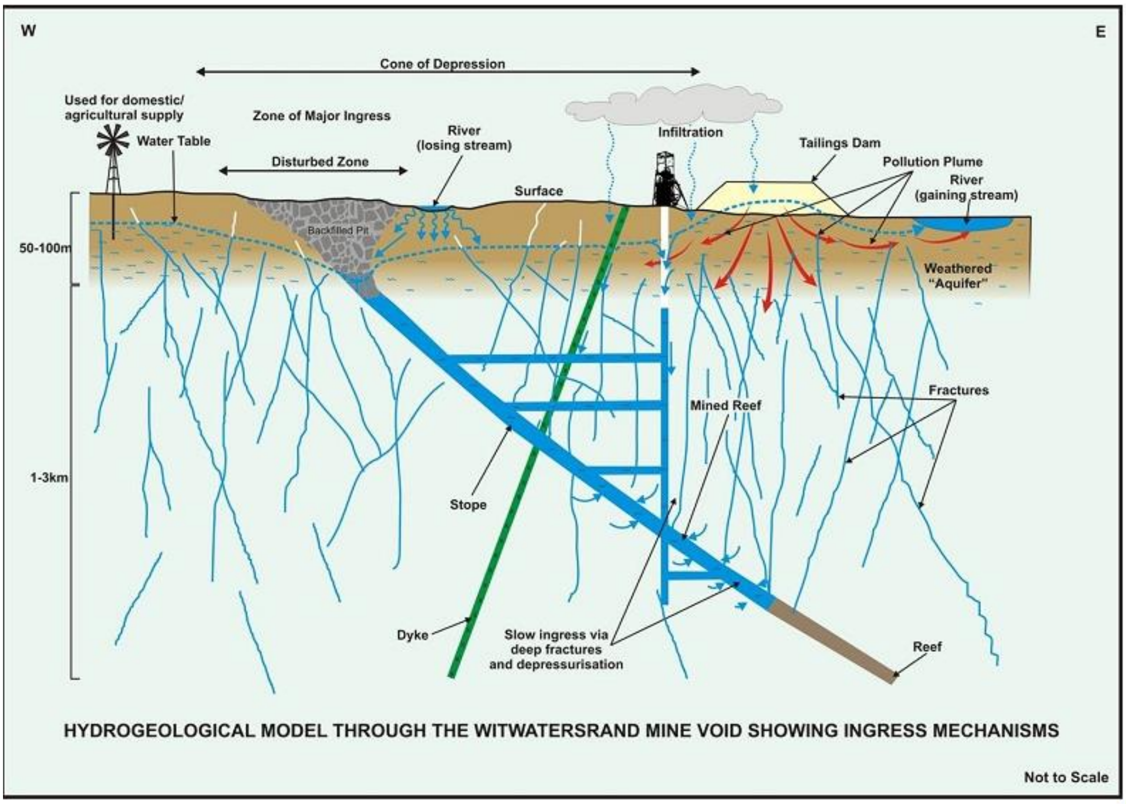

Figure 3: Water ingress into a deep-level mine[2]

When mining operations intersect groundwater, the groundwater needs to be removed or diverted from the mining operations to prevent flooding [7], [10]. However, groundwater can rarely be diverted; therefore, the only option is to remove it. However, the removal of groundwater increases the overall mining operations and utility costs [15]. In addition, the complexity of the dewatering system increases as more pipe networks and pumps are added to the system [28]. Therefore, more detailed planning is required to ensure that an existing system is sustainable for future

[2] Department of Water and Sanitation, "Feasibility study for a long-term solution to address the acid mine drainage associated with the east, central and west rand underground mining basins," Pretoria. [Online]. Available: https://www.dws.gov.za/iwrp/AMDFSLTS/default.aspx.

operations [29]. The detailed planning of dewatering systems should include the expected amount of groundwater, followed by the planned water usage of mining operations [8].

Numerous studies have focused on developing methodologies towards designing a dewatering system [7]–[9], [30], [31]. These methods mainly included three phases:

- Doing a hydrogeology study.
- Selecting a dewatering system.
- Doing a feasibility study.

A **hydrogeology study** is done by drilling boreholes next to the mining operation to test the quantity and depth of regional groundwater [9], [30], [31]. One method used for quantifying regional groundwater is to determine the expected inflow rate. An example of such a method is to measure the recovery rate of a borehole. Chironga described how a borehole recovery rate test was done on an opencast mine [30]. In this method, a submersible pump was used to remove water from a borehole. First, the running time and water flow of the pump were measured alongside the water level. Thereafter, the values were used to calculate the quantity of water. Lastly, the time was measured for the groundwater to recover to a certain level to determine the recovery or seepage rate. The data collected was used to estimate the expected seepage rate of the groundwater into that specified region. From the data, a simulation model was created to estimate the regional groundwater [30].

A **dewatering system** design is based not only on the hydrogeology study, but also on the water usage for the planned production. Numerous studies have used the concept of benchmarking the water usage of a mine towards its production [21], [32]. Combining the two values produces an estimated peak water quantity that needs to be removed. Therefore, the design criteria of a dewatering system should include pumps that are specified according to the amount of groundwater and the expected peak production quantities over the life of mine (LOM) [10].

During the **feasibility study** the designed dewatering system capital and working cost must be included. A feasibility study evaluates the amount of capital needed to build and operate dewatering infrastructure and the expected energy consumption thereof. If the dewatering system's infrastructure and running cost exceed the mine's production income, the mine has to consider alternative methods for diverting or removing the groundwater to remain feasible [7].

1.3 Existing dewatering system design methods

The background section introduced the basic concept of a water reticulation system on a mine. This section will provide a more detailed understanding of how previous studies have designed and applied simulation models. This section aims to identify a research gap in the use of a simulation model on dewatering systems to assist with future dewatering planning on a mine.

1.3.1 Dewatering simulations

Several studies have used integrated simulation models that were verified against existing systems to recommend and implement water reticulation changes on the dewatering systems. These studies have also proven the accuracy of simulation software for modelling and replicating water reticulation systems. The accuracy of these simulation models was achieved by calibrating and verifying the simulation models against existing systems [10], [21], [33].

A study done by Stols, Groenewald and Van Rensburg used a simulation model to quantify the energy usage of the dewatering system [33]. The capability of such a simulation was used by Van Niekerk to improve the existing pumping schedule of a deep-level gold mine [24].

Simulation models of mines have further been used to ensure that energy initiatives reduce energy costs without affecting the mining operations. Some of these initiatives include load shifting and peak clipping [34]. The existing infrastructure and capacity need to be verified before load shifting can be implemented on a mine. Load shifting consists of only pumping water out of the mine during off-peak hours. Thus, reducing up to three times the energy costs by reducing the power usage in the peak demand hours [33].

A study successfully reconfigured a mine’s dewatering infrastructure by using a simulation model. The focus of the study was on automating the dewatering system of a mine and implementing load shifting. Load shifting was implemented on a mine after simulation models and water balances were used to prove that it would be feasible [10].

A similar study developed breakdown procedures to be implemented on a mine dewatering system. The outcome of this study was to develop mitigations to implement on an existing dewatering system to sustain energy-saving initiatives during a breakdown. These breakdown procedures included equipment malfunction and power outages. In case of equipment malfunctions, for instance when a pump fails, several pumps are usually on standby and are used immediately to prevent mine flooding. When these breakdowns occur, the primary concern is to prevent the mine from flooding, in which case energy-saving opportunities are disregarded [25].

1.3.2 Dewatering planning

Baselines and benchmark models are commonly known for their ability to predict upcoming months' utility consumption and costs [10], [15], [21]. These models are used to estimate the required infrastructure to prevent a mine from flooding. Studies on opencast mines have developed dewatering design methods for monitoring the groundwater flow rate into a mine. These models apply the same principle to estimate the expected groundwater alongside water used for mining operations such as deep-level mines. These dewatering estimation models are used as the design criteria for a dewatering system on the mine [8], [9].

Studies on opencast mines have developed hydrogeological regional groundwater models. These models estimate the amount of water that seeps into the mine over the expected LOM. The engineering division of a mine uses these models to forecast the required dewatering infrastructure over the LOM [8], [9], [35], [36].

A similar study has been done on the development phase of a new deep-level mine. The study used a hydrogeological groundwater model to develop a prediction model for the dewatering design requirements. The groundwater prediction model developed was used as the design criteria for the mine for the next 15 years [31].

1.3.3 State-of-the-art evaluation

Combining the hydrogeological model approach used in open-pit mining alongside the simulation modelling on deep-level mines will result in more sustainable planning over the expected LOM. The accuracy of using simulation models has been verified in numerous studies. Integrating the hydrogeological model results with a dewatering simulation model will result in comprehensive future LOM planning on the dewatering system. These models will ensure that the mine can expand its existing dewatering system to include redundancies and energy initiatives on the system being designed.

Several studies related to dewatering system design were reviewed. This section will focus on how these studies approached the dewatering design. The aim of this section is to identify similarities and shortcomings between these studies. First, a short overview of each study will be provided, followed by the study's outcomes.

Study 1: Reconfiguring deep-level mine dewatering systems for increased water volumes [10]

The study objective focused on reconfiguring and improving a deep-level mine's existing water reticulation system for excess water. Simulation software, namely REMS, was used to model the existing dewatering system. The study used a simulation-based method to recommend reconfigurations to the existing dewatering system. As a result, the recommended reconfigurations made from the simulation model were installed, and the efficiency of the existing system was improved. Thus, the study successfully used a simulation model to recommend and reconfigure a dewatering system of a mine. The study, however, did not consider the LOM planning requirements of the dewatering system.

Study 2: A strategic approach to the design and implementation of an effective mine dewatering system [9]

The study was done on an opencast iron mine. The objective was to design an effective dewatering system for any surface mining operation. The objectives for the design included: reducing slope instability, reducing the effect of groundwater on mining operations, and reducing the operational cost. A hydrogeological numerical analysis model was used to estimate the groundwater quantities and depths. From this model, the required dewatering infrastructure was specified and installed to remove the groundwater. In addition, a well was created to remove the groundwater before it seeped into the mining operations, thereby reducing the cost and environmental impact of contaminated groundwater. The study, however, did not use a dewatering system simulation or consider the LOM planning requirements of the dewatering system.

Study 3: Water and energy assessment for dewatering in opencast mines [8]

The study identified the need to estimate the water removal rate of an opencast mine to ensure that the dewatering system design was energy conservative and practical. The objective of this study was to forecast the energy consumption and water removal rate required to dewater the mine as the operations expanded. Thus, determining the dewatering requirements over the expected LOM. The study used an analytic model developed from historical data to estimate the expected water removal rate. As the mine expanded, more groundwater and rainwater collected in the opencast mine. The excavation plans were used to estimate the water removal rate per tonne of material removed from the area. The model included the regional rainfall and ground-water ingress into the mine. As a result, the model was able to forecast the expected water removal rate of the dewatering system. The dewatering pumps were specified and a strategy was developed to increase the pumping capacity as the mine expanded. This study did not use an integrated simulation model for LOM planning.

Study 4: Predicting underground mine dewatering requirements: A case study of a precious metal mine in a subtropical environment [31]

This study aimed to develop a groundwater model to predict the dewatering requirements of an underground mine. The study used several geological surveys to develop a groundwater estimation model. From the model, the expected groundwater removal rate was determined over 15 years. The model identified several key aspects of the regional groundwater aquifers. The model was able to show that the groundwater would reduce gradually over the first five years of operations. After five years, the water ingress into the mine would settle and the water stored by the underground aquifers would be drained. The model would be used to design the dewatering system as the mine deepened. The case study mine was still in the development phase when the model was created.

Study 5: Underground mine dewatering system below +500 MASL South Ciurug [35]

During the development of a decline ramp on a deep-level mine, the mining operations intersected several groundwater sources. Unfortunately, the seepage rate of the groundwater caused the working areas to flood. After this incident, a study was done to assist with mitigation strategies to prevent future flooding. The study used hydrogeological surveys to estimate the amount of groundwater that could be intersected. From the estimations, a new dewatering system was specified to remove the groundwater during the developments. The study highlighted the importance of using a groundwater estimation model to ensure that the correct dewatering infrastructure would be in place as the mine expanded. In addition, the study recommended that a more continuous design process on the dewatering system would be beneficial to reduce the risk of flooding. The study did not use an integrated dewatering system simulation.

Study 6: Quantifying the effects of system constraint improvements on the electricity cost of dewatering pumps [33]

The study aimed to reduce constraints on a dewatering system by using an integrated simulation model. The constraints investigated on the dewatering system were low pump efficiencies, no redundancy on the installed pumps, and limited dewatering storage capacities. The study used a simulation model to address these constraints. The results from the simulation concluded that an estimated R21 million could be saved per annum if the identified constraints were resolved. Thus, the integrated simulation model was used effectively to quantify possible energy reductions alongside configuration changes on the dewatering system that would yield R21 million per annum. The study further used the simulation model to implement load shifting on the dewatering system itself. The simulation model ensured that the dewatering infrastructure would withstand the conditions of load shifting, and tests were done over three months. As a result, the implementation of load shifting reduced the energy cost by more than R5 million per annum. The study did not consider using the developed simulation model for LOM planning.

Study 7: Cost savings on mine dewatering pumps by reducing preparation- and comeback loads [37]

The objective of this study was to benchmark the electricity consumption of several deep-level mines in South Africa. The study further aimed to introduce the concept of energy-intensive mining operations and to consider the importance of energy-saving techniques. These benchmarks were used to compare the electricity usage of the various mining operations. The study further identified several influencing factors on all these benchmarks. These benchmarks form a comparison criterion for evaluating the mine's efficiency and identifying energy-intensive operations. One of the benchmarks compared the energy usage of a deep-level mine with the groundwater removed. This comparison revealed that the energy consumption increased as the volume of groundwater increased. Figure 10 in Section 2.2.4 will discuss the concept in more detail. The study did not consider using the benchmarks for LOM planning.

Study 8: Improved control processes to sustain electricity cost savings on a mine water reticulation system [25]

The study identified the need for developing a control strategy when critical components fail during peak-hour Eskom tariffs. During critical component failures on a mine, energy initiatives such as load shifting are disregarded to ensure that the mine does not flood. The study developed a mitigation strategy to be implemented should a critical component fail on the water reticulation system during these peak hours. A verified simulation model of the entire water reticulation system was used to evaluate each control strategy developed. Some of the mitigation strategies were implemented during a critical component failure on a mine. The results indicated R3.8 million of savings for the annum without posing additional risk to the mining operations. The study did not include LOM planning on the dewatering system.

Study 9: Improving the underground pump scheduling of a dewatering system for a hydropowered gold mine [24]

The study aimed to apply demand-side management initiatives to a dewatering system of a mine to improve the effectiveness thereof. Therefore, a simulation model of the dewatering system was developed. The simulation model was used to evaluate the existing dewatering system's capacity. In addition, the simulation model was used to evaluate whether the dewatering system would withstand the conditions of load shifting. The simulation provided supportive evidence that implementing load shifting would be possible. The estimated saving that was achieved per year by implementing load shifting was R940 000. The study did not consider applying the method to LOM planning on the dewatering system.

Study 10: Reconfiguring mine water reticulation systems for cost savings [21]

The study focused on developing a method for evaluating the cost and energy savings on the dewatering system when the water reticulation system was reconfigured. The reconfiguration included replacing cooling cars with BACs. The study used a verified integrated simulation model to evaluate the energy consumption of the dewatering system before and after the reconfiguration was implemented. The estimated energy and cost savings of implementing this reconfiguration on the mine were R31.8 million per annum. The study did not consider applying the model over the LOM.

1.3.4 State-of-the-art summary

Several keywords were identified from the studies discussed in Section 1.3.3. These keywords were used to summarise and evaluate the studies to identify a research gap for this study. Below are the keywords identified with a short description of the focus points of each:

- **Simulated:** Did previous studies consider using simulation software to model an existing system? Simulations are essential for identifying how previous studies built simulations and what software would be adequate.

- **Integrated:** If the study used a simulation software package, can it solve multiple integrated equipment? This criterion will assist in selecting a simulation software package and the capability of the simulation.

- **Verified:** Did the study verify its simulation model on an existing system? Verification includes comparing the model's results with the existing systems' input and output values. The verification methods from previous studies will be used as a guideline to form a verification method for this study.

- **Redundancy planning:** Did the study focus on the design requirements or redundancy of a system? The criteria will be used to identify what possible redundancy constraints there are on existing dewatering systems.

- **Energy-saving planning:** Did the study focus on reducing the existing system's energy cost by implementing energy-saving techniques? Identifying energy-saving techniques on dewatering systems and including the configuration requirements in the design will contribute to energy savings from day one.

- **LOM planning:** Did previous studies include planning systems or reconfigurations to extend over the LOM? This includes whether studies have developed a method for analysing the infrastructure requirements in upcoming years. These methods used will be adapted and applied to plan for future infrastructure requirements.

Table 1 summarises the evaluation criteria. The legend used in the table consists of two colour schemes. Green represents that the previous studies included the criteria mentioned above. Red indicates that the criteria were excluded in previous studies. The conclusion drawn from Table 1 is that previous studies have either used an integrated simulation model to reconfigure a dewatering system or to plan the requirements of a dewatering system for future expansions. However, these studies have not considered combining a verified integrated simulation model to include planning over the LOM to reduce energy consumption and ensure that the system adheres to the required redundancy capacity. Thus, creating a research gap for a study considering the combination of all these criteria.

Table 1: State-of-the-art matrix

Source	Dewatering simulations			Dewatering planning			Comments
	Simulated	Integrated	Verified	Redundancy	Energy savings	LOM	
[10]							Reconfigured a deep-level mine's water reticulation system by using simulations.
[9]							Developed an estimation model to determine the required pumping infrastructure.
[8]							Developed a planning model for opencast shafts dewatering system with expanding operations.
[31]							Developed a prediction model to estimate the groundwater volume.
[35]							Recommended a more detailed approach to design dewatering systems on an opencast mine.
[33]							Using simulation software to quantify energy savings.
[37]							Recommended that dewatering systems should be designed with increased capacities.
[25]							Method to achieve energy savings on a mine while a breakdown occurred.
[24]							Improving the pumping schedule of a Mine dewatering system.
[21]							Evaluated the accuracy of cost savings on a mine's water reticulation system using simulation models.

1.4 Need for the study

Deep-level mines have complex dewatering systems that are subjected to constant changes. These changes include the increase of water usage underground due to mining expansions, an increase in groundwater, and the integration of shafts to reduce costs. Therefore, baselines and benchmarking methods have been developed to estimate the water usage towards the tonnes of ore mined.

Numerous studies have demonstrated the effectiveness of using an integrated simulation for modelling an existing system. Furthermore, the accuracy of using these simulation models has been verified by comparing the simulations with the existing systems' inputs and outputs [10], [19], [21], [24], [25].

Several studies have developed methods for evaluating the dewatering capacity requirements of existing systems, such as evaluating the redundancy capacity of mines. These studies included developing an expected water demand that had to be removed for the coming months and years as operations expanded. These estimation models could be used to plan the required infrastructure over the expected LOM with the required redundancy [8], [21].

The literature review results summarised in Table 1 introduced a research gap to combine all the criteria. Therefore, the need for the study identified is the following: To develop an integrated simulation-based method to assist with planning and feasibility evaluations of proposed dewatering system reconfigurations.

1.5 Objectives

The mining industry seldomly needs to make ad hoc decisions [38]. These decisions do not always consider the future consequences of the modifications [19]. However, these decisions still need to be made to maintain production or prevent the mine from flooding [38]. These ad hoc decisions could lead to additional capital expenditures to mitigate the effects thereof [19]. Using a simulation-based method will assist with future planning to ensure that a project is feasible before it commences by taking the LOM into consideration.

The objective of the study is to develop a method to assist planning in:

- Evaluating an existing mine's dewatering system capabilities on the simulation model.
- Using the simulation model to evaluate the newly proposed reconfiguration on the system.
- Evaluating the feasibility of the newly proposed reconfigurations.

1.6 Overview of study

Chapter 1: The chapter introduced the background knowledge of the dissertation, followed by the literature review and objectives of the study.

Chapter 2: The chapter will discuss the development of the simulation-based method by using various techniques and methods adapted from literature. The method will be developed for dewatering systems of deep-level mines.

Chapter 3: The chapter will verify and validate the method developed in Chapter 2 using a case study.

Chapter 4: The chapter will summarise the dissertation's findings, followed by recommendations for future studies to be done.

Chapter 2: Development of an integrated simulation method

Underground pump chamber[3]

The chapter will discuss the development of the simulation-based method for mine dewatering planning followed by the verification process.

[3] Photo taken by author.

CHAPTER 2: DEVELOPMENT OF AN INTEGRATED SIMULATION METHOD

2.1 Preamble

This chapter will focus on developing an integrated simulation-based method to assist in deep-level mine dewatering planning. For the development of the method, several studies were considered as a guideline to form this methodology. Figure 4 illustrates the process flow diagram that was adapted from several studies [10], [19], [21], [25], [34], [39].

The purpose of this methodology is to formulate the processes to develop an integrated simulation-based method to assist in mine dewatering planning. In addition, the method includes a verification process adapted from several studies [19], [25], [33].

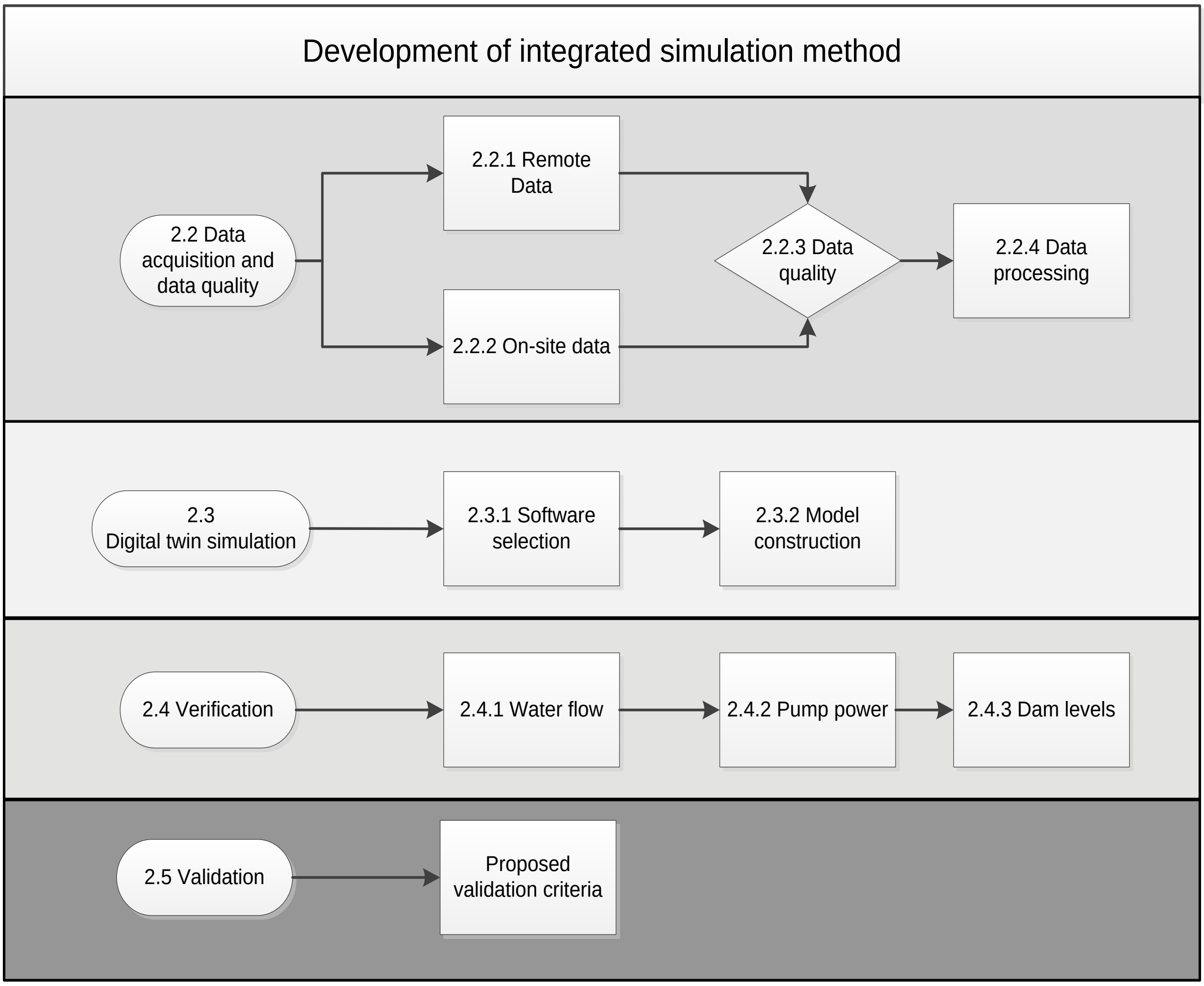

Figure 4: Methodology process flow chart

2.2 Data acquisition and data quality

Before the data-gathering process can begin, it is crucial to understand the mine's dewatering system. Understanding the water reticulation system of the whole mine will assist with data processing and interpretation [10].

Methods for gathering data on a site-specific dewatering system are divided into two methods. The first method consists of remote viewing of the mine's data and infrastructure information. The first method is usually done by using a supervisory control and data acquisition (SCADA) system and collaborating with mine personnel to retrieve the information of the installed infrastructure [40]. The second method consists of doing site visits to physically observe the different pumping levels to better understand the installed dewatering system and gather additional information if necessary [10], [41].

2.2.1 Remote data

The first data collection method can be done remotely without being on the mine physically. However, arranging on-site meetings with site personnel tends to ease the information-gathering process and mitigate the risk of receiving or interpreting data incorrectly. The information that needs to be gathered includes:

- SCADA access.
- Tag names of the instruments.
- Map of the underground infrastructure.
- Dewatering infrastructure sizes and specifications.

SCADA access

The SCADA system consists of multiple programmable logic controllers (PLCs) that allow the end user to monitor the existing running parameters and switch equipment on or off [42]. Thus, enabling the mine to operate the equipment via a centralised system [34]. The centralised system is controlled in a control room. An operator can switch the dewatering pumps on or off remotely with only a mouse button click. The pumps can further be switched on or off automatically by using a pumping schedule [11].

The SCADA system logs the data on a database (historian) if present. Each control, sensor or flow meter is connected to a PLC system with an assigned address. The assigned address is linked to a tag that stores the timestamped data from the PLC on the historian. The historical data is viewed by using the tag name as the reference when accessing the historian. The data is used to view the performance of the equipment or to create baselines and benchmarks for predicting trends of upcoming months to come [10], [21], [40].

A third-party control software can be used in parallel with the SCADA system to make decisions based on real-time data [40]. An example of a third-party control software is the Real-Time Energy Management System (REMS). The software uses real-time data to control the dam levels by switching pumps on or off to maintain the set-point parameters of the dam [10], [21].

Tag names of the instruments

The tag names can be simplified as a data log containing all the selected instruments' historical data [21]. These instruments measure the following parameters: water flow, power, current, temperature, and dam levels. The instruments are connected to a PLC system that stores the data under the corresponding tag name. The SCADA system must be accessed to retrieve the tag names of all the instruments on the dewatering system. The following instrumentation's data needs to be retrieved [10]:

- Water flows from each level to the next.
- Power usage of the pumps.
- Hot dam levels.
- The water flow of the supply side (mass balance).

The list of tag names is used to retrieve the raw data from the historian. The data can be accessed by either extracting one tag individually or as a batch to extract all the data at once. It is essential to know the format and the units of the data extracted to avoid misinterpreting the data. The historian only logs the data values and not the units of the logged values. For example, both flow and dam level data display a number value with several decimals. Knowing the units of the data logged for each tag allows the end user to distinguish between the different tags.

Underground mine layouts

The mine has tunnel layouts of all the developed sections. Acquiring these layouts assists in understanding the system and configurations of the mine [43]. The layouts are used to build the simulation model. The use thereof will be discussed in detail in Section 2.3.2. The mine layouts further contain the physical coordinates of each tunnel, which allow the end user to calculate the vertical head required by each pump. The head of the pump is defined as the maximum height or distance a pump can transfer a fluid [44].

Alongside the underground mine layouts, actual and planned production data is necessary. The production data is used to measure the efficiency of the mine during a specified period. Several studies have used production data to forecast expected utility usages by using baselines and benchmarks. The actual production data is used to calculate these baselines and benchmarks. Thereafter, the values are forecasted onto the planned production data to estimate the expected utility usages for the selected period [15], [21], [41].

Dewatering infrastructure

The mining personnel will be able to provide adequate information on the installed dewatering system. Several studies have also built a simulation model of a dewatering system. The required information needed from the mining personnel is [10], [21], [33]:

- Number of installed pumps.
- Design specifications of the pumps.
- Size and number of discharge columns.
- Size and number of suction columns.
- Valve sizes in the system.
- Pipe network layout.
- The capacity of the hot dams.
- The capacity of the settlers.
- Hot water and groundwater flow into the hot dams.

Most of the mines have a pump station drawing that contain all the relevant information, an example of a pump layout is shown Figure 5. All the points mentioned above are required to ensure an accurate simulation model. Furthermore, any additional information on the dewatering system is beneficial to the success and accuracy of the model. This information includes insight provided by mine personnel regarding the maximum pumping capacity for each pumping level and problems of the existing system.

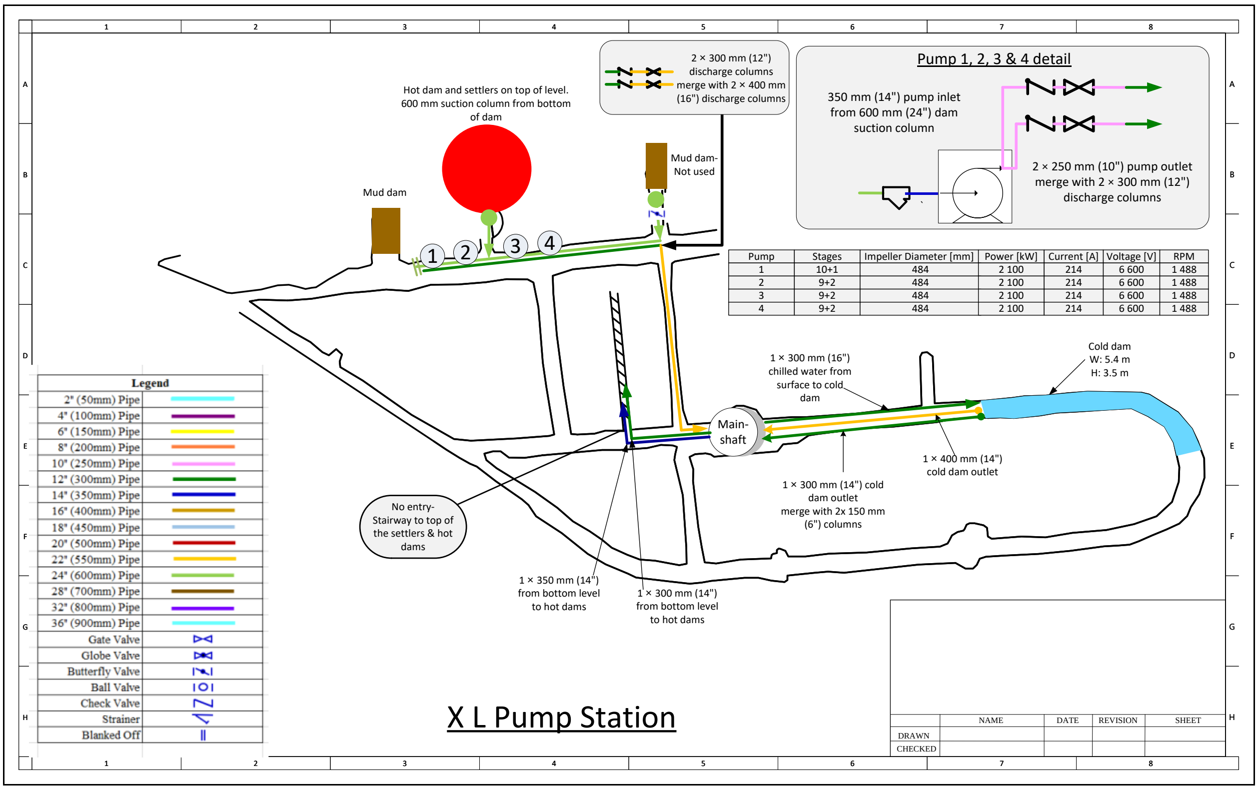

Figure 5: Example of a pipe layout of a pump station on the mine

2.2.2 On-site data

Not all mines are equipped with a system such as SCADA. Therefore, a lack of historical data is a limitation to determining baselines and benchmarks of the mining operations accurately. The only way data can be collected in such a case is by using portable measuring equipment or by installing fixed measuring equipment [10], [43]. Site audits are also used to understand the system better and identify possible constraints [10]. The site audits are used for:

- Spot checks.
- Dewatering layouts.

Spot checks

Most mines do have a SCADA-like system in place. When such a system is not present, portable instrumentation has to be used to sample the data required [10]. Instrumentation is subjected to harsh conditions underground, which can lead to sensors breaking or measuring equipment getting vandalised. Site audits can assist in identifying faulty installed equipment. The audits also verify whether the measuring instruments or sensors transmit the correct values [45]. Thus, site audits assist with the verification process [23].

Due to the vast size of a mine dewatering system, it is not possible to verify and check each installed PLC instrument. However, doing spot checks on several of these instruments provides adequate verification of the data [46]. The type of instrumentation that should be verified is water flow meters on the water reticulation system of the mine [46]. A clamp-on ultrasonic flow sensor is generally used in these types of verification processes [10], [43], [47]. Figure 6 illustrates a clamp-on ultrasonic flow sensor used to verify the flow on a dewatering column.

Figure 6: Clamp-on ultrasonic flow sensor[4]

Dewatering layouts

As previously mentioned, visiting the site assists with gaining an overall understanding and interpretation of the data [10], [41]. Some mines do not have pipe layouts of their infrastructure. By doing a walk-through audit, a detailed pipe layout of the dewatering system can be created. Figure 5 illustrates a detailed pipe layout created after a walk-through audit. All the relevant dewatering infrastructure is listed with their corresponding locations on the layout. The information includes the size of the pipes, valves, and pump specifications. The layouts will be used to build the simulation model in Section 2.3.2. In addition, the layouts assist with providing feedback to the client on proposed reconfigurations.

[4] Photo taken by author with permission.

2.2.3 Data quality

The raw data needs to be processed into the desired format. Prior to processing and being used in a simulation, the data needs to be evaluated to ensure that it is error-free. Although there are numerous approaches for evaluating data quality, the data evaluation method of Booysen [48] was used. Figure 7 demonstrates Booysen's proposed methodology for evaluating a data set [48].

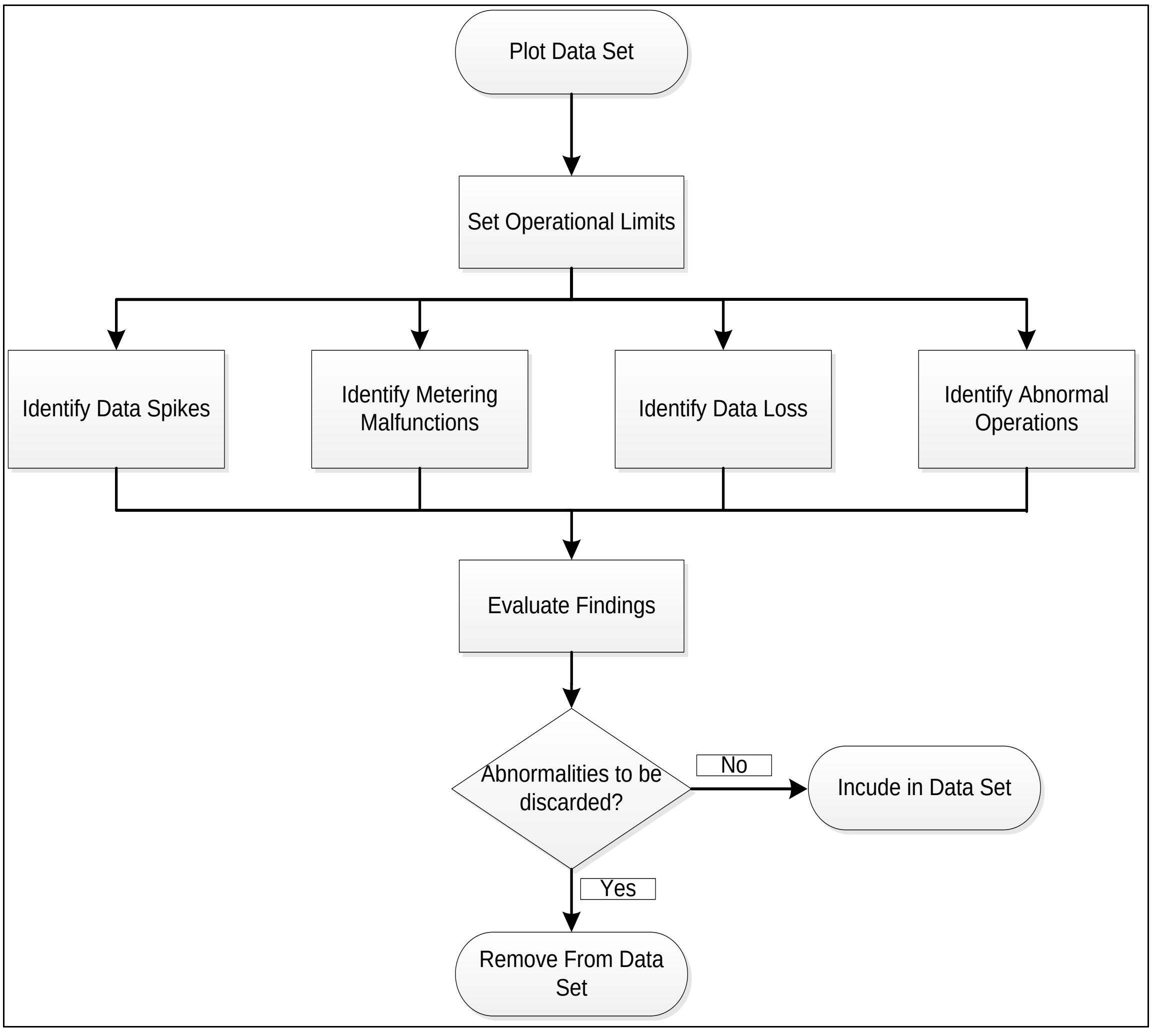

Figure 7: Data quality control overview (adapted from Booysen [48])

Firstly, the raw data is extracted from the SCADA's historian and plotted on a spreadsheet. Microsoft Excel is a popular software used to plot data sets on spreadsheets [41], [48]. Figure 8 illustrates the method developed by Booysen applied to a set of data [48]. After the data has been plotted, the set points of the data set must be defined.

Set point refers to the operating value of the selected measuring instrumentation. For example, on the dewatering system, the measured water flow on the delivery side of the pump cannot be negative because one-way valves are usually installed on the outlet side of the pump to prevent backflow [21]. In this case, the minimum set point is zero, and the maximum set point is the combined flow of all the pumps connected to the selected column.

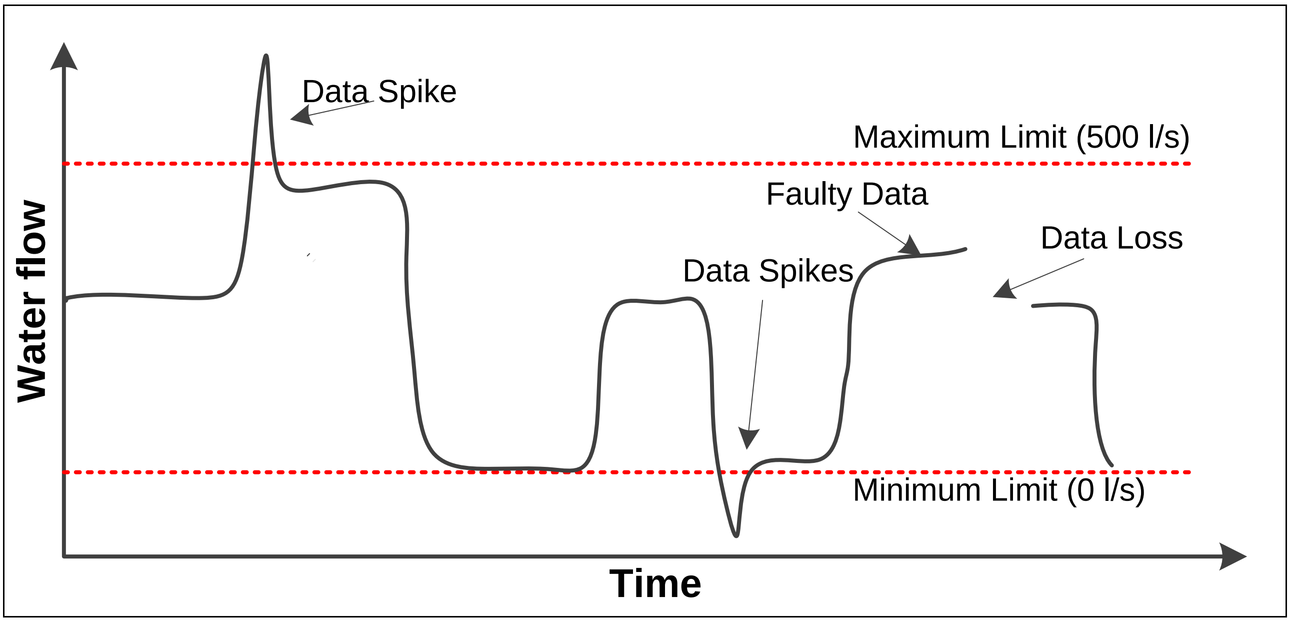

Figure 8: Data quality process (adapted from [48])

Any values outside these limits are disregarded from the data set and referred to as data spikes [48]. Instrumentation malfunction often occurs on mines, resulting in data loss or inaccurate measurements being logged on the historian [46]. When data loss occurs, these values are omitted from the historian. Thus, the data is displayed as a blank cell in the retrieved data from the historian. Any flow meter malfunction, faulty setup or calibration error will cause it to transmit incorrect values. For example, knowing the possible flow rate of a pump, any value exceeding the specified flow of the pump indicates incorrect data.

Irregular mining activities could also add to abnormal operations and should be neglected if the activity is not considered essential to future design conditions. After the irregular data has been removed, the data quality process is complete [48].

2.2.4 Data processing

All irregular data points were removed during the quality assessment process above. During data processing as described below, the performance of the dewatering pumps will be evaluated. Baselines and benchmarks will also be developed from the data to assist with the planning and forecasting models.

Baseline methods

A baseline is a comparison model used to define a measured system's demand over a specified period [49]. Figure 9 demonstrates an example of a baseline developed on the chilled water supply system of a mine. The red line represents the average monthly chilled water measured on a mine over a period of 24 hours. The blue line represents the measured flow rate for one day. The applications of a baseline can be used in various ways. First, the baseline curve can be used to monitor system changes on a day-to-day basis. The variance between the two curves is due to either production increases or wastages caused by pipe leaks and misuse on that specific day [41].

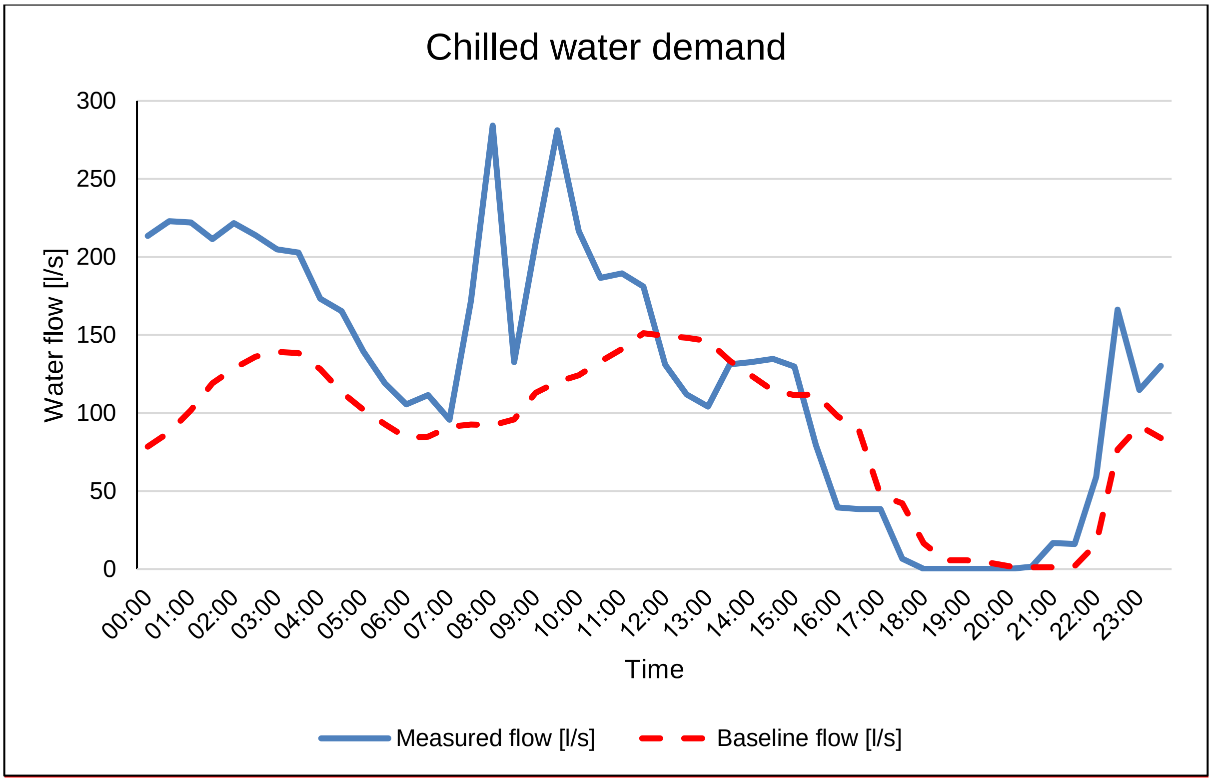

Figure 9: Baseline water flow over 24 hours of a mine

A baseline model is further used to estimate the upcoming months' water usage. The baseline is adjusted with correction factors to compensate for changes in the upcoming months. An example of these changes includes seasonal changes that can affect the power usage of a mine. In the winter months, the total power consumption of the surface plants decrease with approximately 4 megawatt (MW) compared with the summer months. Cooler ambient temperatures contribute to the energy reduction [15].

The same principle is applied to the dewatering system of a deep-level mine. A baseline is created by using the flow rate of the water supplied to mining operations. The amount of groundwater is estimated by using the water mass balance of a system. The mass balance is defined as: the total water inflow of a mine is equal to the amount that needs to be removed from the mine [50]. Equation 1 represents the mass balance formula. The amount of water that is sent down the shaft for mining operations is a known variable. The amount of water removed from the shaft is also a known variable. The difference between these two values results in the groundwater volume flowing into the mine.

$$Water_{in} + Groundwater = Water_{out} \qquad \text{Equation 1}$$

A baseline model is mainly created from historical data. Therefore, it is a valuable comparison model for planning and monitoring the effect of operational parameters. These comparison models are known as benchmarking values, which are used to compare the parameters of the existing system with the system deliverables. These deliverables are usually tonnes of ore produced per kilolitre water used [15], [32], [50].

Benchmarking

Combining the demand-side baseline with production produces an estimate of the demand required per production unit or the demand used per production unit. Benchmarking is the term used when these two values are combined. The concept is applied on the dewatering side by comparing the energy usage with the mine's fissure water to be removed. The fissure water referred to is the same as groundwater. For consistency, fissure water will be referred to as groundwater. An example of such a benchmark can be seen in Figure 10. The energy consumption is expressed as a function of the fissure water that needs to be removed from the mine [15].

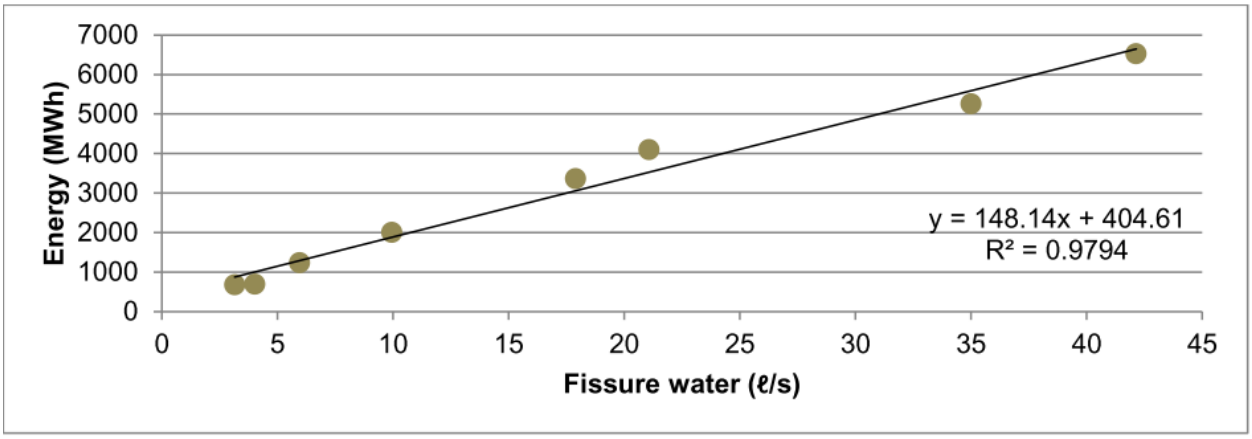

Figure 10: Benchmark of energy consumption per litre fissure water removed [15]

The benchmark model is applied to a selected mine to evaluate the installed dewatering capacity, which will withstand an increased chilled water demand in the coming months. In addition, the water usage ratio per tonne ore removed can be calculated from the previous month's data. Then, knowing the planned tonnes for the upcoming month, the water usage ratio benchmark can be multiplied by the planned tonnes to calculate the expected water to be removed from the mine. Thereafter, the estimated water usage is compared with the installed pumping capacity of the mine to determine if the dewatering capacity can withstand the increased water demand [21]. Numerous studies have shown the effectiveness of this method with reasonable accuracy for predicting water demands [15], [21].

2.3 Digital twin simulation

The purpose of this dissertation is to use a simulation-based method to assist in mine dewatering planning. A suitable software package will need to be selected to ensure that the software will execute the proposed planning. A simulation will be built in the selected software.

2.3.1 Software package selection

The use of a simulation software package forms part of the methodology of this dissertation. Several studies have been consulted regarding their software selection process to aid with choosing a suitable package for this study. The selection criteria adapted from these studies concluded that the requirements from the software are to be listed first [19], [51], [52]. These requirements include:

- **Digital twin:** Can the whole dewatering system of the selected mine be modelled accurately on the software? The criteria are essential to ensure the software package can produce an accurate digital replica of the mine to be used in the planning stage of the dissertation [25].

- **Dynamic analysis:** Does the software package allow for a dynamic evaluation of the simulation model? The dewatering system of a mine has multiple dynamic input values. The software needs to include a dynamic analysis of the system to allow for more in-depth analysis.

- **Scenario investigation:** Can the software be used to simulate various scenarios? The simulation software will be used to plan for future dewatering infrastructure on a mine. Multiple solutions and scenarios will need to be simulated.

There are numerous simulation software packages available for deep-level mine dewatering planning and modelling [19], [51], [52]. For this dissertation, only a few related software packages were considered and evaluated. Table 2 summarises the evaluation of various suitable software packages.

Table 2: Simulation software summary

No.	Software	Selection criterion		
		Digital twin	Dynamic analysis	Scenario investigations
1	EES[5]	N	N	Y
2	Excel[6]	N	N	Y
3	Flownex[7]	Y	Y	Y
4	AFT[8]	Y	Y	Y
5	PTB[9]	Y	Y	Y
6	EPANET[10]	Y	Y	Y

Four of the software packages were suitable to be used for the dissertation. In addition, the availability of the software was also considered. The software Process Toolbox (PTB) was selected as simulation software to model the dewatering system. PTB is an in-house software developed specifically for the mining environment. One of the advantages of using PTB is the three-dimensional (3D) modelling capability of the software. This allows the author to create a 3D replica of the mine dewatering system instead of a 2-D model used in several of the above software packages.

PTB is a transient thermal-hydraulic system simulation tool developed to analyse, design and optimise a system's performance. The liquid flow solver used in PTB consists of an incompressible quasi-steady-state semi-implicit solver [41], [52], [53]. Several studies have successfully used PTB to model a mine's dewatering system. Furthermore, the accuracy of the simulation software PTB has been evaluated in several studies [19], [25], [51], [52], [54], [55]. Thus, PTB is a suitable choice for this dissertation.

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[6] The Editors of Encyclopaedia Britannica, "Microsoft Excel," Britannica, 16 Jan. 2019. [Online]. Available at: https://www.britannica.com/technology/Microsoft-Excel.

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[10] EPA, "EPANET", 2022. [Online]. Available at: https://www.epa.gov/water-research/epanet"

2.3.2 Building the simulation model

After the appropriate software has been selected for the simulation model, the simulation model is constructed from the information gathered from the site. The building process of the simulation model is divided into three phases:

Phase 1: Skeleton view

The first phase consists of building the simulation model without adding all the detailed information. The purpose of this phase is to understand the dewatering system of the mine. The underground tunnels are visualised using a drawing exchange format (DXF) file provided by the mine. The DXF file contains the coordinates and depth of the mine. Thus, every line seen in Figure 11 represents an underground position with X, Y and Z coordinates.

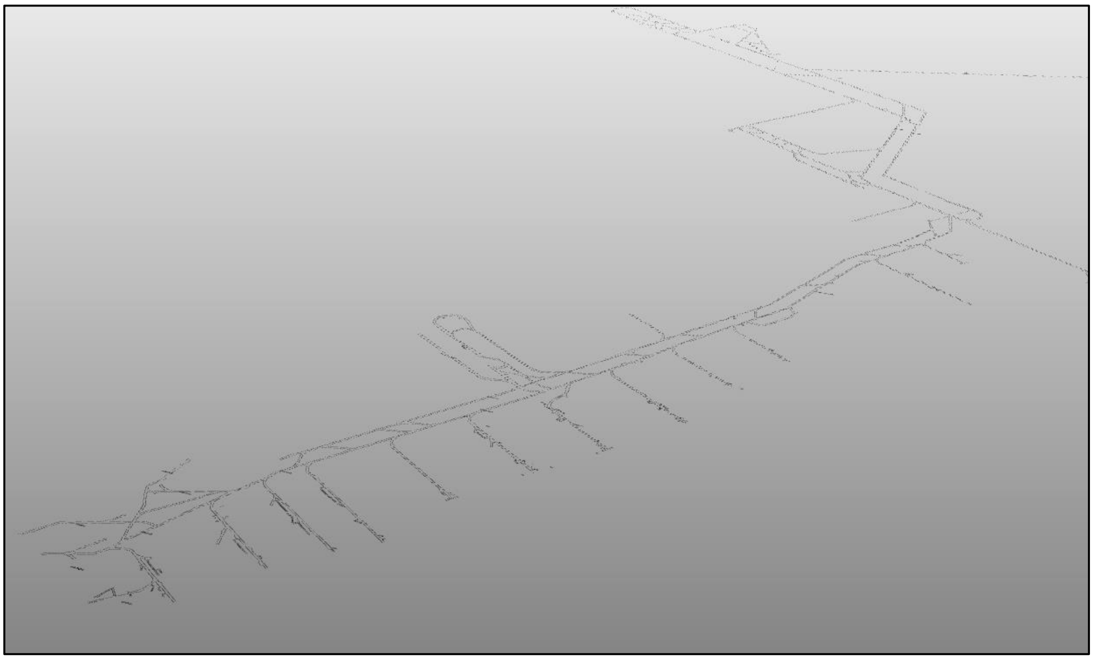


Figure 11: Imported DXF file in PTB

PTB uses a drag-and-drop feature that makes it easier to insert components into the simulation model. Dragging and dropping a component onto the DXF line updates the component's coordinates automatically to the exact coordinates from the DXF file. Figure 12 illustrates this concept.

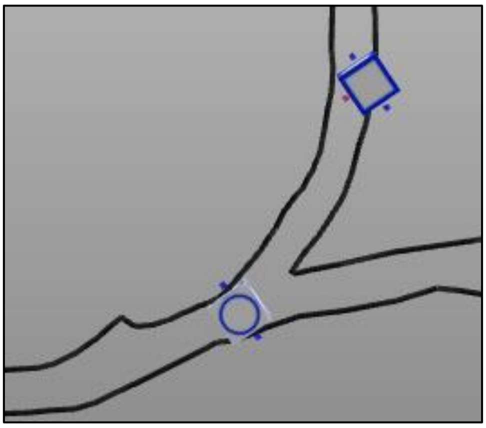


Figure 12: Water components on the DXF file

Figure 13 illustrates a completed pumping level for a mine with the positions of the pumps and dams as confirmed by site audits. A similar process is followed for all the pumping levels of the shaft.

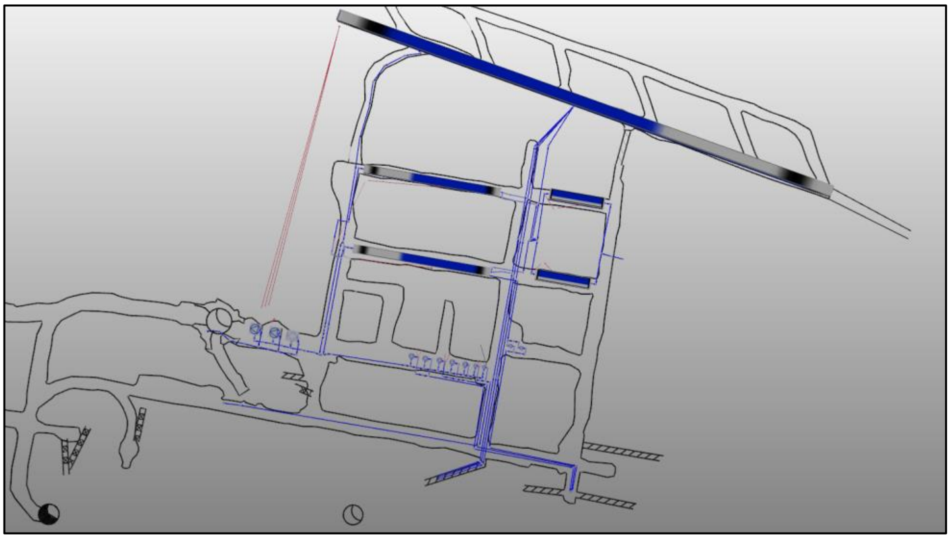


Figure 13: Dewatering infrastructure constructed in PTB

Thereafter, all the pumping levels are merged to form a skeleton layout of the shaft's dewatering infrastructure. The completed skeleton view of the shaft can be seen in Figure 14 and Figure 15. After all the pumping levels have been combined and connected, the next phase starts.

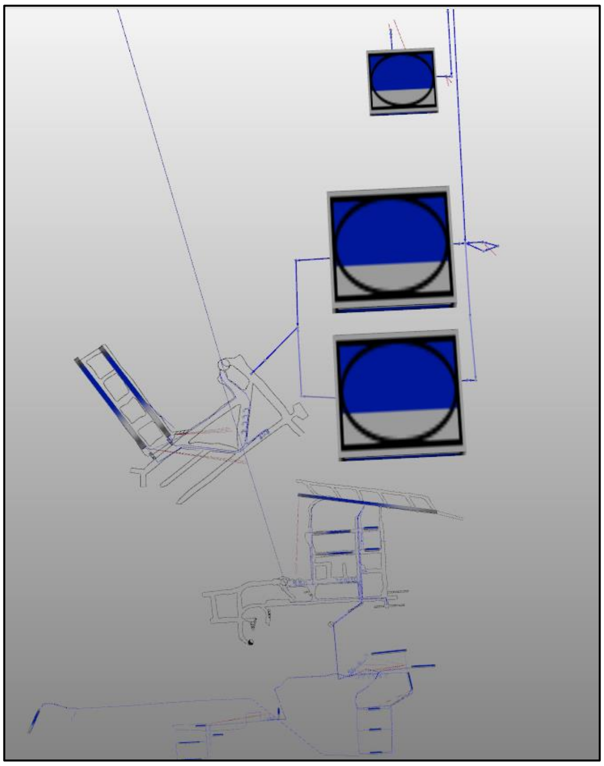


Figure 14: Skeleton view of the shaft

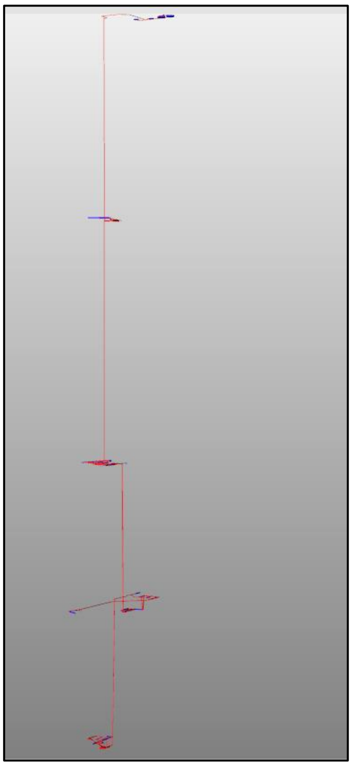


Figure 15: Side skeleton view of the shaft

Phase 2: Equipment specification

In the second phase, more details are added to the simulation. These details include the sizes and specifications of the following equipment: pipe sizes, dam sizes and pump specifications. PTB has a built-in library of standard pipe sizes that can be selected and imported into the simulation model. Figure 16 illustrates the library of standard pipe sizes.

Every pumping level was audited to obtain the pipe sizes, dam sizes and pump specifications. The dewatering layouts created from the audits, as demonstrated previously in Figure 5, were used to assist with the pipe sizes and the locations.

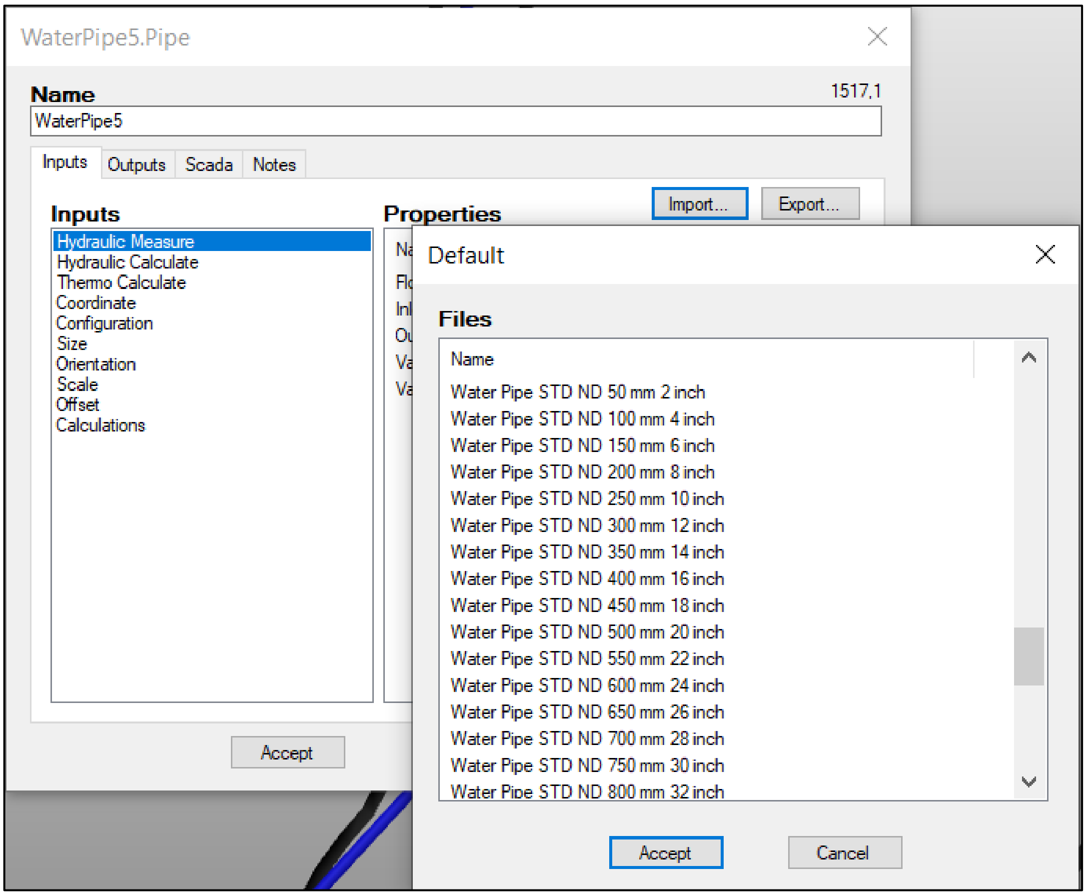


Figure 16: PTB built-in library of standard components

Phase 3: Calibration process

PTB has a built-in function that allows the user to specify the pump curve of the component. By using the pump specifications given by the mining personnel, this function can be used. Figure 17 indicates the inputs required for PTB to plot a pump curve. The required details are the following:

- Power of the pump motor.
- Pump flow.
- Pump motor efficiency.
- Pump efficiency.
- Pumping elevation.

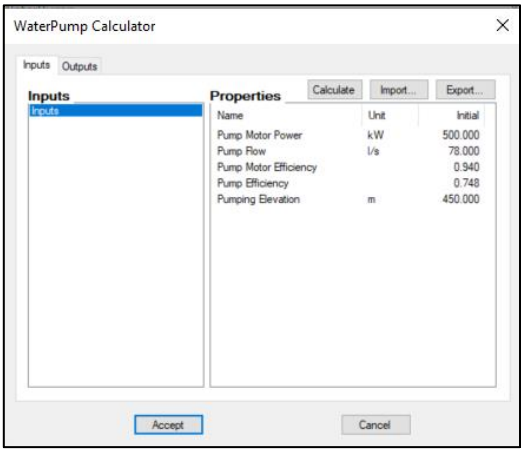


Figure 17: PTB water pump calculator

The only known values that remain the same for the pump during the calibration process are the power, water flow and pumping elevation. Therefore, the calibration process consists of adjusting the parameters of the pump until it matches the pump's measured flow on the mine. The values that are adjusted are mainly the efficiency parameters of the pump. A test bench is used to ease the calibration process. The test bench is a simplified version of the simulation model. Figure 18 illustrates an example of a test bench on PTB.

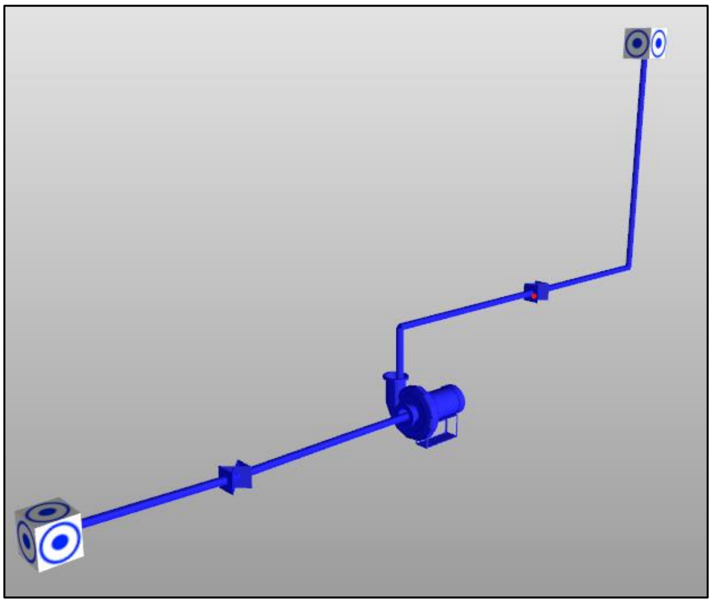


Figure 18: Example of a test bench on PTB

The water boundary conditions (simulation inputs) are adjusted to replicate the head that has to be overcome for the water to reach the end location. As demonstrated in Figure 19, the total head that the pump needs to overcome is 4 500 kPa. After importing the pump specifications into the water pump calculator, it automatically calculates and imports the pump curve into the simulation.

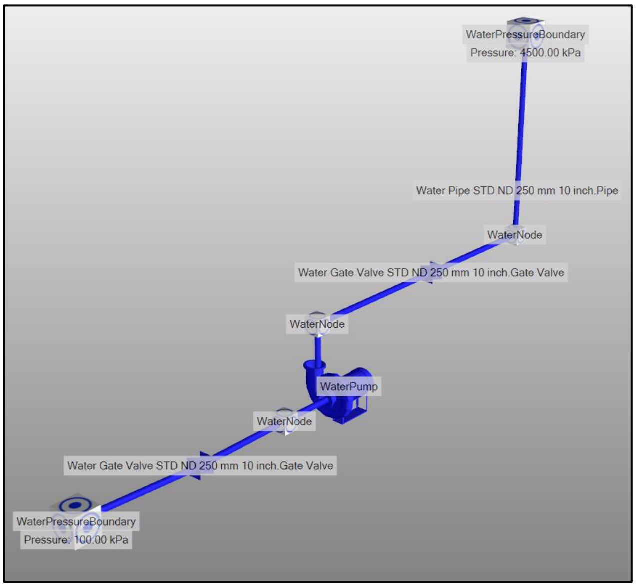


Figure 19: Test bench boundaries

The results of the calibrated pump are illustrated in Figure 20. An example of the pump curve plot feature can also be observed in the figure. Each component's calibration process is repeated until the difference between the simulated and measured values is less than 5%. Next, similar calibration steps are done on all the dewatering pumps. Finally, when all the dewatering pumps have been calibrated on a test bench, they are imported into the completed simulation.

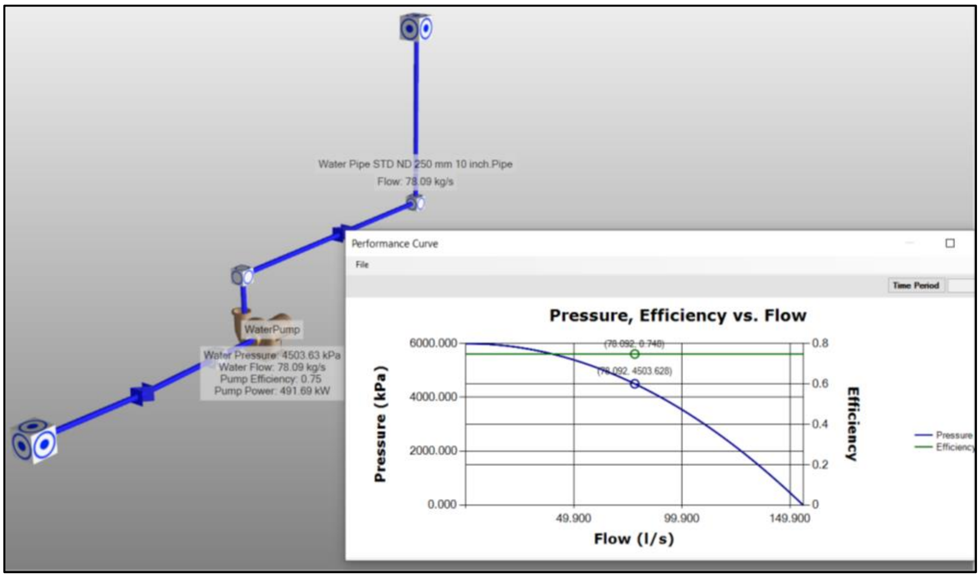


Figure 20: Test bench result

2.4 Verification

To ensure that the simulation model is accurate and able to solve the study's objective, it has to be verified. Verifying means providing adequate proof that the simulation model can replicate the existing system's data. Several studies have used simulation models in their research [10], [25], [28], [51]. The verification process of these studies was adapted to develop evaluation criteria for this study. The verification process will consist of the following:

- Comparing the model with the measured results.
- Calibrating the model within 5% error of the measured results.

Firstly, the verification process compares the results from the simulation with the values from the existing system. Comparing the two sets of results identifies a difference between the data sets. In accordance with prior studies, the difference between the simulated and measured results should not exceed 5% [21], [51]. Therefore, the simulation model is recalibrated until the difference between the data sets is less than 5%. After the verification process has been applied to the simulation model, it is considered verified.

In this study, the following three components in the simulation model will be verified against the measured results:

- Water flow.
- Pump power.
- Dam levels.

2.4.1 Water flow

A previous study verified the accuracy of their simulation model by comparing it with the water flow rate through a BAC [19]. Figure 21 illustrates the study's findings. The difference between the simulation and measured value was less than the required 5% [19]. Therefore, the evaluation of the accuracy of water flow through the BAC is adapted and applied to the water flow of the dewatering pumps. The combined flow of each pumping level is used and compared with the measured results from the site.

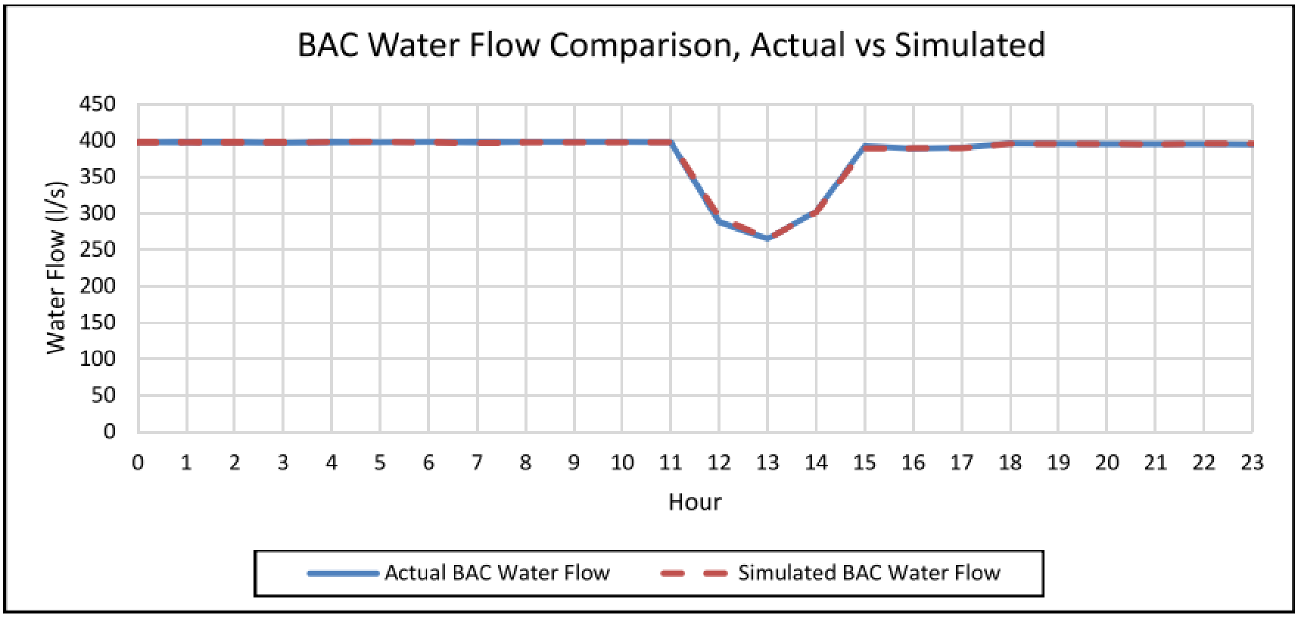


Figure 21: Water flow through BAC comparison [19]

The expected results of the comparison between the simulated and measured results are presented in Figure 22. The simulated and measured water flow of each pump station are plotted over the duration of 24 hours. The difference between the simulated and measured data should be less than the required 5%.

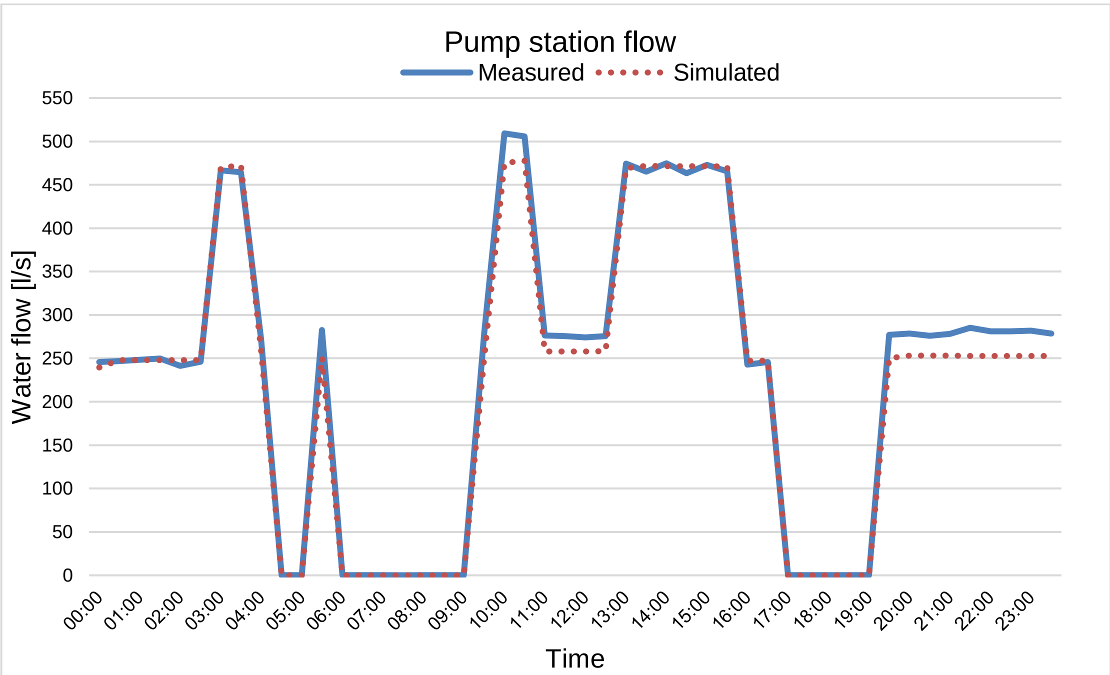


Figure 22: Pump station flow verification

2.4.2 Pump power

The effectiveness of verifying the simulation model by evaluating it against the power consumption has been proven in several studies [10], [21], [33], [34]. Stols *et al*. compared simulated and measured power for 24 hours; the results thereof are illustrated in Figure 23 [33]. The difference between the two data sets was less than the required 5%. In this study, the verification process from these studies will be adapted and applied to each pump level's power consumption.

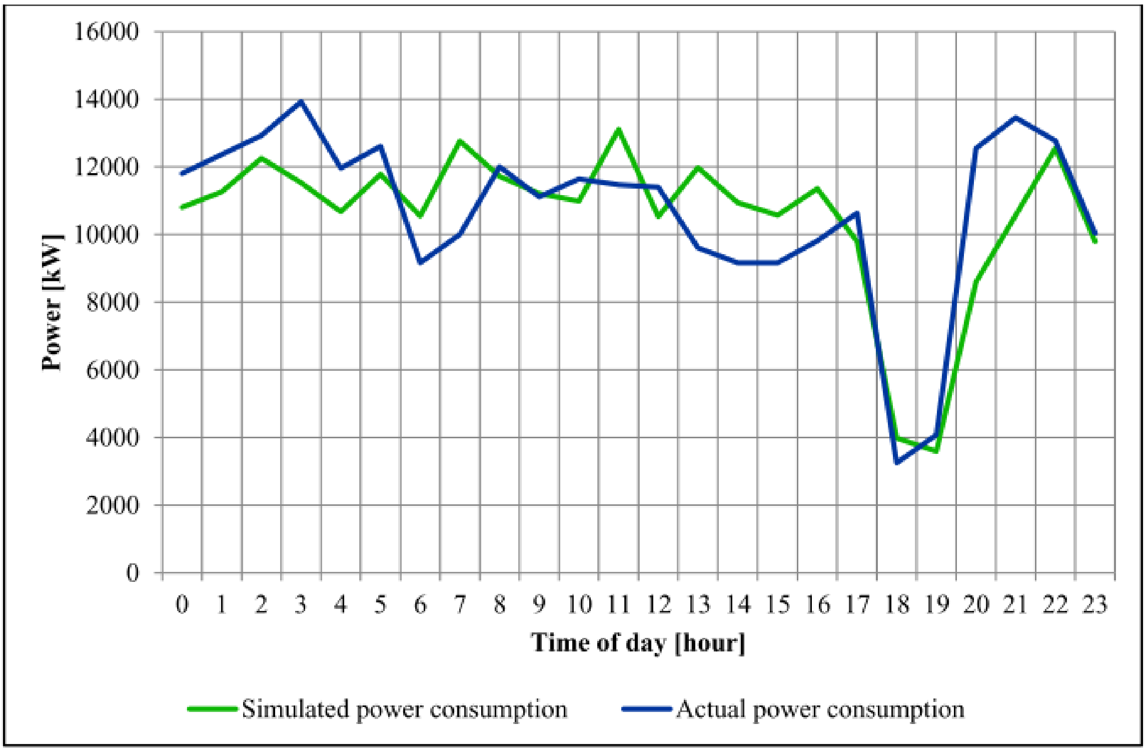


Figure 23: Power verification on the model [33]

2.4.3 Dam levels

A study done by Pascoe [25] used a simulation model that was verified by the power usage of the mine as discussed above (Section 2.4.2), followed by the outlet temperatures of a BAC. The simulation was used to forecast the expected dam levels over five days. The results of the forecasting model can be seen in Figure 24 [25].

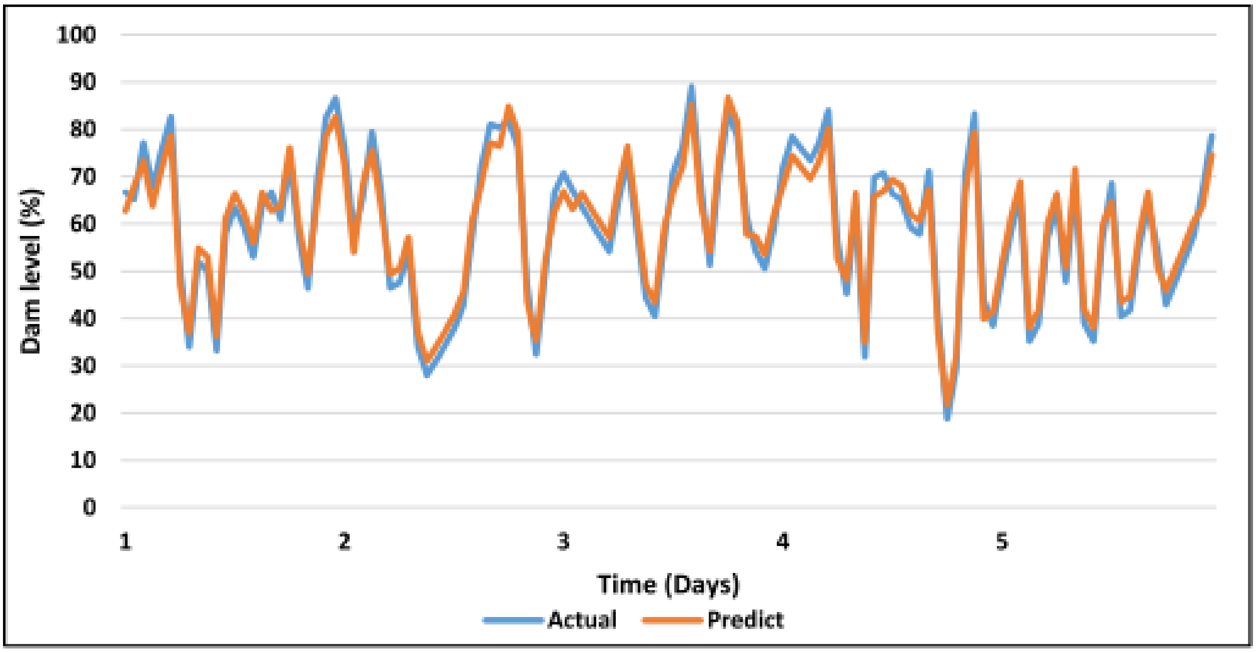


Figure 24: Dam level prediction model [25]

Knowing that the simulation model can predict the dam level within the required 5% error margin, the strategy will be adapted to verify the simulation model used in this study. The dam levels of the simulation model will be compared with the measured dam levels from a selected day. The comparison between the two results will also be plotted over a 24-hour duration.

2.5 Validation of method

The validation process consists of affirming that the proposed solution is suitable for the identified problem. For the method to be validated, it has to be applied to a case study. Therefore, developing a validation process is not possible without knowing the conditions of the case study. However, this section will serve as a guideline on how to validate the methodology developed. The validation processes of several studies were considered. From these studies, two general validation methods were identified:

- Validation Method 1: Implementing the solution on an actual system and evaluating the findings [10], [24], [33].
- Validation Method 2: Using a verified simulation model to evaluate the proposed solution [25].

Validation Method 1: Implementing the solution on an actual system and evaluating the findings

Venter [10] implemented a proposed reconfiguration on a deep-level mine to increase the dewatering capacity. The expected results from the proposed configuration change were compared with the actual results after the configuration had been applied. The results showed that the proposed solution increased the efficiency and dewatering capacity of the water reticulation system of the mine. Thus, the methodology developed by Venter was validated.

Similar studies were done by Van Niekerk [24] and Stols *et al*. [33]. Their methodologies were applied to case studies. Both methodologies identified several energy initiatives that would reduce the energy cost of mines. After using simulation models and several proposed tests, their proposed solutions were implemented on the case study mines. The results forecasted by the simulation models were compared with the actual results after implementation. The conclusion drawn from these studies is that the simulation can forecast the effects of these changes with a considerable amount of accuracy.

Validation Method 2: Using a verified simulation model to evaluate the proposed solution

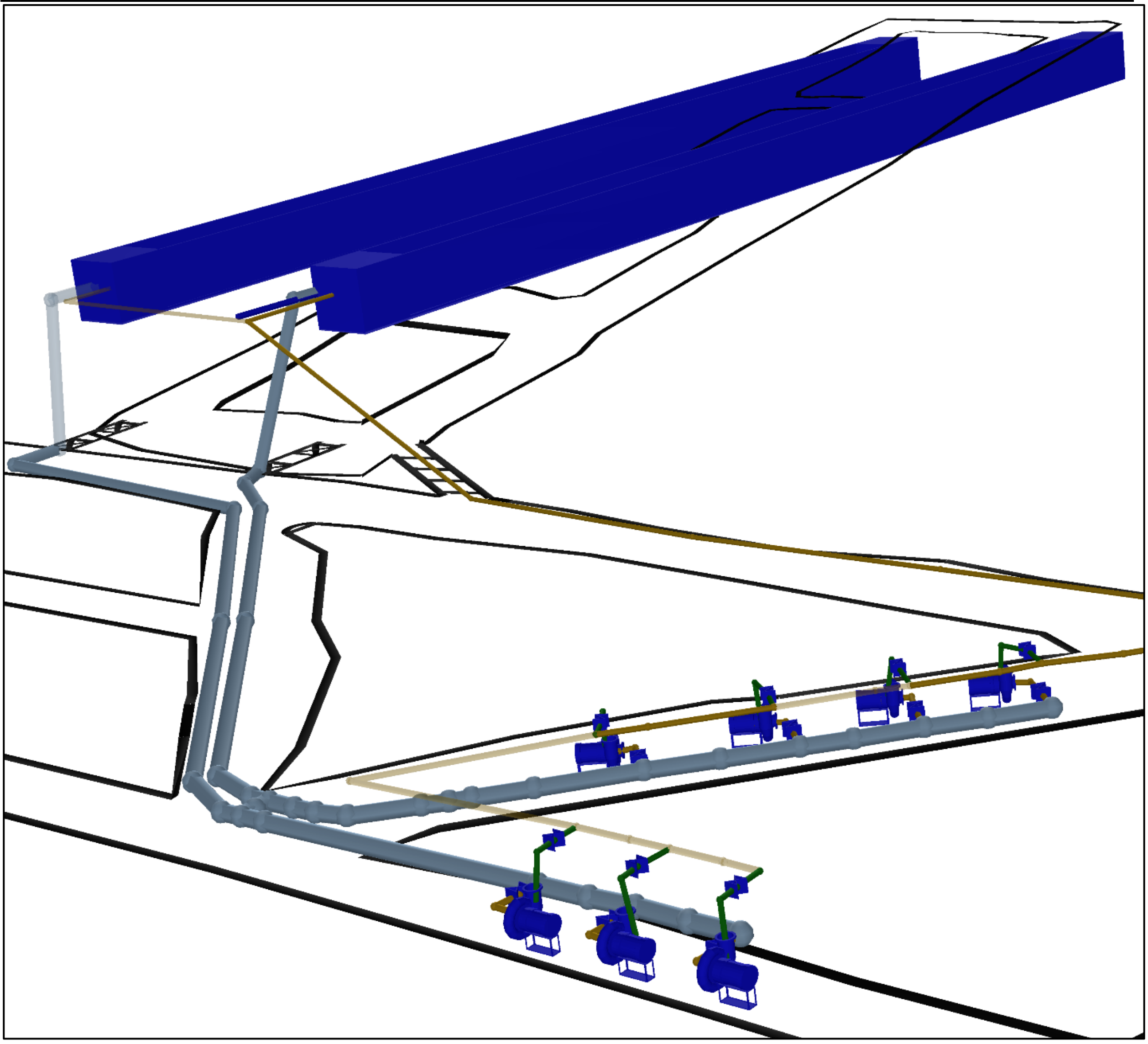
The second validation method involves validating the proposed solution using a verified simulation model in solutions that involve significant risk. For example, a study done by Pascoe [25] developed a mitigation strategy for equipment failure on a mine. The mitigation strategy involved turning the equipment off during vulnerable operational conditions of a mine. The financial impact of testing the mitigation strategy would be significant if the mitigation failed. However, using a verified simulation model of the mine, the strategy was tested and evaluated to be suitable for use. The mitigations developed by the study were implemented during several equipment failures on the mine. The verified simulation model estimated the results from the existing system's response with considerable accuracy.

The same validation principle can be applied to projects that have a significant amount of capital at stake or a more prolonged implementation phase over several years. Therefore, the study is unable to obtain physical results to validate the proposed solution. However, a verified simulation model can be used to evaluate the system's response to the proposed reconfigurations. As demonstrated by several studies, a verified simulation model is able to predict the effects of proposed reconfigurations on a system with considerable accuracy [10], [19], [21], [24], [25], [39].

2.6 Conclusion

The chapter discussed the development of an integrated simulation-based method to assist mines with planning. The method was formulated by combining several methods adapted from various studies in designing dewatering systems. In the next chapter, the methodology will be applied to a case study to verify and validate the method accordingly.

Chapter 3: Verification and validation



A rendered view of the pump station on the digital twin model in PTB

The chapter will focus on applying the methodology developed in the previous chapter on a case study.

CHAPTER 3: VERIFICATION AND VALIDATION

3.1 Preamble

This chapter will discuss how the simulation-based methodology developed in Chapter 2 was applied to Mine A. The deep-level gold mine consists of multiple integrated shafts. Several underground levels of these shafts intersect one another. Mine A was investigating the pre-feasibility of closing one of their care and maintenance (C&M) shafts that were only used for removing groundwater. Depending on the pre-feasibility study results, Mine A will conduct an in-depth feasibility investigation on the project.

In this study, the C&M shaft is referred to as Shaft 1. The shaft is a vulnerable asset to Mine A. Removing the groundwater at Shaft 1 prevents the other neighbouring shafts from flooding. The amount of groundwater removed from the shaft each day is approximately 40 ML. The groundwater will continue seeping into the mining areas around Shaft 1 after the shaft is closed, which could cause the neighbouring shafts to flood. An additional problem is that the water cannot be walled off or diverted from the other operating shafts. Thus, there is a large quantity of water that still has to be pumped out at one of the intersecting shafts.

The study investigated the pre-feasibility of closing Shaft 1 and diverting the water using columns to a neighbouring shaft, which is referred to as Shaft 2. This chapter will explain how applying the simulation-based method discussed in Chapter 2 resulted in a proposed solution. The process flow diagram adapted from the methodology in Chapter 2 is illustrated in Figure 25. The first process started with information gathering.

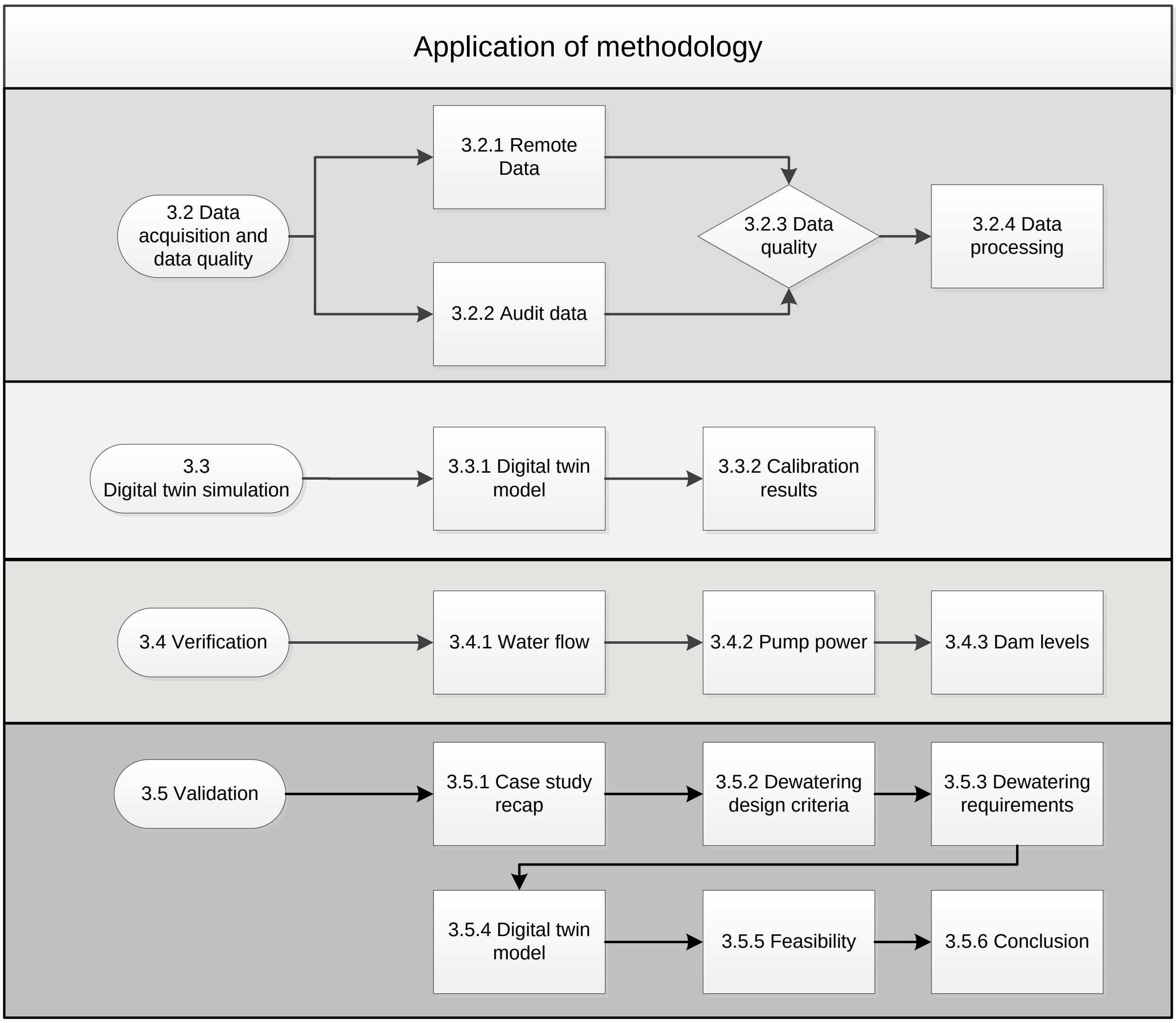


Figure 25: Process flow diagram of Chapter 3

3.2 Data acquisition and data quality on case study

The data-gathering process started with obtaining an understanding of the whole dewatering system of Mine A. The SCADA viewer provided an overview of all the dewatering infrastructure on the mine. The SCADA viewer was used to identify the number of pumps on each pumping station and the dam capacities on the levels containing dams. Figure 26 illustrates a simplified version of all the pumping levels of the mine on their SCADA system.

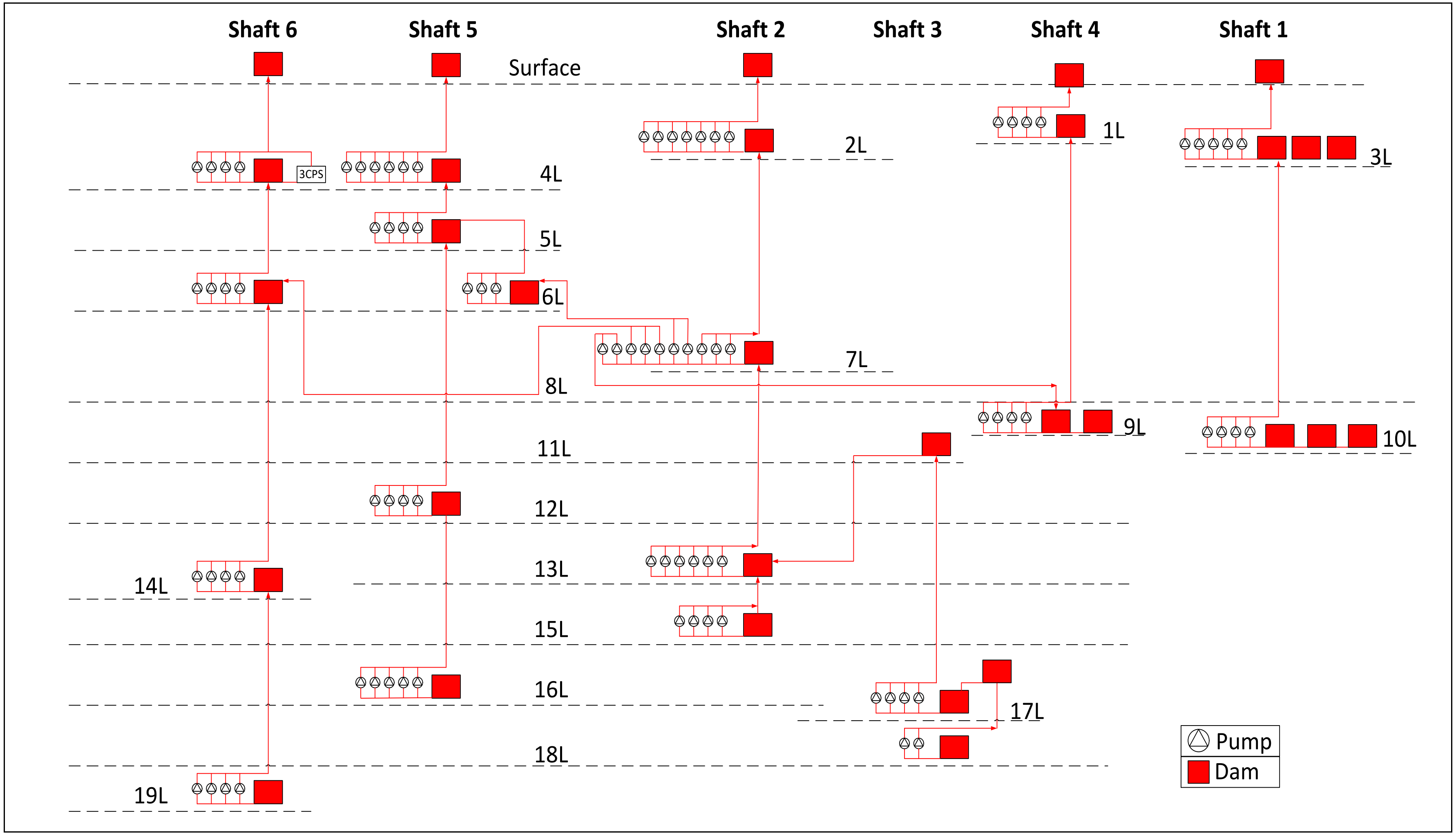


Figure 26: Mine A's integrated shafts' dewatering system

The study focused on Shafts 1, 2 and 3. Shaft 1 was the C&M shaft that was being investigated for closure. Shaft 2 was the neighbouring shaft where the water would be redirected from Shaft 1. Shaft 3 was a shaft that was also considered for closure. Shaft 3 transferred its mining water to Shaft 1 using a gravity-feed column from 11 Level (L) to 13L. By the implementation phase of closing Shaft 1, all mining activities on Shaft 3 would be decommissioned. Thus, the mine water from Shaft 3 was disregarded for the pre-feasibility study.

The only dewatering system investigated in detail was Shaft 2. Figure 27 gives a focused overview of Shaft 2's dewatering system. The shaft consisted of four pumping levels and multiple hot water dams for storage purposes on these levels. The settlers were located on three levels where the mud ingress was separated from the hot return mine water. The mud and separated mine water were transferred into separate dams and pumped to the surface. The focus of this study was only on mine water removal.

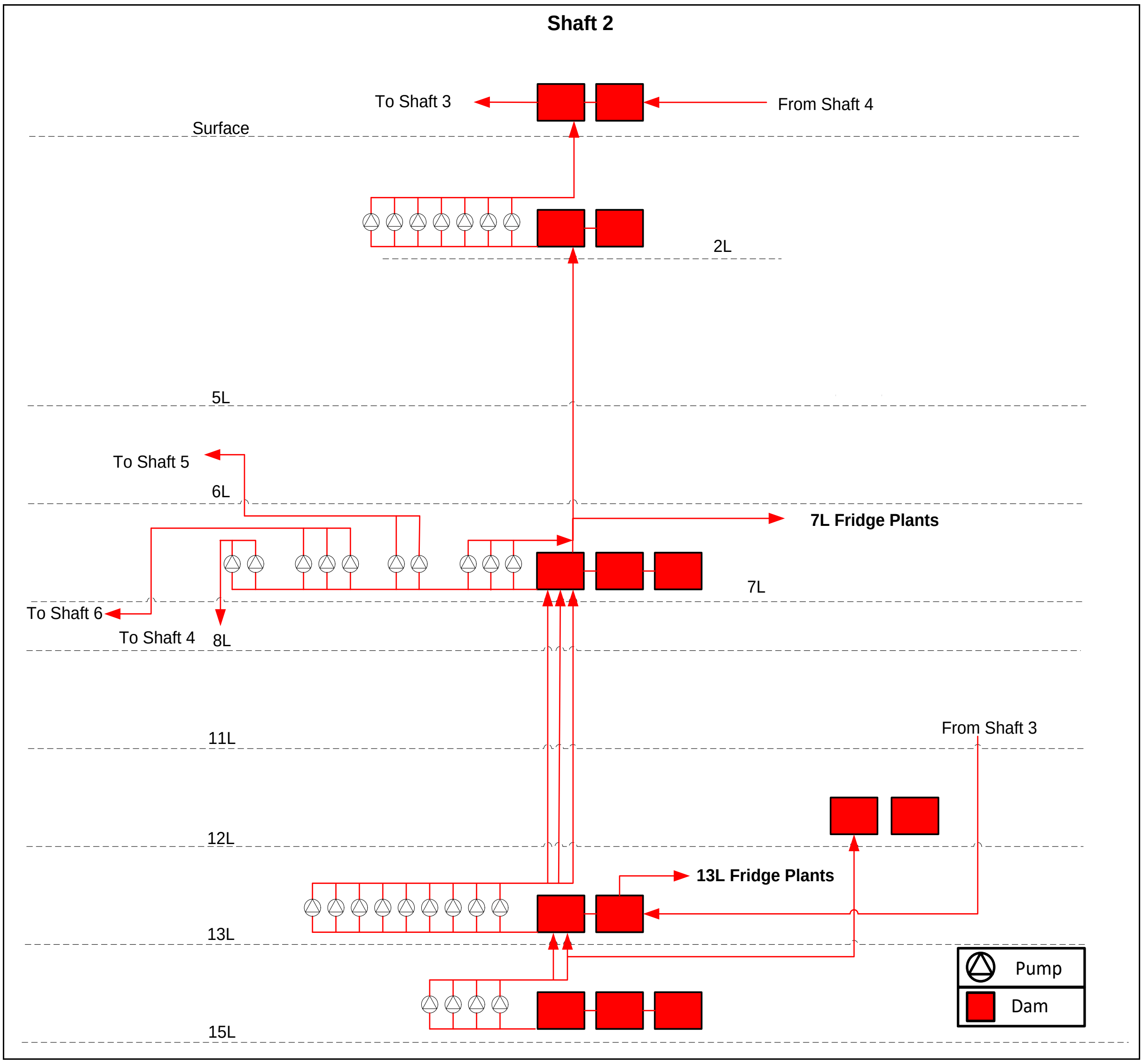


Figure 27: Dewatering system of Shaft 2

Shaft 2 used fridge plants located on two levels to cool down the water and send it back into the closed-loop cooling system. The fridge plants located on 13L were used for a closed-loop BAC cooling system. The closed-loop system was topped up with cleaned mine water from the hot water dams. The fridge plants on 7L were connected to an inline cooling BAC system. The water travelled from the fridge plants through the BACs and returned to the chilled dams on 8L. Thereafter, the water was used for mining operations. By reusing the mine water underground, the amount of water pumped back to the surface was reduced.

After gaining an understanding of the dewatering system of the investigated mine, the data-gathering process discussed in Section 2.2 was applied to Shaft 2. The data-gathering process was divided into two methods, namely remote data and on-site data

3.2.1 Remote data

Due to the unforeseen circumstance of lockdown and travel restrictions caused by the Covid-19 pandemic, most information was collected remotely to keep site visits to a minimum. Therefore, the remote data-gathering process discussed in Section 2.2.1 was followed.

The first step was to gain viewer access to the SCADA server from Mine A. Viewer access of the SCADA server provided a clear oversight of the whole mining operation at Mine A. For example, most of the dewatering systems could be observed from the SCADA view in Figure 26. In addition, the number of dams, pumps and columns could be seen from the SCADA view. In other sections of the SCADA viewer, each shaft could be viewed separately. These SCADA views of each shaft included dam levels, water flow, power usage and other relevant information.

Further investigation found that some information in the SCADA viewer was outdated. For example, as confirmed by the shaft engineer, pump station (PS) 3 on 13L only had nine pumps installed. Three were removed and used on other systems throughout the years. Thus, only nine dewatering pumps were installed on the level and not 12 as displayed on the SCADA view in Figure 26.

The SCADA viewer of Mine A had a historical database on all the measuring instruments allowing the data to be extracted as discussed in Section 2.2.1. The historical data of each measuring instrument was downloaded and used to create baselines and develop benchmarks for the simulation model. The details of the baselines and their application will be discussed in Section 3.2.4. Unfortunately, the measuring instruments' real tag names and PLC addresses may not be disclosed in this document due to information restrictions and privacy policies. For this reason, a short description of the tag name is given instead of the tag name itself.

The design of the dewatering pump information supplied by the mining personnel of Shaft 2 is listed in Table 3. Shaft 2 used 23 pumps dedicated to removing the water from underground operations towards the surface. A fourth dewatering pump on PS2 was being installed during this investigation. The pump will be included in the validation phase of the study. In addition, several additional pumps were used to top up the fridge plants on two levels and for emergency purposes, as illustrated in Figure 27.

Table 3: Dewatering pump information

Pump station	Level	No. of pumps	Pump characteristics		
			Flow rate per pump [ℓ/s]	Head [m]	Motor power [kW]
1	2L	7	150	874	1 800
2	7L	3	250	1 042	3 600
3	13L	1	170	685	2 100
		8	130	685	1 500
4	15L	1	160	620	1 200
		3	180	620	1 350

Table 4 summarises all the hot water dam locations and estimated capacities in megalitres. The dam sizes could only be estimated according to the given length, width, and height recorded on old dam surveys. Twelve dams are located underground with a combined capacity of 40 ML, including the emergency dam capacities.

Table 4: Dewatering dam information

Description	Level	Dam capacity
Surface hot dam 1	Surface	5 ML
Surface hot dam 2		5 ML
Hot dam 1	2L	1.5 ML
Hot dam 2		1.5 ML
Hot dam 1	7L	1 ML
Hot dam 2		1 ML
Hot dam 3		5 ML
Emergency dam 1	12L	7 ML
Emergency dam 2		5 ML
Hot dam 1	13L	3 ML
Hot dam 2		3 ML
Hot dam 1	15L	2 ML

Description	Level	Dam capacity
Hot dam 2		4 ML
Hot dam 3		6 ML

The dewatering columns between these levels are summarised in Table 5. All pump levels except 7L and 2L had more than one dewatering column installed.

Table 5: Dewatering column information

Pump level	Description	Column size
1	Column from 2L to surface	400 mm
2	Column from 7L to 2L	400 mm
3	Column 1 from 13L to 7L	350 mm
	Column 2 from 13L to 7L	350 mm
	Column 3 from 13L to 7L	350 mm
4	Column 1 from 15L to 13L	300 mm
	Column 2 from 15L to 13L	300 mm

A summary of all the information gathered on the dewatering system is shown in Figure 28. The schematic includes all the dam sizes, dewatering column sizes, depth underground, and number of pumps on each level, followed by their power and flow rating. Several additional pumps used for emergency purposes are also included in the schematic. These pumps were located on 7 Level.

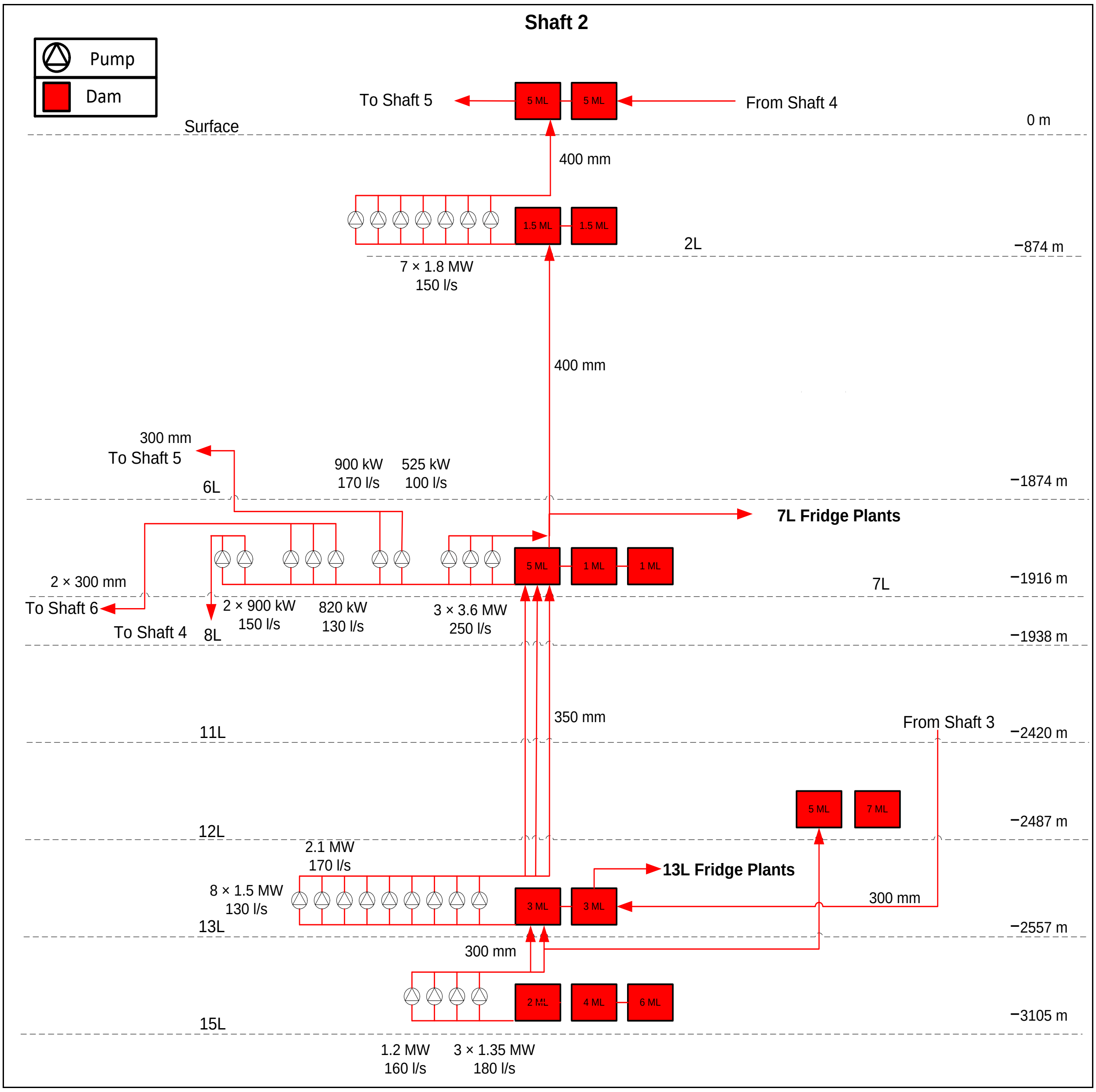


Figure 28: Detailed dewatering system of Shaft 2

The mine provided level layouts that were used during the on-site visits. An example of a mine level layout used during the audit is given in Figure 29. In addition, the mine level layouts were used as the reference points for building the simulation model, as discussed in Section 2.3.2.

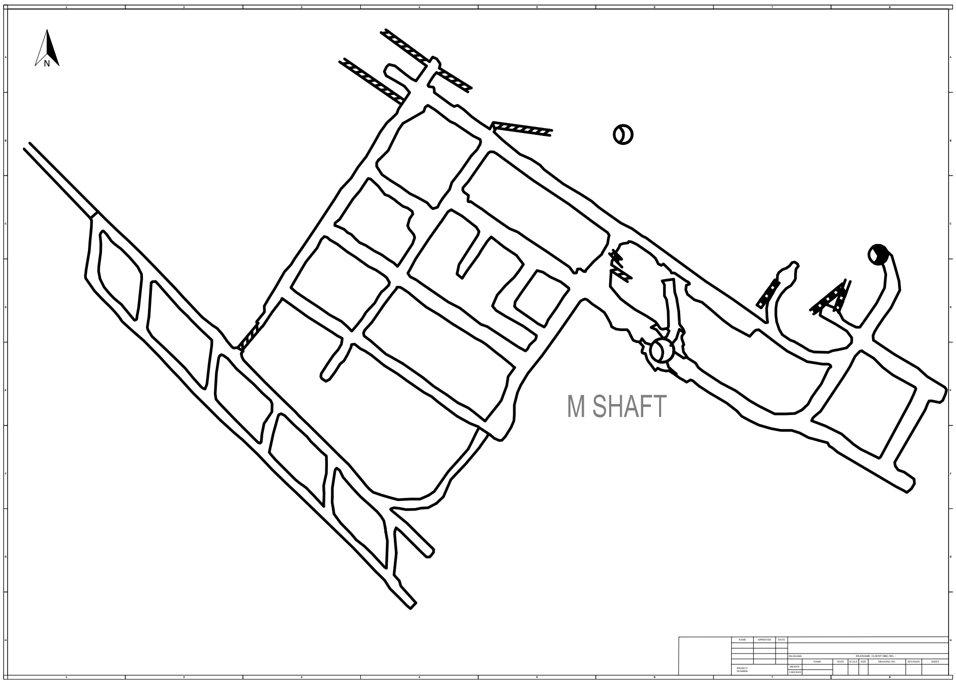


Figure 29: Mine level layout

The annual peak tonnages that were planned to be hoisted from Shaft 2 are shown in Figure 30. The shaft’s production would peak in Year 3. The actual LOM planned tonnages were not included in the study. To protect the confidentiality of the mine, only eight of the highest production years were selected for the calculations. The benchmark that will be calculated in Section 3.2.4.2 is the water usage ratio per tonne of ore removed.

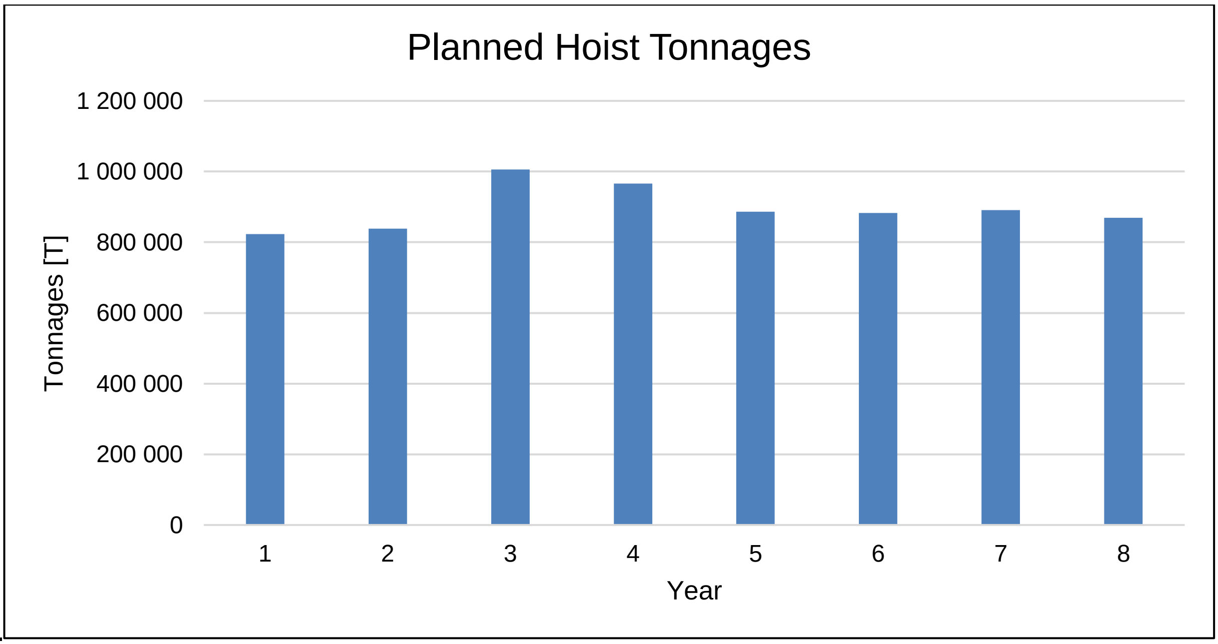


Figure 30: Planned tonnages of Shaft 2

3.2.2 On-site data

The aim of site audits is to do spot checks on the measuring instrumentation and verify the installed infrastructure sizes. A walk-through audit was done on each level to map the locations of the pumps and pipe infrastructure. The locations of the dams were also indicated as discussed in Section 2.2.2. The same layouts were created for each pumping level, as illustrated in Figure 5 in Section 2.2.1. These layouts will be used to build the simulation model in Section 3.3.1.

The walk-through audits confirmed the size of the dewatering pumps and the motors by capturing the motor specification plate of each pump. Unfortunately, several older motor and pump specification plates have been damaged over the years. Therefore, it was not possible to verify whether the design flow rate matched the specifications provided by the mining personnel. The site visit to 13L further verified that only nine dewatering pumps were installed, thereby confirming that the SCADA viewer data was outdated.

The dewatering columns between the levels were verified by measuring the outside diameter of the columns. The dam sizes could only be estimated according to the given length, width, and height on old dam surveys. The sizes of the dams that were provided correlated with the given sizes by the mining personnel.

Due to the vast number of flow meters installed on the water reticulation system of the shaft and the limited site visits, only several flow meters' readings could be verified. Therefore, a clamp-on ultrasonic flow meter was installed on a dewatering column and the flow measured was compared with the flow displayed on the SCADA viewer. From all the flow instrumentation verified, the difference was less than 5%.

3.2.3 Data quality

The methodology discussed in Section 2.2.3 was applied throughout the data acquisition. First, the data from the SCADA historian was processed using Booysen's method. Thereafter, the maximum and minimum values were identified for each dewatering column flow. In addition, faulty data and data losses were eliminated by applying data filters to exclude the points from the calculations.

Figure 31 illustrates Booysen's method that was applied to the measured values of PS2. Between 19:00 and 23:00 in the evening, the flow meter measuring the water flow from PS2 to PS1 logged a water flow rate. After evaluating the power usage of PS2, it was established that none of the pumps were running during that time. Thus, the measured water flow during these times was adjusted to zero.

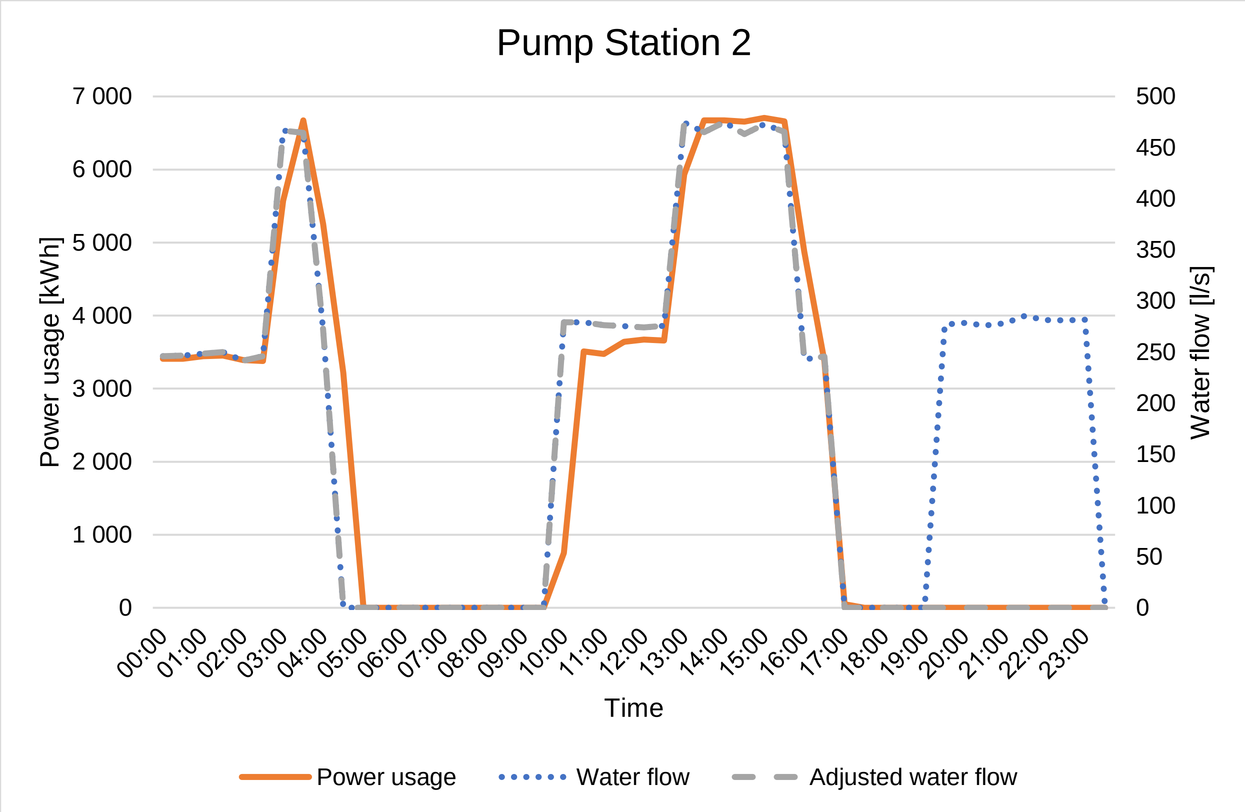


Figure 31: Data quality example

Several similar occurrences were identified. One of the power measuring instruments connected to Pump 7 on PS3 transmitted questionable measurements. The rated power consumption of the motor was 1 500 kW and the average measured power was 775 kW. The electrical foreman of the shaft confirmed that the instrumentation was indeed faulty and was scheduled for repair. The pump power Equation 1 adapted from [33], [56] was used to calculate the theoretical power usage of the pump. Head (*H*), volume flow (*Q*), density (ρ) and gravitational acceleration (*g*) were known variables. The only unknown variable was the efficiency ratio of the pump and motor (η).

$$P = \rho g H Q / \eta \qquad \text{Equation 2}$$

Using Equation 1, the theoretical power required for the pump to transfer the water to PS2 was calculated to be at least 874 kW without considering any efficiency losses. However, during a pump test done by an external contractor, the pump produced 158 ℓ/s of water flow. The contractor further questioned the measured power consumption of the pump. Therefore, the theoretical power was recalculated using the water flow rate of 158 ℓ/s at a head of 685 m, resulting in 1 010 kW. Considering the average efficiency value used on the PTB calibrations of 70% (combined motor and pump efficiency), the calculated power usage of the pump had to be around 1 443 kW. Therefore, the calculated power usage of the pump was used to mitigate the error in the calibration process.

On the other hand, Pump 2 on PS3 was rated for 2 100 kW, but only used 1 420 kW. On further investigation it was found that several pump stages were removed to reduce the pump's flow rate, which reduced the head of the pump [15].

The data limits of the various measuring instruments varied from one another. The maximum limit for each dewatering column was set according to the allowable number of pumps to be run simultaneously. Table 6 summarises the dewatering system's limits. Applying Booysen's method, any water flow outside the flow limits were considered data spikes.

Table 6: Dewatering system limits

Column	Column size	Flow limits	No. of pumps running per column	No. of pumps connected to the column
2L column flow to surface	400 mm	0–500	4	7
7L column flow to 2L	400 mm	0–500	2	3
13L column 1 flow to 7L	350 mm	0–300	2	3
13L column 2 flow to 7L	350 mm	0–300	2	3
13L column 3 flow to 7L	350 mm	0–300	2	3
15L column A flow to 13L	300 mm	0–360	2	3
15L column B flow to 13L	300 mm	0–360	2	3

Configuring pumps in parallel would increase the flow rate. However, increasing the number of pumps running in parallel would also increase the column's overall friction losses. Hence, effectively reducing the amount of flow as more pumps are connected in parallel [21]. The effect thereof was observed in the flow data on the column from 2L to the surface. Four running pumps should provide a flow of 600 ℓ/s for each pump with a flow rate of 150 ℓ/s. The maximum water flows the four pumps could transfer to the surface was thus 500 ℓ/s.

The data limits for the dams were between 0% and 100%. Therefore, only dam percentages between these limits were used. The operating levels for the dams on Shaft 2 were between 60% and 100% as provided by the shaft engineer. The high percentages were due to mud ingress that built up at the bottom of the dam. The particles in the water could cause the dewatering pumps to wear faster [57].

Each pump installed on Shaft 2 was fitted with power meters on the feeders that measured each pump's energy consumption separately. The data limits for the pumps were set according to their designed motor sizes. Considering that all the pumps had non-return valves on the outlets, no water would flow back to the pumps [21]. Thus, any power measurement below 0 kW and any power usage that exceeded the design ranges were discarded.

3.2.4 Data processing

3.2.4.1 Baselines

Shaft 1: Groundwater baseline

The groundwater seepage rate had several influencing factors. These factors included daily rainfall, rainfall infiltration, depth of the mine, mine development rate, and water table position [8]. From information gathered on-site, mining activities on Shaft 1 were last commenced in 2010. Thus, no development took place on the shaft after 2010. Furthermore, groundwater is seldomly intersected when mining development takes place, as explained in the background section. Therefore, because no development has taken place on Shaft 1 in ten years, it was assumed that no additional groundwater source would have been intersected or exposed.

Table 7 summarises the average daily water removed from Shaft 1 for eight consecutive months during 2020. Column 1 was under maintenance and care due to a column burst in 2019. Thus, the column was not in use during the data-gathering process. From Table 7, the amount of rainfall was assumed to be constant throughout the year. Dewatering systems are always designed to include the maximum amount of water removed from the system [8]. The difference between the average water removed during these eight months and the peak water removed in June was less than 5%. Thus, the average groundwater was used as the seepage flow rate into the mine.

Table 7: Groundwater removed during 2020

Month	Column 1 [ℓ/s]	Column 2 [ℓ/s]	Column 3 [ℓ/s]	Total water flow out of shaft [ℓ/s]
Jan	0	309.0	155.8	464.7
Feb	0	272.0	167.2	439.3
Mar	0	300.2	175.0	475.1
Apr	0	308.6	167.2	475.7
May	0	309.2	157.5	466.7
Jun	0	328.1	160.1	488.1
Jul	0	314.2	158.3	472.5
Aug	0	315.9	136.2	452.0
Average	0	307.1	159.6	466.8

Based on the assumption that no excess groundwater was intersected from mining developments and that the effect of rainfall was negligibly small, the groundwater seepage rate was assumed to be constant. The water pump profile of the groundwater removed from Shaft 1 over 24 hours is shown in Figure 32. Therefore, the dewatering system was designed to include the water seepage rate according to the water removal curve presented in Figure 32.

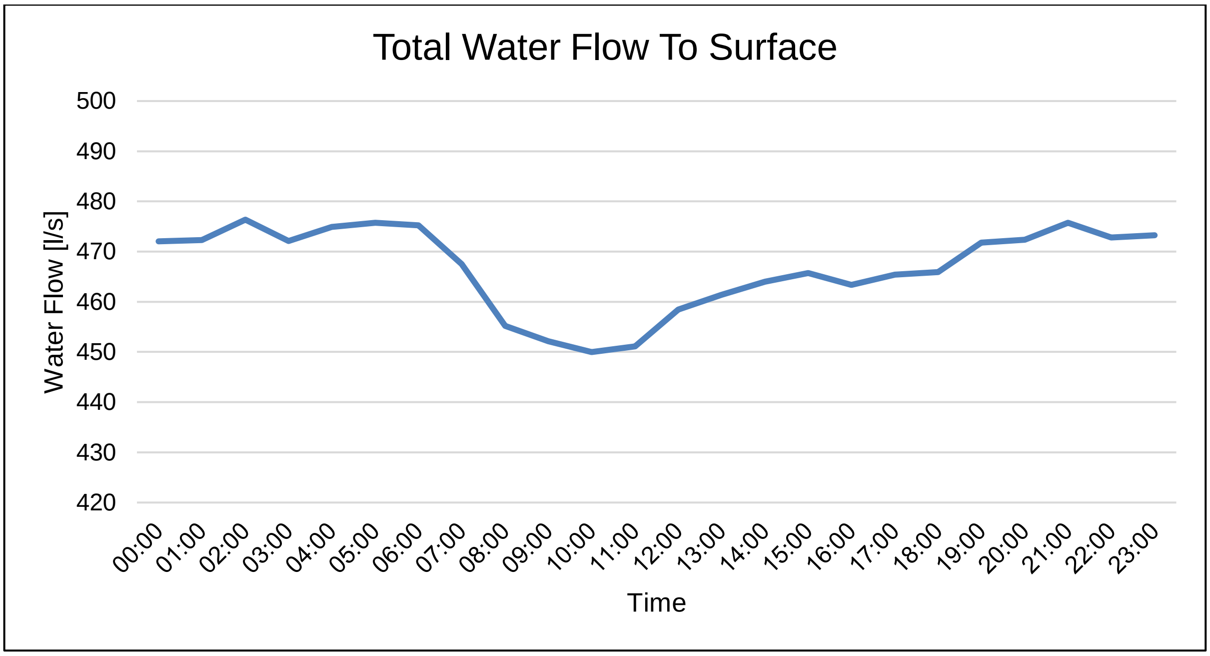


Figure 32: Monthly average dewatering profile of Shaft 1

Shaft 2: Groundwater baseline

The mining operations at Shaft 2 intersected two groundwater sources. The first groundwater source was between Shaft 2 and Shaft 5 on 8L, and the second one was located above 2L on Shaft 2. The hydrogeologist reported that the estimated amounts of groundwater were approximately 1.3 ML and 3.9 ML, respectively, on these levels per day.

The first groundwater source between the two shafts was located closer to Shaft 5. However, the water was removed by Shaft 2. The geological position of Shaft 2 on 8L was lower than Shaft 5. Thus, the groundwater flowed to Shaft 2 due to gravity.

The second source was located above 2L, where several levels above 2L had intersected groundwater. These levels were mainly used during the development of the mine and were not in use at the time of the study. The water was being removed with several borehole pumps. The borehole pumps would be decommissioned for future applications, and the water would be redirected to the dewatering dams on 2L. The additional groundwater that would flow into the 2L dams was 3.9 ML per day. Therefore, the new dewatering system had to include the additional groundwater on 2L.

Shaft 2: Service water flow baseline

Shaft 2 was used to supply top-up water to Shaft 6 throughout the day. The amount of water sent to Shaft 6 equated up to 5 ℓ/s (0.4 ML) on average throughout the day. The water was mainly used to top up the closed-loop cooling system on Shaft 6's side underground.

For the benchmark to be developed, the service water usage baseline had to be determined. There were two main service water dams located on 8L and 12L. The service water was distributed from 8L to the 12L dams. The service water dam on 8L received chilled water from the 7L fridge plants and from Shaft 3 on 8L. The 8L dam had two main outlets. One fed to the 12L service water dam, and the other outlets supplied levels above 12L with service water.

To calculate the service water flow to these levels, respectively, a mass balance was applied over the 8L dams. The month of February 2020 was selected for calculating the mass balance. February was selected because it was the last month of regular mining shifts pre-Covid-19. Thus, more crews worked during this month, resulting in more water being used.

Using the monthly average water flow of each inlet and outlet flow of the dams on 8L, a 24-hour profile was created. The difference between the inlet and outlet was less than 1.9%. A more detailed summary of the inlet and outlet flows can be seen in Table 8.

Table 8: Mass balance over 8L dam

February 2020						
Time	IN			OUT		
	ℓ/s	ℓ/s	ℓ/s	ℓ/s	ℓ/s	ℓ/s
	Chilled water from 7L fridge plants	Chilled water from Shaft 3	Total into 8L chilled dam	To mining below 8L	To 12L holding dam	Total out 8L chilled dam
00:00	54	151	205	232	33	265
01:00	54	163	218	359	44	403
02:00	55	164	219	365	64	429
03:00	53	169	221	385	67	452
04:00	52	176	228	262	49	311
05:00	51	181	232	193	38	231
06:00	52	190	241	183	33	216

February 2020						
Time	IN			OUT		
	ℓ/s	ℓ/s	ℓ/s	ℓ/s	ℓ/s	ℓ/s
	Chilled water from 7L fridge plants	Chilled water from Shaft 3	Total into 8L chilled dam	To mining below 8L	To 12L holding dam	Total out 8L chilled dam
07:00	52	188	240	167	22	189
08:00	52	202	254	155	26	181
09:00	53	220	273	266	35	301
10:00	53	218	271	284	47	331
11:00	53	215	269	290	49	339
12:00	53	215	268	300	47	347
13:00	55	203	258	236	41	277
14:00	63	193	256	219	35	254
15:00	63	186	249	199	32	231
16:00	63	148	210	96	15	111
17:00	63	97	159	4	0	4
18:00	63	86	149	0	0	0
19:00	63	94	157	0	0	0
20:00	62	121	183	16	5	21
21:00	54	107	161	65	15	80
22:00	48	104	153	136	24	160
23:00	44	123	167	172	31	204
Average	**55**	**163**	**218**	**191**	**31**	**222**

The service water baseline developed from Table 8 was used in the simulation model as input as shown in Figure 33. The average water supplied from the 8L dam to the levels above 12L was 192 ℓ/s. The water supplied to the levels below 12L was 31 ℓ/s. Therefore, the total daily average water usage of Shaft 2 was 223 ℓ/s for February.

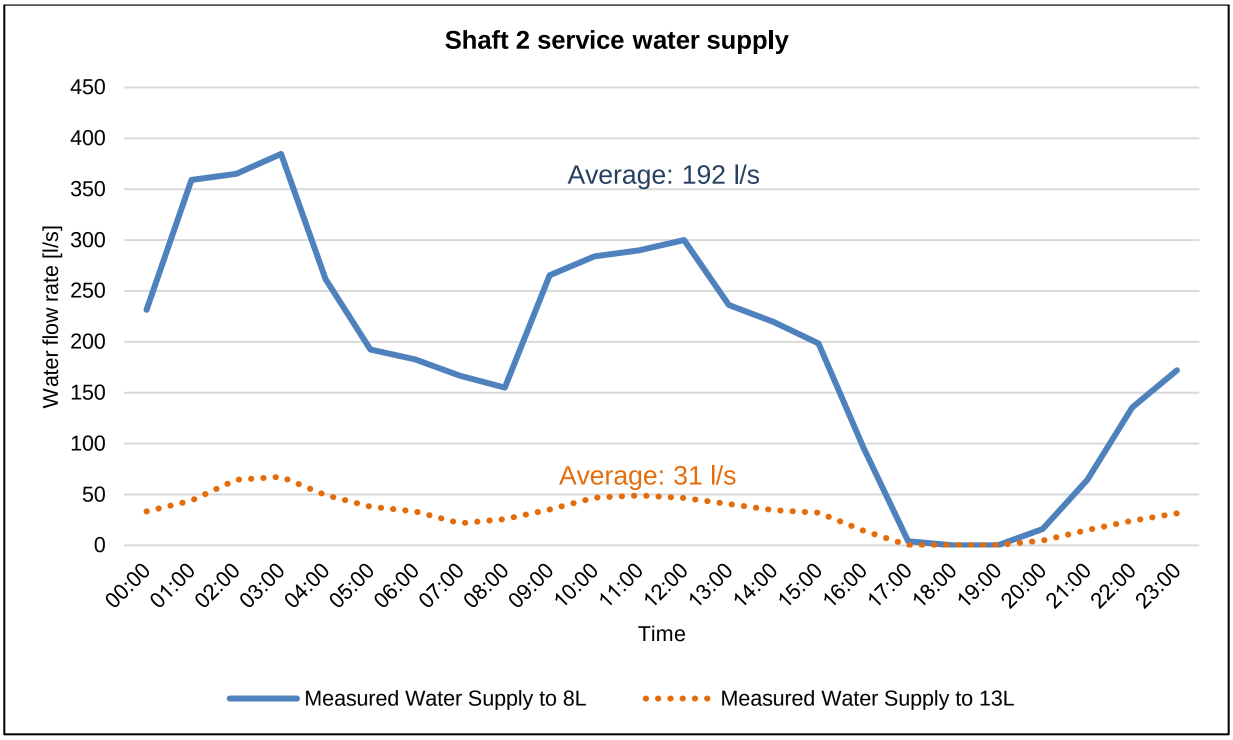


Figure 33: Shaft 2 service water supply

The service water supply will be adjusted to compensate for the increased usage of the peak production in Year 3. The benchmark will be used to estimate the service water usage for Year 3.

Shaft 2: Dewatering pump measured value baseline

Using measured data from each pump increases the overall accuracy of the simulation model [51]. Figure 34 illustrates the performance of a dewatering pump over eight months. The maintenance period can be observed from the figure. After each maintenance repair on the pump, the flow of the pump increased up to 257 ℓ/s. The efficiency of the pump slowly deteriorated to 215 ℓ/s throughout the seven-month maintenance schedule.

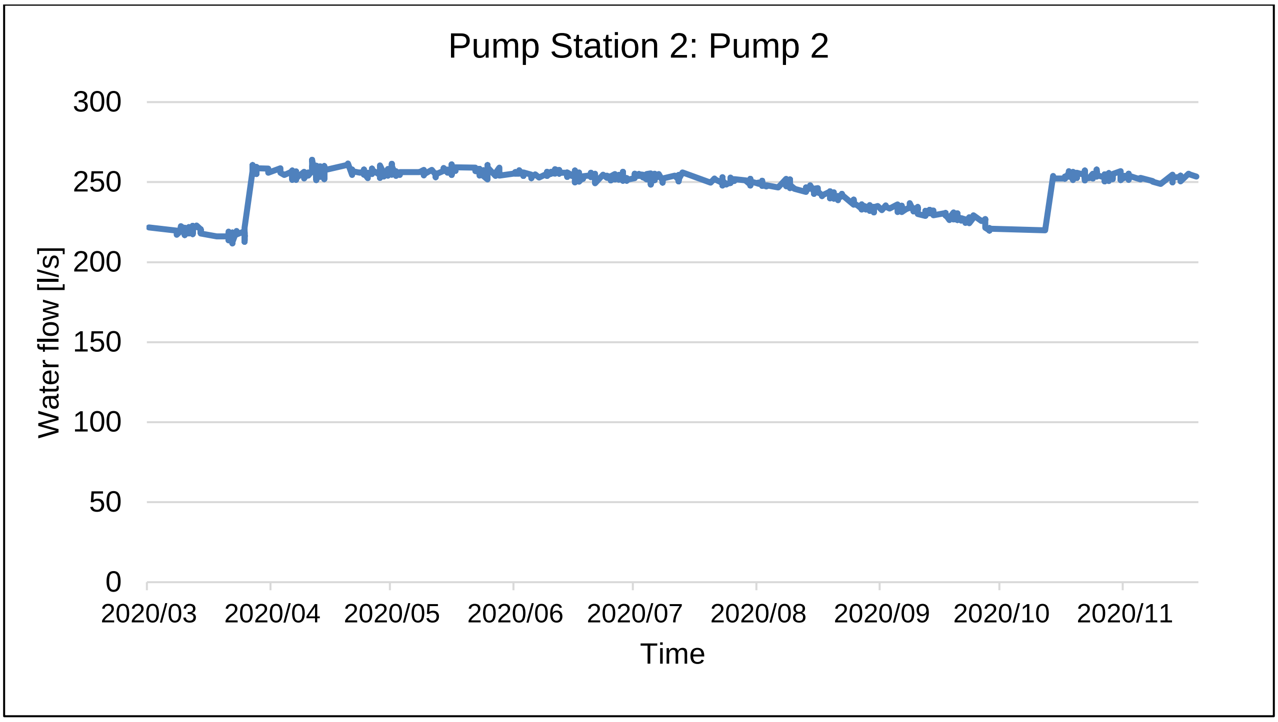


Figure 34: Performance of Pump 2 over time

The pump deterioration was included in the calibration of the pumps to ensure the pump was as accurate as possible. Most deterioration happened during the last two months as observed in Figure 34. In the first five months, the pump only deteriorated by 10 ℓ/s. Therefore, the average water flow value was sufficient to be used for the calibration set point [21].

The same principle was applied to the average power used by each dewatering pump. Table 9 summarises the average measured values for each dewatering pump. These values will be used in Section 3.3.2 to calibrate the dewatering pumps on the test bench.

Table 9: Average measured pump performance

Description	Average measured value	
	Water flow [ℓ/s]	Power [kW]
PS1 Pump 1	138	1 647
PS1 Pump 2	146	1 925
PS1 Pump 3	149	1 964
PS1 Pump 4	151	2 024
PS1 Pump 5	156	2 085
PS1 Pump 6	141	1 908
PS1 Pump 7	152	1 810
PS2 Pump 1	239	3 442

Description	Average measured value	
	Water flow [ℓ/s]	Power [kW]
PS2 Pump 2	247	3 370
PS2 Pump 3	258	3 512
PS3 Pump 1	144	1 414
PS3 Pump 2	142	1 420
PS3 Pump 3	121	1 136
PS3 Pump 4	149	1 472
PS3 Pump 5	126	1 208
PS3 Pump 7	158	1443
PS3 Pump 8	146	1 416
PS3 Pump 10	122	1 414
PS3 Pump 12	122	1 338
PS4 Pump 1	153	1 347
PS4 Pump 2	167	1 415
PS4 Pump 3	186	1 487
PS4 Pump 4	162	1 368

3.2.4.2 Benchmarking

The water usage ratio as discussed in Section 2.2.4 was calculated using the daily average service water usage and the tonnages removed during February 2020. The assumption was made that the water usage ratio will remain the same for the coming years. From the mine planning data supplied by the mine, the planned tonnages for the peak production month for Year 3 was available. By knowing the planned tonnages to be removed followed by the water usage ratio, the litre of water to be used during month could be calculated. The value was refined to a daily average water usage in litre per second. Table 10 summarises the results of the calculations.

Table 10: Water usage calculations

Description	February 2020	February Year 3	Units
Tonnes removed per month	60 860	83 810	T
Daily average water usage	223	306	ℓ/s
Litre water used[11]	385 344 000	530 655 285	ℓ

[11] Total of 20 production shifts during February 2020.

Description	February 2020	February Year 3	Units
Water usage ratio	6 332	6 322	ℓ /T

The water usage was estimated by distributing the tonnages evenly for each month and assuming the water ratio distributed to the mining operations below 8L and 12L would remain the same. The results can be seen in Table 11. The only change on the system during Year 3 would be that the chilled water supplied from Shaft 3 will be replaced by chilled water from Shaft 5[12].

Table 11: Monthly service water estimation for Year 3

Year 3 monthly service water demand						
Time	IN			OUT		
	ℓ/s	ℓ/s	ℓ/s	ℓ/s	ℓ/s	ℓ/s
	Chilled water from 7L fridge plants	Chilled water from Shaft 5	Total into 8L chilled dam	To mining below 8L	To 12L holding dam	Total out 8L chilled dam
00:00	74	207	281	317	46	363
01:00	74	224	298	492	60	552
02:00	75	225	300	500	88	588
03:00	72	231	303	527	92	619
04:00	71	242	313	359	68	426
05:00	71	248	319	264	52	316
06:00	71	260	331	250	46	296
07:00	71	257	328	228	30	258
08:00	71	277	348	212	35	248
09:00	72	301	374	364	49	412
10:00	73	298	371	389	64	453
11:00	73	295	368	397	67	465
12:00	73	294	367	411	64	475
13:00	75	278	353	324	56	379
14:00	86	265	351	301	47	348
15:00	86	255	341	272	44	316
16:00	86	202	288	132	20	152

[12] Shaft 3 is scheduled for closure after the implementation phase as discussed in Section 3.2.

17:00	86	132	218	6	0	6
18:00	86	118	204	0	0	0
19:00	86	129	215	0	0	0
20:00	85	166	251	22	7	28
21:00	74	147	221	88	21	109
22:00	66	143	209	186	33	219
23:00	60	168	229	236	43	279
Average	**76**	**223**	**299**	**262**	**43**	**306**

The expected service water baseline developed from the benchmark calculations in Table 11 are illustrated in Figure 35. The forecasted amount of service water used during the peak production year will be used as the water to be removed from the mine alongside the groundwater as discussed in Section 3.2.4.1. In addition, the service water forecasted will be used in Section 3.5.3 for the dewatering requirements and the service water demand input inside the simulation model.

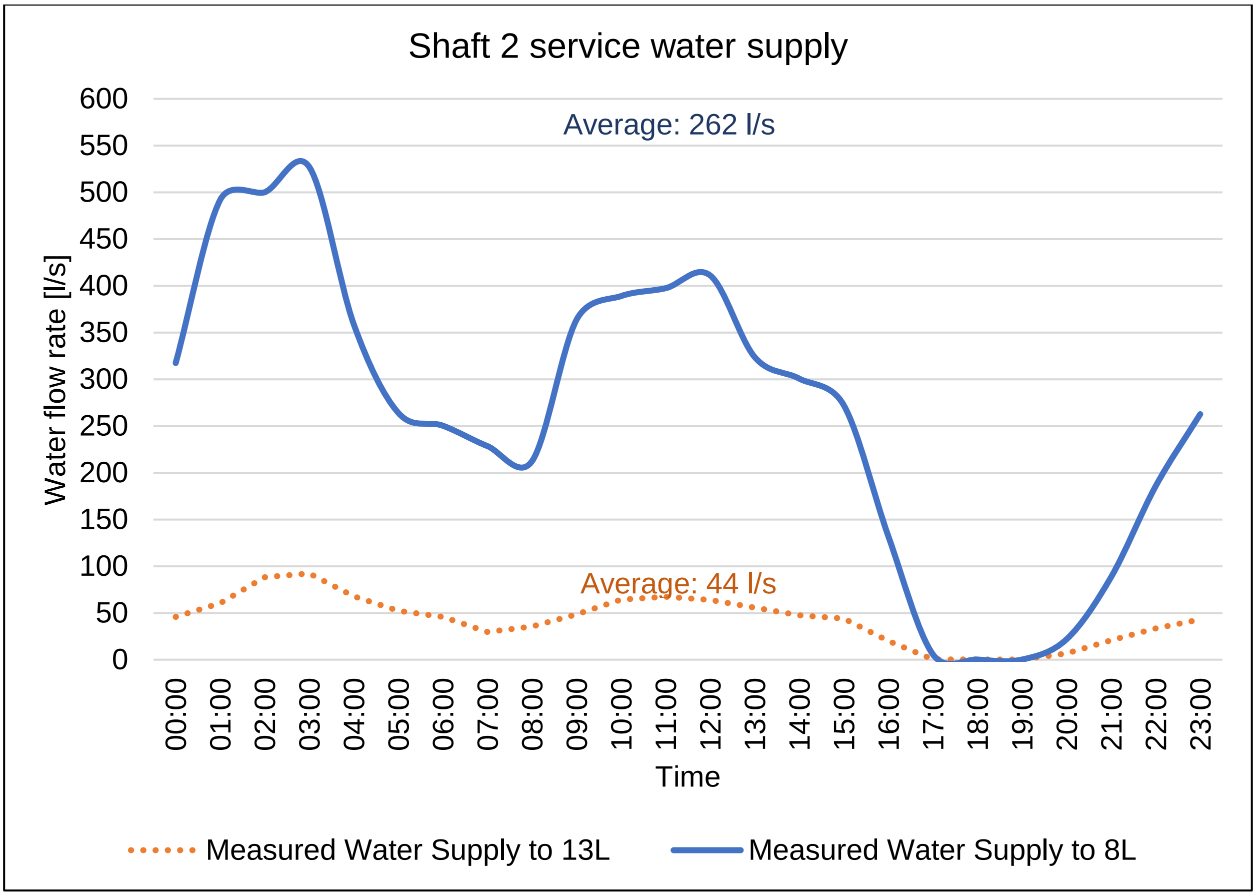


Figure 35: Forecasted service water supply for peak production Year 3

3.3 Digital twin simulation of Mine A

The digital twin simulation model was created to consist of two versions. The first version will be used to verify the existing dewatering infrastructure of Shaft 2. The second version will be used in Section 3.4.1 to validate the pre-feasibility of closing Shaft 1.

3.3.1 Digital twin model

The simulation model was built as discussed in Section 2.3. The first building phase used the underground layouts from the site visits to build the model's skeleton layout. Secondly, the pipe layouts were built to match the corresponding infrastructure on the mine. Thereafter, the pumps and dams were placed in their corresponding positions as verified on the mine itself. Figure 36 demonstrates a skeleton view of PS1 on Shaft 2. The same was done for all the pump levels on Shaft 2.

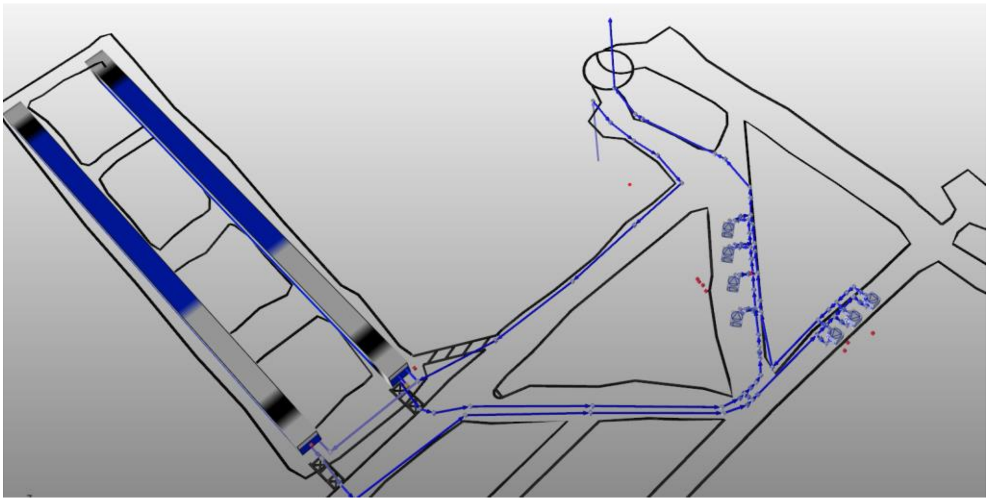


Figure 36: Skeleton view of PS1[13]

All the levels were linked with their corresponding number of dewatering columns connecting the levels. For example, Figure 37 indicates the dewatering column that connected two of the pumping levels. The dewatering column between the two levels shown in Figure 37 stretched over 1 040 m between the two levels.

[13] Figure 36 to Figure 38 are screenshots captured from the author's simulation model.

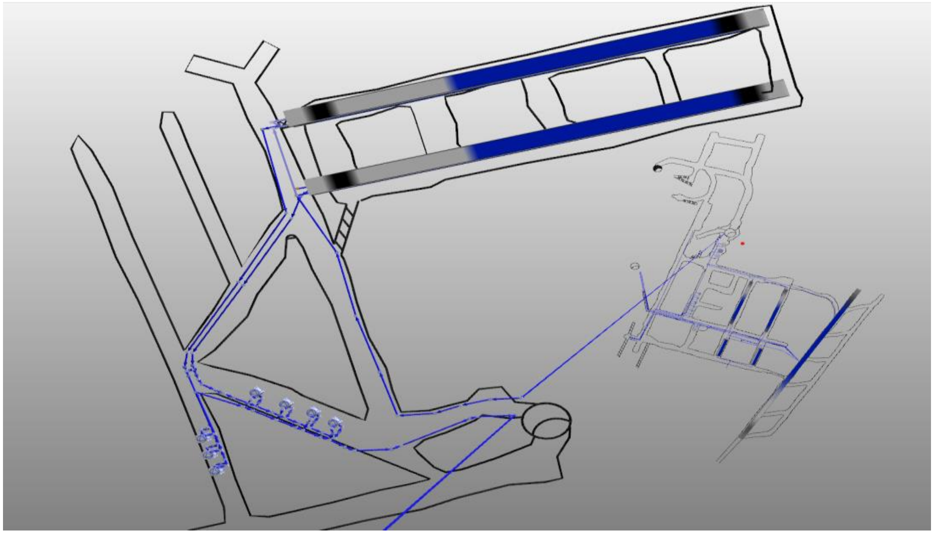


Figure 37: Top view of connected pump levels

The second phase entailed adding the dewatering infrastructure sizes to the skeleton model. PTB has a built-in legend system that colour-codes the sizes of the dewatering columns accordingly. An example of this can be seen in Figure 38.

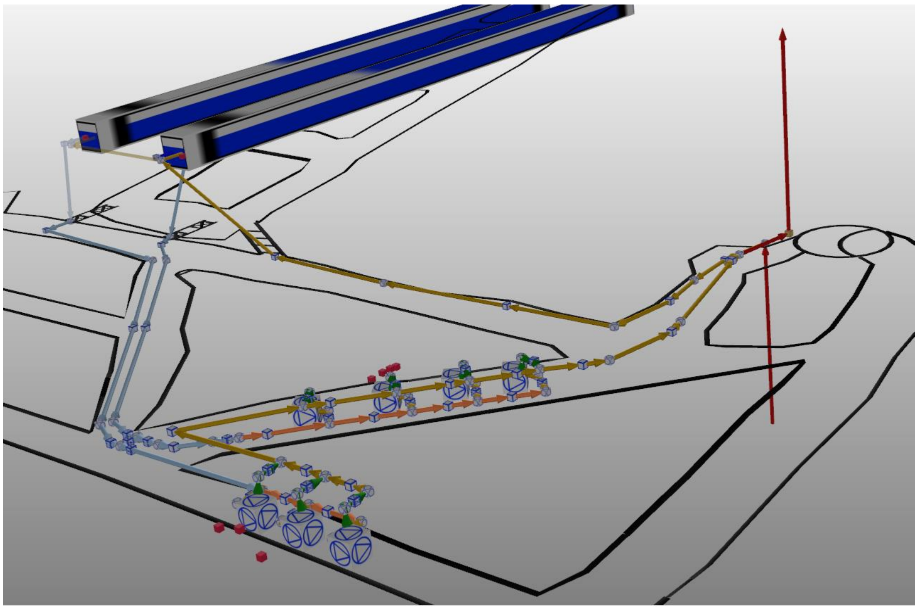


Figure 38: Detailed column overview

The legends used by PTB are displayed in Figure 39. The legends help to distinguish between different pipes and assist with ease of reference when providing feedback to the client.

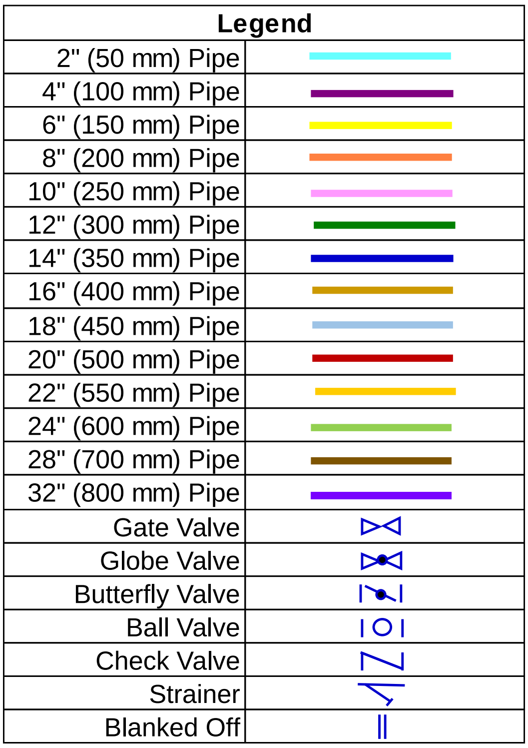


Figure 39: PTB legend

The next phase consisted of importing and calibrating the design conditions of each pump. The calibration was done by using the measured data from the SCADA historian.

3.3.2 Calibration results

The calibration process discussed in Section 2.3.2 was applied to all the dewatering pumps. The design information for each pump received from the site was used alongside the measured data from the historian to calibrate the simulation model. The values from Table 9 were used to calibrate each pump on the test bench. The performance curve plotted by the PTB pump calculator for Pump 4 on 2L is shown in Figure 40.

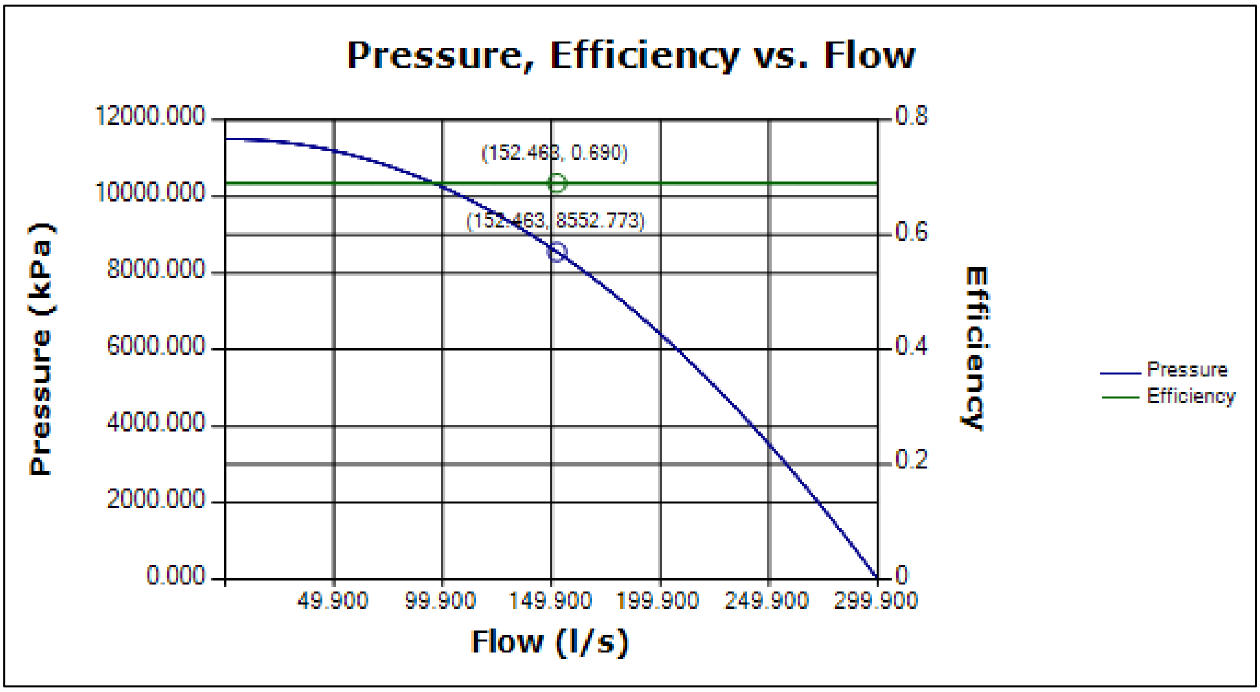


Figure 40: Pump curve on PTB

The test bench method was applied to all the dewatering pumps to show the difference between the measured and simulated values, which are given in Table 12. Therefore, all the calibration results of the pumps were below the specified 5%.

Table 12: Calibrated pumps

Description	Average measured value		Simulated values		Difference	
	Water flow [ℓ/s]	Power [kW]	Water flow [ℓ/s]	Power [kW]	Water flow [%]	Power [%]
PS1 Pump 1	138	1 647	136	1 690	1.4%	−2.6%
PS1 Pump 2	146	1 925	143	1 974	2.1%	−2.5%
PS1 Pump 3	149	1 964	151	1 902	−1.3%	3.2%
PS1 Pump 4	151	2 024	152	2010	−0.7%	0.7%
PS1 Pump 5	156	2 085	155	2 024	0.6%	2.9%
PS1 Pump 6	141	1 908	140	1 903	0.7%	0.3%
PS1 Pump 7	152	1 810	151	1 806	0.7%	0.2%
PS2 Pump 1	239	3 442	238	3 437	0.4%	0.1%
PS2 Pump 2	247	3 370	245	3 397	0.8%	−0.8%
PS2 Pump 3	258	3 512	255	3 548	1.2%	−1.0%
PS3 Pump 1	144	1 414	145	1 430	−0.7%	−1.1%
PS3 Pump 2	142	1 420	143	1 427	−0.7%	−0.5%
PS3 Pump 3	121	1 136	120	1 184	0.8%	−4.2%
PS3 Pump 4	149	1 472	150	1 500	−0.7%	−1.9%

Description	Average measured value		Simulated values		Difference	
	Water flow [ℓ/s]	**Power [kW]**	**Water flow [ℓ/s]**	**Power [kW]**	**Water flow [%]**	**Power [%]**
PS3 Pump 5	126	1 208	129	1 206	−2.4%	0.2%
PS3 Pump 7	158	1443	159	1 473	−0.6%	−2.1%
PS3 Pump 8	146	1 416	146	1 436	0.0%	−1.4%
PS3 Pump 10	122	1 414	123	1 428	−0.8%	−1.0%
PS3 Pump 12	122	1 338	125	1 390	−2.5%	−3.9%
PS4 Pump 1	153	1 347	152	1 352	0.7%	−0.4%
PS4 Pump 2	167	1 415	167	1 425	0.0%	−0.7%
PS4 Pump 3	186	1 487	185	1 492	0.5%	−0.3%
PS4 Pump 4	162	1 368	160	1 380	1.2%	−0.9%

3.4 Verification of digital twin

The verification process compared the measured results from the mine with the model's simulated results. The verification methodology discussed in Section 2.4 was applied to the dewatering infrastructure of Shaft 2.

The first step of this verification process was to select a weekday to evaluate the accuracy of the simulation model. A day with the fewest data errors and data losses was selected to ensure the accuracy of the comparison model.

3.4.1 Water flow

There were four pumps installed on PS4. On the selected day, only one of the four pumps was used throughout the day. The same pump that ran during the day was used for the simulation model to ensure that the simulation was calibrated accurately. Figure 41 illustrates the pump flow results of the simulation model compared with the measured results. The difference between the measured and simulated results was 1.8%.

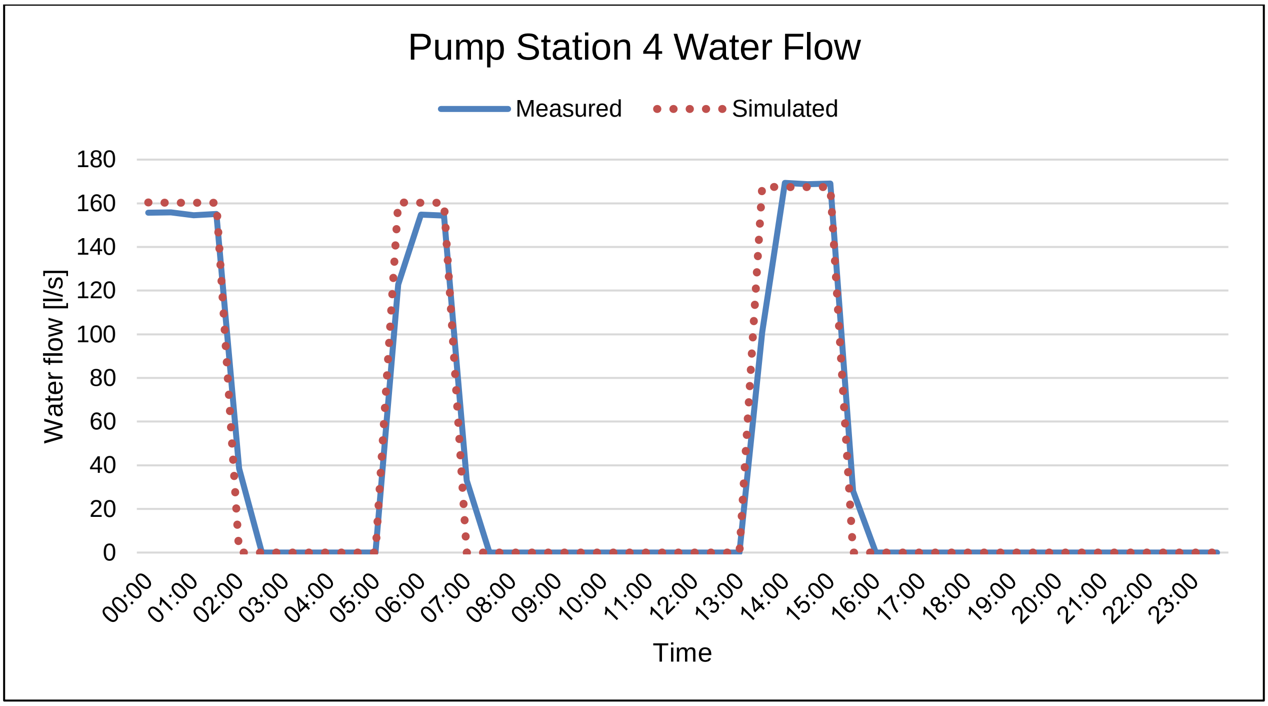


Figure 41: PS4 water flow

The same method was applied to the other three pumping stations on the selected day. Table 14 shows the summarised results. The detailed results can be seen for each pumping station in Appendix A to C. As a result, the difference between the measured and simulated values was less than the required 5%. The difference can be ascribed to the pump maintenance deterioration, as observed in Figure 34.

Table 13: Water flow comparison percentage

Pump station	No. of pumps running	Water flow percentage difference [%]
1	3	4.5
2	2	4.6
3	4	4.0
4	1	1.8

3.4.2 Pump power

Plotting the measured meter power usage from the feeders of pump number 2 of PS 4 from the section above against the simulation results provided a difference of -2.6%. Figure 42 shows the measured power usage compared with the simulated power usage.

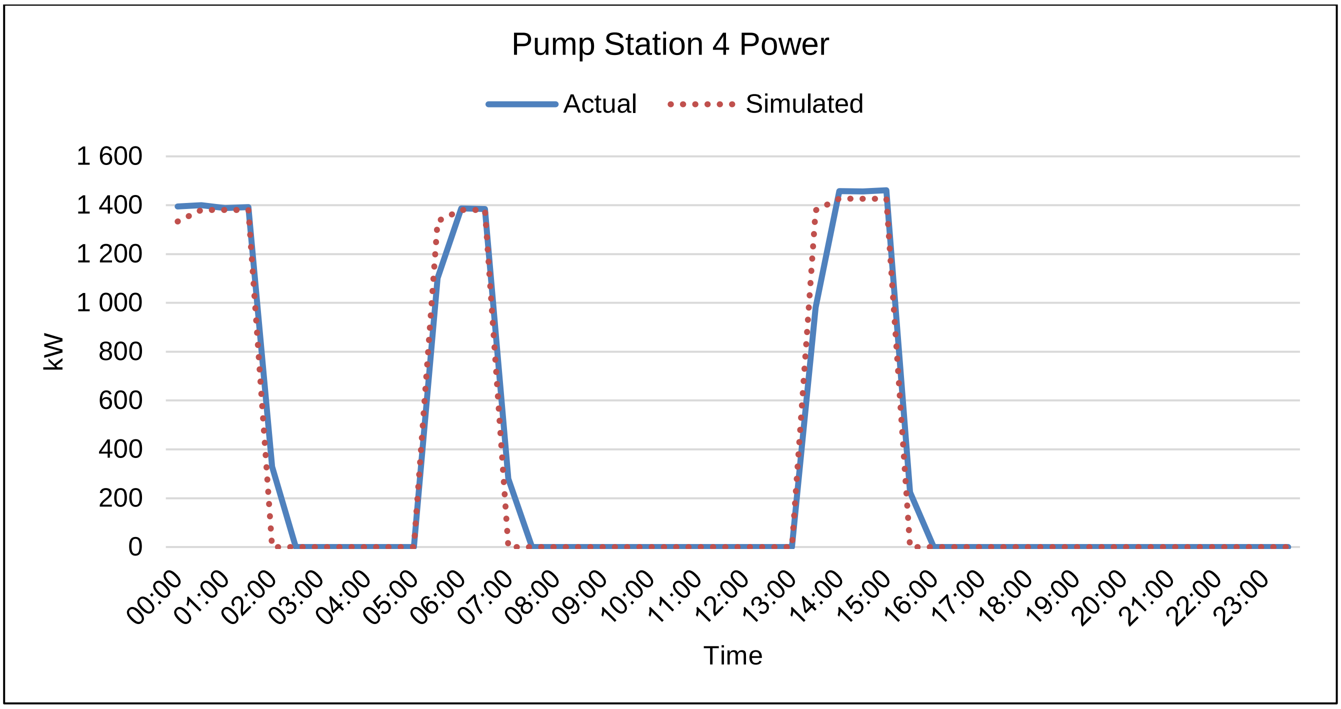


Figure 42: Measured versus simulated power

The same was done for the three remaining pump stations. Table 14 shows the difference between the comparison of the measured and simulated power. The detailed results can be seen for each pumping station in Appendix A to C. Again, all the values were within the 5% requirement criteria.

Table 14: Pump power difference

Pump station	No. of pumps running	Pump power percentage difference [%]
1	3	−4.2
2	2	2.3
3	4	1.3[14]
4	1	−2.6

3.4.3 Dam level

The measured dam levels for the same day were compared with the simulated dam levels. PS4 had three dewatering dams. On the verification day, two of the dams were used. The flow distribution between the two dams was controlled manually. When Dam 1 reached a level of 95%, the water was diverted towards the next dam by physically opening and closing the valves. The

[14] The calculated power usage of the pump was used.

measured dam levels were combined and used for the comparison. The same was applied to the simulation model. Figure 43 shows the measured dam levels of PS4 compared with the simulated level. The difference between the results was 1.4%.

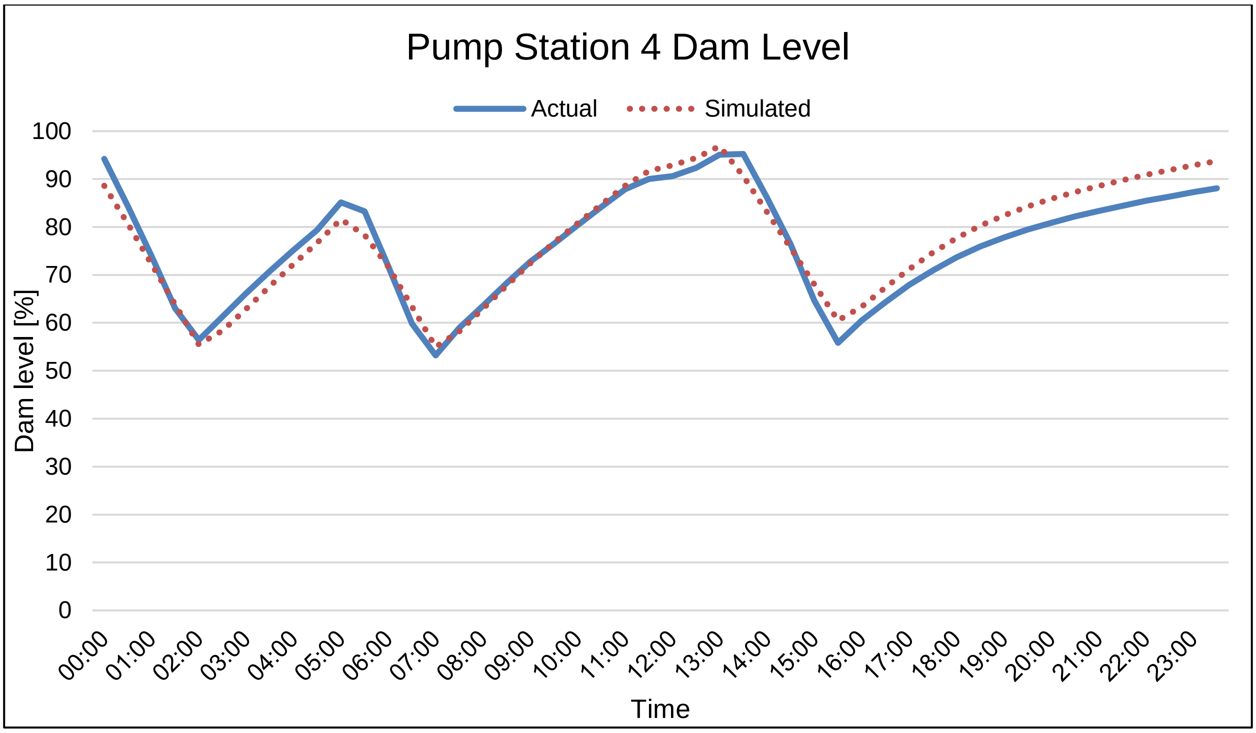


Figure 43: Dam level verification

The same was done for the remaining three dewatering levels. The results are displayed in Table 15. The detailed results can be seen for each pumping station in Appendix A to C. The difference between the measured and simulated dam levels was less than the required 5%.

Table 15: Dam level verification comparison

Pump station	No. of pumps running	Dam level percentage difference [%]
1	3	−0.2
2	2	2.1
3	4	2.6
4	1	1.4

3.5 Validation of method

3.5.1 Case study recap

The verified digital twin model created on the dewatering infrastructure of Shaft 2 was used to investigate the pre-feasibility of diverting the groundwater from Shaft 1. As discussed in Section 2.5, two general methods of validation were identified. In addition, Mine A (the client) was investigating the pre-feasibility of closing Shaft 1 to reduce the cost over the LOM of the other five integrated shafts. Therefore, the study would be validated by supplying the client with a solution and investigating the pre-feasibility of closing Shaft 1. The aim was to:

- Investigate Shaft 2's dewatering system capabilities.
- Determine the future infrastructure required for integrating the dewatering infrastructure of Shaft 1 with Shaft 2.
- Investigate the pre-feasibility of closing Shaft 1.

After defining the aim of the validation approach, the dewatering design requirements of Mine A was investigated.

3.5.2 Mine A's dewatering design criteria

The dewatering design criteria are the requirements that need to be met by a new proposed design configuration. Each mine in operation has the same goal, namely, to prevent the mining operations from flooding. However, from experience working on various mines, each mine has developed their own unique dewatering operating preferences from engineering ingenuity throughout the years of operation. As a result, the required dewatering redundancy of each mine will differ. The redundancy of a mine refers to the operating preferences and design criteria for an existing and new dewatering system.

This dissertation aimed to ensure that all the new recommended dewatering infrastructure and dams adhered to the design requirements. Mine A's dewatering design criteria included the following:

- 100% redundancy on all the dewatering pumps running during standard pump operation conditions.
- At least two dewatering columns are required between two levels.
- 48-hour emergency storage capacity for groundwater.
- Load shifting had to be possible.

Standard pump operating conditions refer to the number of pumps running each day to remove water without implementing load shifting. For example, if two pumps are running throughout the day, two additional pumps are needed. When load shifting is implemented, it reduces the running time of the two pumps. In that case, one of the standbys is used to ensure that the dam remains at the specified level to prevent flooding during the next load-shifting period. Thus, three pumps were required to run and one had to be on standby. The number of pumps running during load shifting was excluded from the redundancy required. Therefore, the number of pumps on the level remained four.

The additional dewatering column between the pumping levels ensured that a dewatering column was always available if one of the two columns failed or needed maintenance. The existing Shaft 2 did not have two columns installed from PS2 up to the surface. Thus, two levels did not meet the required redundancy set by the mine.

All mines have a set of emergency planning and procedures in place if such an event occurs. For example, Mine A required all their dewatering systems to withstand a 48-hour power outage. Therefore, when a power outage occurs, all production is stopped on the mine. However, ground-water will continue seeping into the mine. Therefore, new proposed dewatering dams should be designed to handle at least 48 hours of groundwater seeping into the mine.

The energy required to remove the water from the mine remained the same. The only variable that could be changed was the cost of the energy used. Using more energy during the off-peak hours, as discussed in Section 1.3.1, reduces the overall energy cost. Including load shifting in the design criteria ensured that the mine reduced its overall utility cost. Indirectly, it could also result in the LOM being extended.

The design requirements were used throughout the design and evaluation process of the pre-feasibility of the shaft closure investigation. The next step was to identify the dewatering requirements for Shaft 2.

3.5.3 Dewatering requirements

The dewatering requirements of Shaft 2 with the additional water from Shaft 1 had to be determined. Figure 44 summarises the new dewatering requirements for Shaft 2, calculated in Section 3.2. The new dewatering demand was calculated by considering the peak water demand usage (Service water), followed by the additional groundwater from Shaft 1.

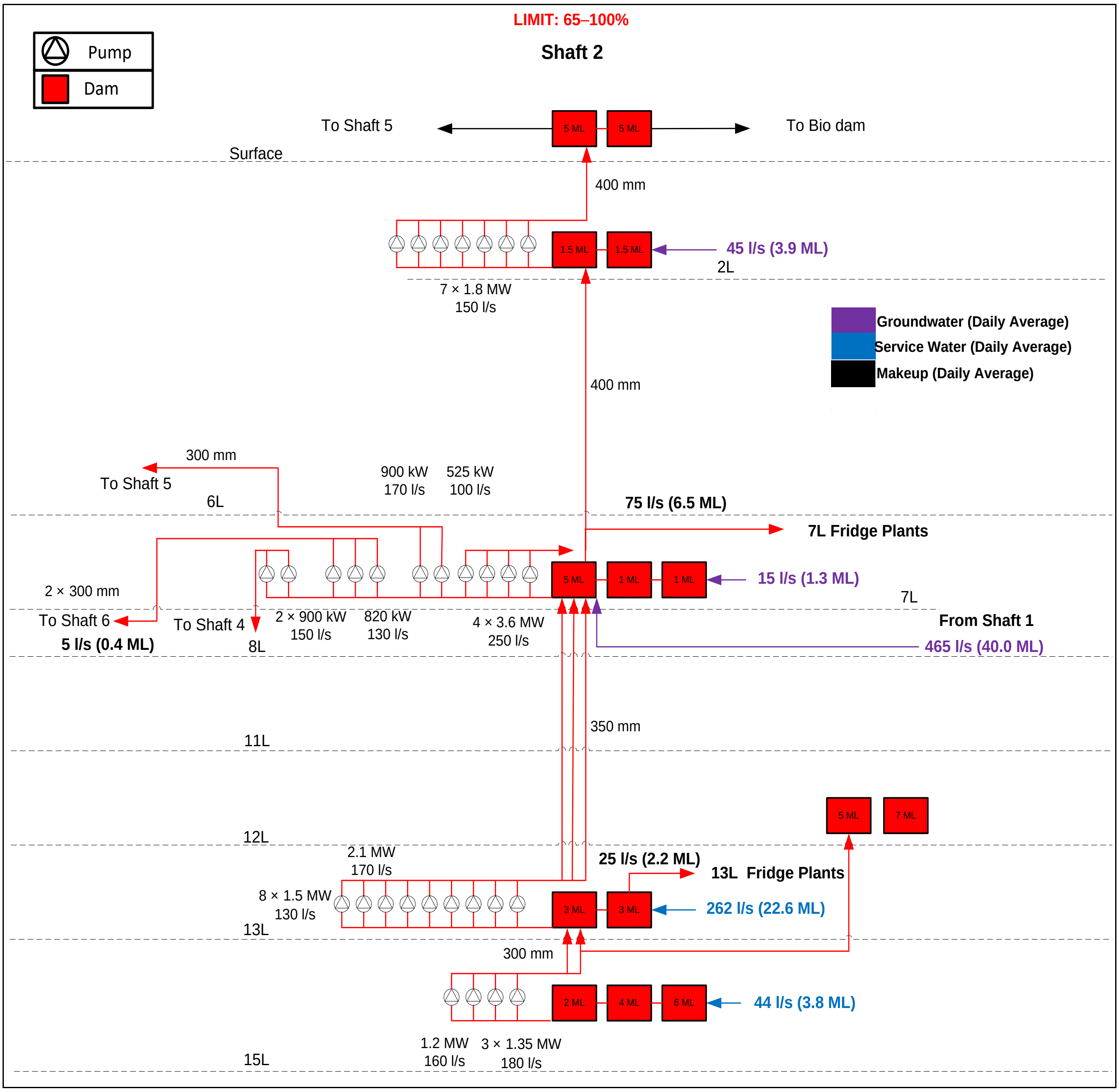


Figure 44: Shaft 2 new dewatering requirements

The water requirements were categorised into three sections, namely groundwater, service water and makeup water. The average daily water that was expected from each category is summarised in Table 16.

Table 16: Total dewatering requirements

Description	Daily average water [ℓ/s]	Legend
Groundwater	525	
Service water	306	
Makeup water	105	

The groundwater consisted of 40 ML water being diverted from Shaft 1 – 1.3 ML of groundwater on 8L and 3.9 ML of groundwater on 2L. Thus, the total groundwater that had to be removed was 45.2 ML per day (525 ℓ/s daily average).

The service water was calculated by using the LOM planning and water usage benchmark developed in Section 2.2. The total service water to be used was 16.5 ML during peak production. Therefore, the service water would return on 13L and 15L, respectively, as shown in Figure 44.

The makeup water was the mine water that would be recirculated by the underground fridge plants as discussed in Section 3.2. An additional 0.4 ML of mine water per day was transferred to Shaft 6 for makeup water. Thus, the daily average makeup water was subtracted from the total water that had to be removed each day.

The total water that had to be removed from Shaft 2 during peak production and diverted groundwater from Shaft 1 was approximately 63.1 ML per day (730 ℓ/s daily average).

3.5.4 Digital twin model

After calculating the dewatering requirements and understanding the design criteria for a new dewatering system, the dewatering capacity of Shaft 2 was investigated. The verified simulation model was used to simulate the peak production water usage of Shaft 2. The dewatering requirements were the same as shown above in Figure 44, except that the groundwater from Shaft 2 was excluded.

Shaft 2: Dewatering system with peak demand

The results of the simulation model are shown in Figure 45. Shaft 2 could pump out the expected peak water usage in Year 3 with load shifting from the simulation model. The legend used to indicate if a pump is running or on standby is in the top right-hand corner of Figure 45.

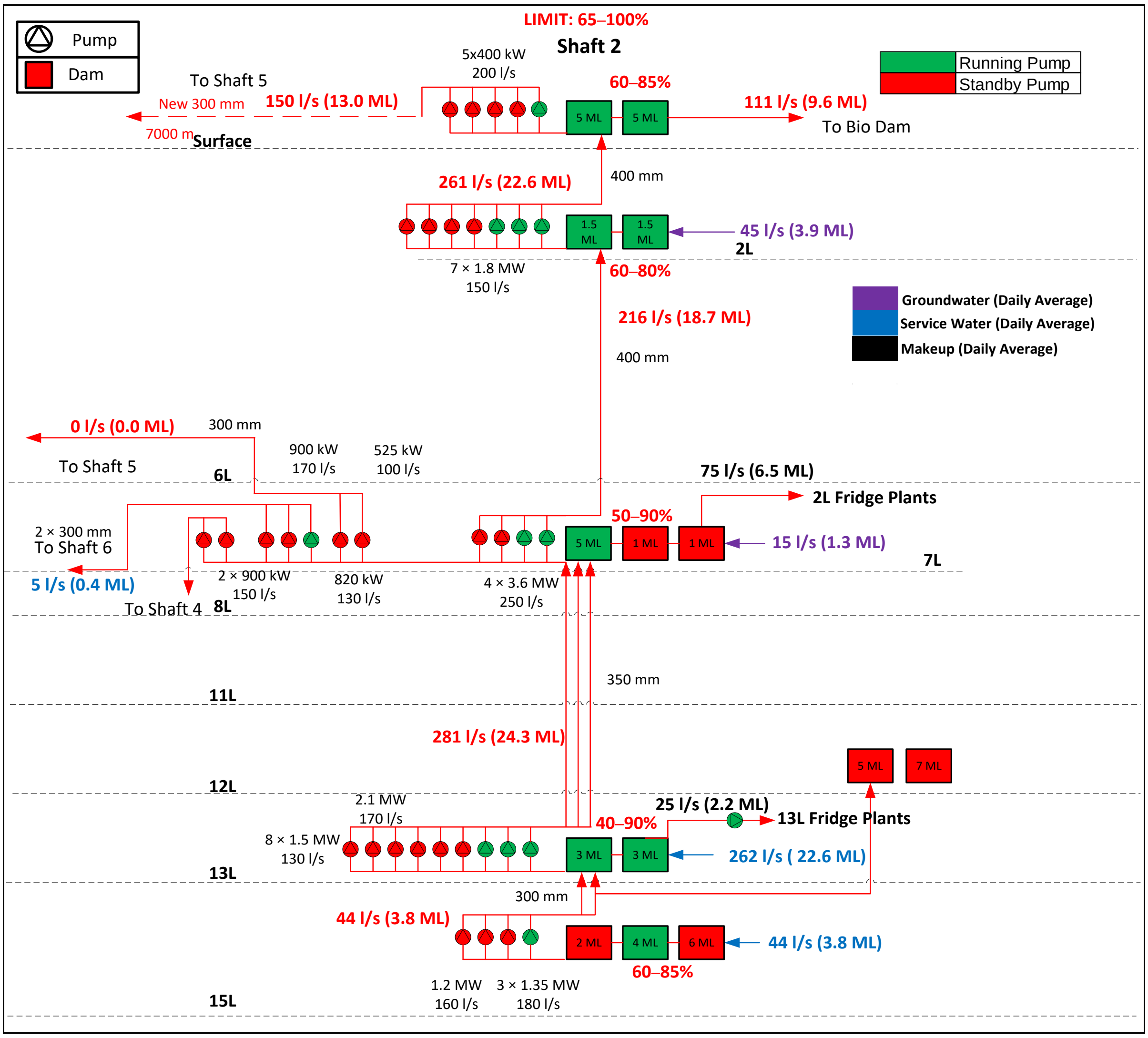


Figure 45: Evaluation of Shaft 2 dewatering system

Table 17 summarises the results from the load shifting and standard operations. All the pumping stations met the required pump redundancy. However, as mentioned in Section 3.5.2, Shaft 2 did not meet the required redundancy criteria of at least two dewatering columns between levels.

Table 17: Shaft 2 peak demand redundancy

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
1	From 2L to surface	7	2	3	Yes	No
2	From 7L to 2L	4[15]	1	2	Yes	No
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

[15] As mentioned in Section 3.2.1, a fourth dewatering pump was being installed on PS2.

Shaft 2: Dewatering system with peak demand and additional groundwater

The next step was to evaluate whether the dewatering infrastructure of Shaft 2 would be able to transfer the additional 40 ML of groundwater from Shaft 1. The dewatering system of Shaft 2 was not able to dewater the required 730 ℓ/s. However, the dewatering system would have been able to dewater the required 730 ℓ/s if there was an additional dewatering column from 7L up to the surface.

The proposed solution was to add a column between the two levels. The solution was simulated, and the results are shown in Figure 46. The additional column would allow Shaft 2 to dewater the 730 ℓ/s water. However, the pump redundancy was not met. Therefore, additional pumps had to installed to meet the redundancy.

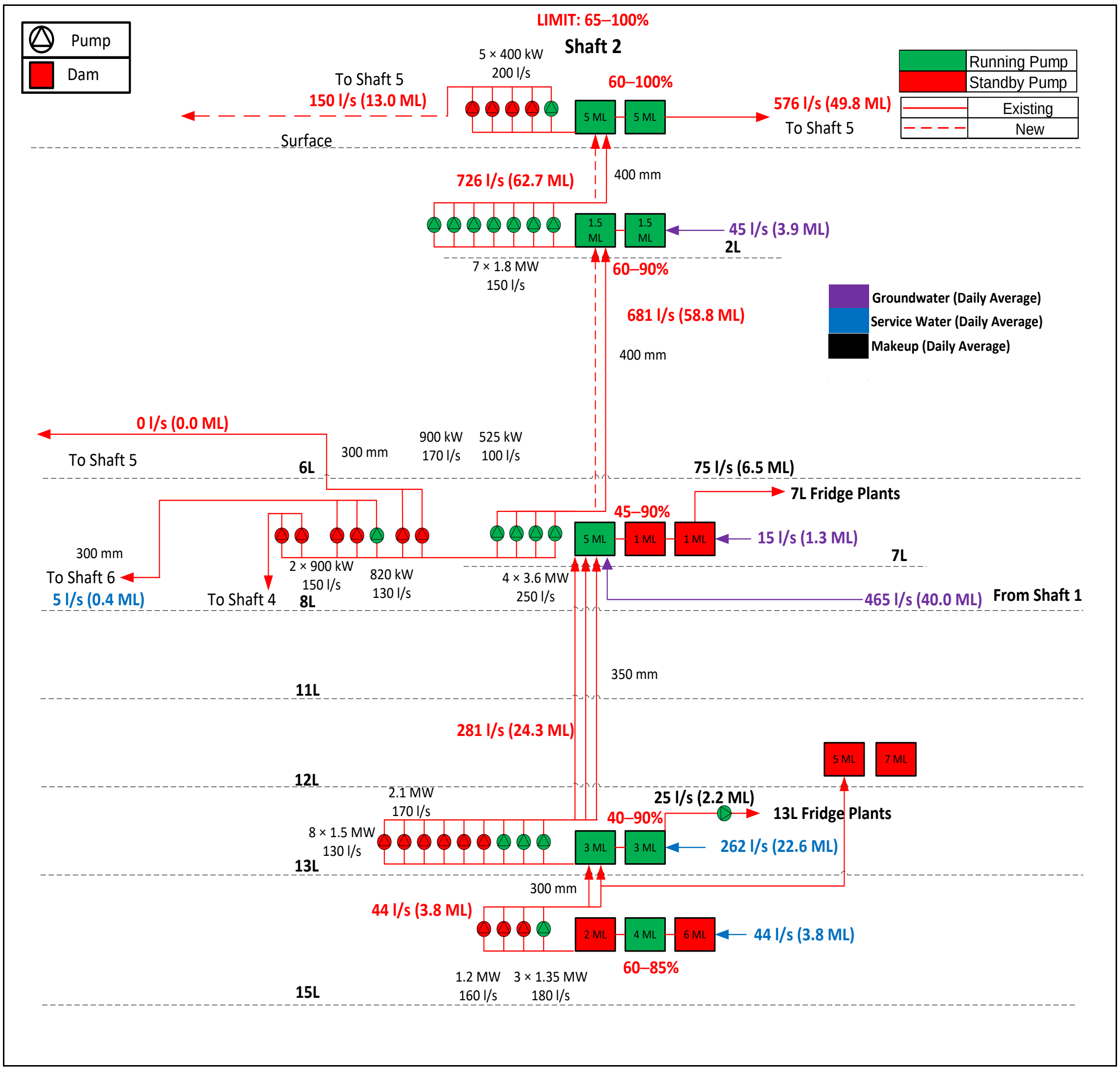


Figure 46: Additional groundwater from Shaft 1

The results from the simulation are summarised in Table 18. The pump redundancy was not met for PS1 and PS2. Therefore, three pumps would be required on PS1 and three pumps on PS2.

The column redundancy would also be met if the additional column was installed. However, if the column was not installed, the dewatering infrastructure would not be capable of removing the required water.

Table 18: Shaft 2 with the additional groundwater

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
1	From 2L to surface	7	5	7	No	Yes
2	From 7L to 2L	4	3	4	No	Yes
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

Shaft 2: Dewatering system with peak demand and additional groundwater with new infrastructure

The solution of installing an additional column and increasing the number of pumps on the two mentioned levels was investigated further. Due to limited floor space, only eight pumps could be installed on PS1. Thus, adding three pumps was not possible. The findings were communicated to the mine and the following solution was investigated.

The proposed solution was to upgrade the seven 1.8 MW pumps with six 2.8 MW pumps on PS1. An additional 1.8 MW pump would be kept on 2L for emergency purposes. For PS2 to meet the redundancy criteria, two additional pumps would also be installed.[16] Furthermore, two additional dewatering columns were also proposed to be installed between PS2 up to the surface.

The proposed solution was evaluated with the simulation model, and the results are shown in Figure 47. The dotted lines indicate the new dewatering infrastructure to be added to the dewatering system of Shaft 2. The new proposed dewatering infrastructure was able to dewater the required 730 ℓ/s.

[16] As mentioned in Section 3.2.1, a fourth dewatering pump was being installed on PS2.

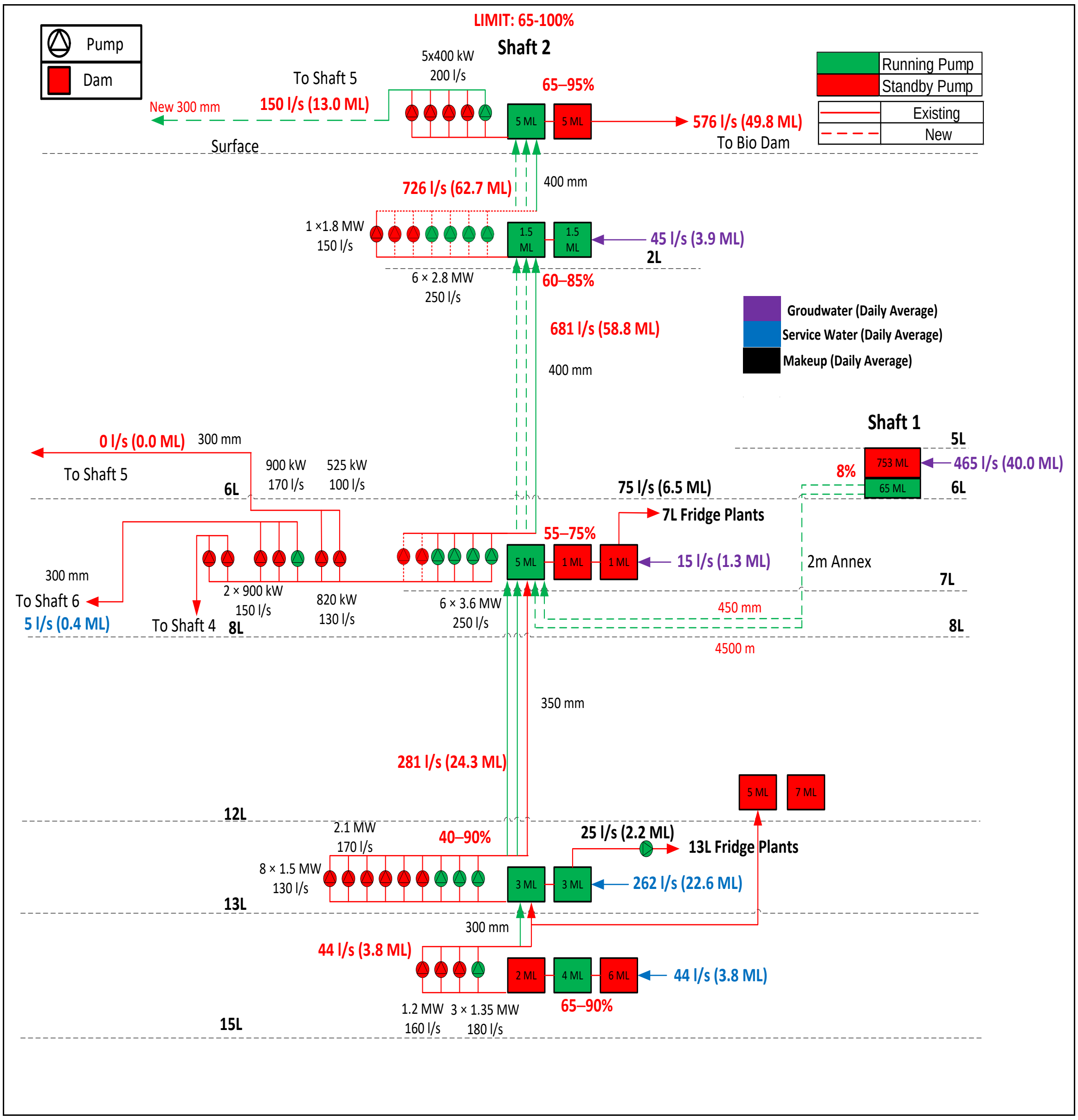


Figure 47: Proposed solution

The summary of the simulated results are given in Table 19. Upgrading the pumps and installing the additional columns would ensure that the redundancy is met.

Table 19: New dewatering infrastructure

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
1	From 2L to surface	7	3	4	Yes	Yes
2	From 7L to 2L	6	3	4	Yes	Yes
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

Newly proposed dam – 48-hour emergency

The diverted groundwater flow from Shaft 1 would be controlled by a large underground dam. The mine supplied the approximate dam size and location of a newly proposed emergency storage dam underground at Shaft 1. The dam's emergency storage capacity was simulated using the digital twin. The water would be redirected from Shaft 1 to Shaft 2 with two underground columns stretching over 4.5 km. The geological height of Shaft 2 was lower than that of Shaft 1. Therefore, no pumps were needed to transfer the water from the dam for the columns would be fed using gravity.

The groundwater would be controlled on Shaft 2's side. For load shifting to be implemented, the water feeding columns from Shaft 1 had to be closed during load shifting. In addition, the valves on the two columns had to be closed on Shaft 2's side to prevent the dewatering dams on 7L from flooding. Thus, no water would flow into the 7L hot dams during load shifting. The next step was to evaluate whether the new dam would sustain a 48-hour power outage. The results from the simulation are given in Figure 48.

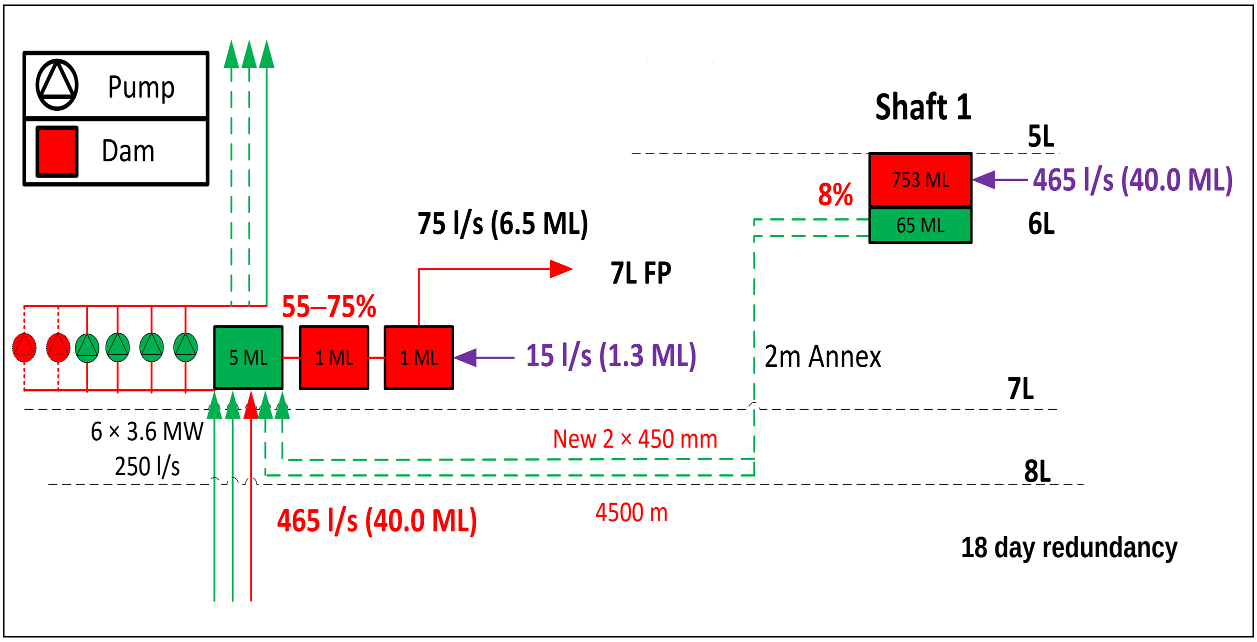


Figure 48: Newly proposed dam emergency testing

The large capacity of the newly proposed dam ensures that the dam will be able to withstand a 48-hour power outage. In a total power failure, the valves on Shaft 2's side will need to be closed. Thus, allowing the groundwater to build up in the newly proposed dam at Shaft 1. As a result, the dam will sustain a power outage for more than 48 hours. The simulation indicated that the dam could take up to 18 days to flood with a constant water flow of approximately 465 ℓ/s of groundwater. However, the dam level must be kept below 10% at all times for this to be possible. The new dam adheres to the required 48-hour redundancy capacity.

3.5.5 Pre-feasibility investigation

The verified simulation model was used successfully to simulate the new dewatering infrastructure upgrades and changes. As discussed in the background in Section 1.2, a dewatering design consists of three phases. The last phase consists of investigating the feasibility of the new dewatering system. This will be done by comparing several costing factors and potential savings achieved by installing the new dewatering system. As discussed in Section 3.1, the dissertation will only focus on the pre-feasibility of the project.

The factors that were reviewed to evaluate the pre-feasibility are:

- Total infrastructure cost.
- Cost savings.
- Pay-back period.

A third-party consulting firm provided the infrastructure cost. The infrastructure included the labour needed to install the infrastructure. A summary of all the infrastructure costs is seen in Table 20. The total approximation of the infrastructure cost needed to close Shaft 1 and divert the groundwater to Shaft 2 was R448.8 million.

Table 20: Total infrastructure cost

Description	**Cost [R million]**
6 × pumps (2.8 MW) on 2L	46.1
2 × pumps (3.6 MW) on 7L	17.8
Floating spare pump (2.8 MW)	7.7
Floating spare pump (3.6 MW)	8.9
2 × columns from PS2 up to the surface	55.7
Electrical feeders	24.0
New dam and diverting columns cost	288.6
Total	**448.8**

The cost savings generated by closing the shaft is the C&M cost of keeping the shaft open. The energy consumption will remain the same. As discussed in Section 3.5.2, the same amount of energy will be used to remove the water from underground. In addition, Shaft 1 is currently implementing load shifting on its existing system. Therefore, the only cost that will be saved overall will be the maintenance cost on the shaft.

The approximate amount of capital needed to keep a shaft under C&M may not be disclosed. However, the approximate amount was multiplied by a random number to provide an estimated cost for this pre-feasibility investigation. The estimated cost for keeping a shaft under C&M is R80 million a year.

The annual inflation rate of South Africa is between 3% and 6% [58]. Therefore, an average inflation rate of 4.5% was used to forecast the yearly C&M cost increase over several years. The forecasted cost increase is shown in Figure 49.

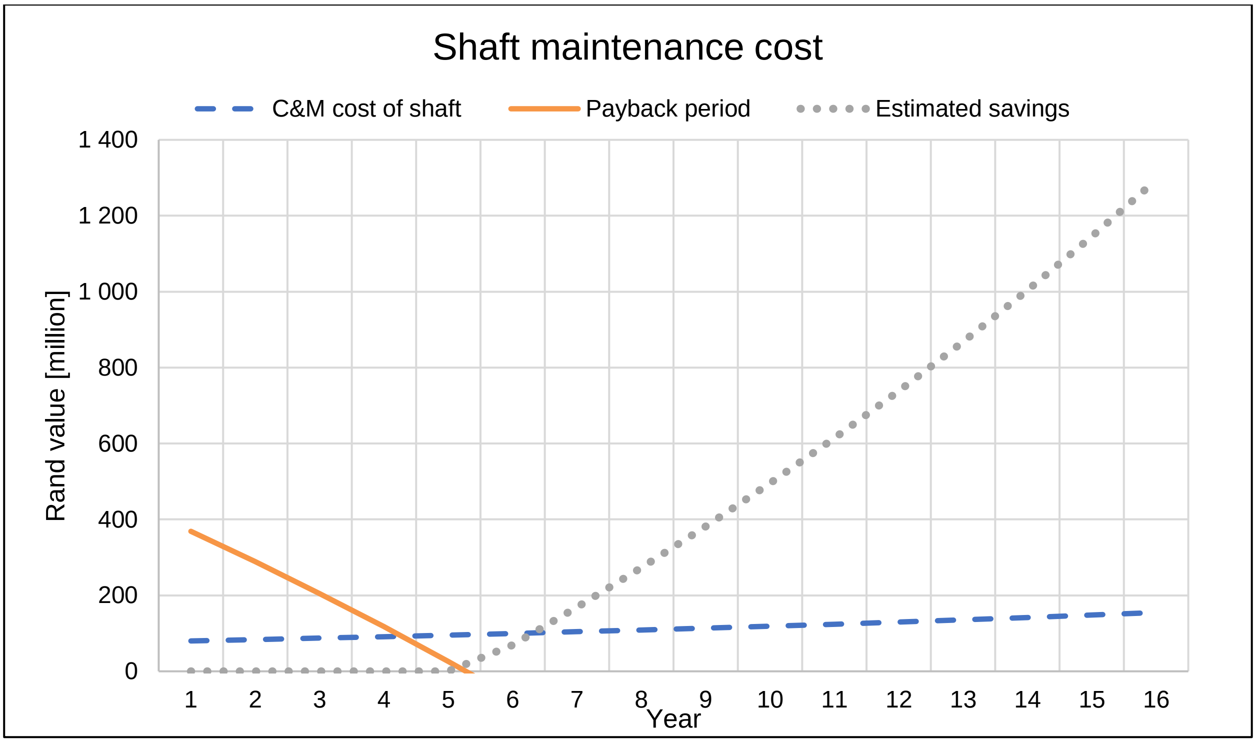


Figure 49: Shaft maintenance cost with inflation

Considering the increase in C&M cost, the estimated payback period for closing the C&M shaft will be in Year six. For industry projects in general, a payback period shorter than two years is acceptable [59]. The LOM benefit, however, will yield high capital savings. For confidentiality, the exact LOM of the mine may not be used. Instead, Microsoft Excel was used to generate a random number between an upper and lower boundary. By using the randomly generated number, the LOM was calculated to be 16 years. The net LOM benefit over the 16 years, considering the inflation rate, will be approximately R1 300 million.

The other factor that influenced the feasibility of this project was the gold price. The LOM is sensitive towards the change in gold price [60]. In a scenario where the gold price decreased, the

LOM would be shortened. Thus, influencing the LOM and reducing the amount of savings. Using the forecasted gold price from Forex Ratings[17] and Trading Economics,[18] the expected gold price was estimated to increase marginally, thus increasing the feasibility of the project. Considering the forecasted gold price and the payback period with the expected cost savings, the feasibility of the project was favoured.

3.6 Discussion of results and validation

The simulation model's accuracy was verified against the measured values of the mine. The verification process was done on all four pumping levels. As discussed in Section 2.4, the goal was to verify that the simulation model was within 5% of the measured system. The results of the verification process are shown in Table 21. The goal was achieved, and the absolute average difference between the measured and simulated values were 1.5%.

Table 21: Verification result summary

Pump station	No. of pumps running	Percentage difference [%]
Pump water flow verification		
1	3	4.5
2	2	4.6
3	4	4.0
4	1	1.8
Pump power verification		
1	3	−4.2
2	2	2.3
3	4	1.3[19]
4	1	−2.6
Dam level verification		
1	3	−0.2
2	2	2.1
3	4	2.6

[17] Forex Ratings, "Gold Price forecast & predictions for 2020, 2025 & 2030," 7 Jul. 2020. [Online]. Available:https://www.forex-ratings.com/forex-forecasts/?id=30397.

[18] Trading Economics, "Gold," n.d. [Online]. Available: https://tradingeconomics.com/commodity/gold.

[19] The calculated power usage was used for pump no. 7.

Pump station	No. of pumps running	Percentage difference [%]
4	1	1.4
Total average difference		**1.5**

The verified simulation model was used initially to validate whether the existing infrastructure on Shaft 2 would sustain the peak service water demand in Year 3. The water usage benchmark developed was applied to estimate the expected water usage during peak production in Year 3. The results of the simulation are given in Table 22. The shaft would be able to dewater the expected peak demand. However, the two levels did not have the required column redundancy, as discussed in Section 3.5.3.

Table 22: Peak water demand of Shaft 2

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
1	From 2L to surface	7	2	3	Yes	No
2	From 7L to 2L	3	1	2	Yes	No
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

The second part of the validation process was to evaluate whether the dewatering infrastructure of Shaft 2 would be able to dewater its expected peak service water and the additional groundwater from Shaft 1. The existing system could not withstand the additional groundwater without an additional dewatering column from PS2 to PS1 and from PS1 to the surface. Therefore, an additional column was added to the simulation model. The results are shown in Table 23. The simulation model required additional dewatering pumps on PS1 and PS2 for pump redundancy.

Table 23: Peak water demand and groundwater from Shaft 1 of Shaft 2

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
1	From 2L to surface	7	5	7	No	Yes
2	From 7L to 2L	3	3	4	No	Yes
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

The third part of the validation process was to evaluate the new prosed dewatering infrastructure of Shaft 2. The new proposed infrastructure upgrades are summarised in Table 24.

Table 24: Infrastructure upgrades on Shaft 2

Description of infrastructure changes
Pump Station 1
6 × new 2.8 MW pumps (250 ℓ/s)
1 × old 1.8 MW pump (150 ℓ/s)
2 × columns to surface
Pump Station 2
2 × new 3.6 MW pumps (250 ℓ/s)
2 × columns to Pump Station 1

The proposed infrastructure was added to the simulation model, and the results are shown in Table 25. The new proposed infrastructure changes on Shaft 2 would be able to dewater the peak water demand, including the additional groundwater from Shaft 1.

Table 25: New proposed dewatering infrastructure of Shaft 2

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
1	From 2L to surface	7	3	4	Yes	Yes
2	From 7L to 2L	6	3	4	Yes	Yes
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

The fourth part of the validation process was to evaluate the capacity of the newly proposed underground dam by using the simulation model. The simulation model was used to evaluate a 48-hour emergency power failure on the dam. The simulation results indicated that the dam would withstand and power outage of up to 18 days.

The final part of the validation process was to investigate the pre-feasibility of closing Shaft 2. The savings to be achieved by closing the shaft included the C&M cost of keeping a shaft open. The total payback period of the project will be within six years. Even though the payback period is longer than an acceptable payback period of two years, the overall benefit stretches over the LOM. The estimated savings after 16 years will be R1 300 million considering that the gold price remains stable.

3.7 Conclusion

The verified simulation model was used to investigate the pre-feasibility of closing C&M shafts used only for pumping. The groundwater from the shaft would be diverted to a neighbouring shaft.

The existing infrastructure of the neighbouring shaft was investigated, and several recommendations were made to ensure the dewatering infrastructure of the shaft would be able to handle the increased dewatering demand.

The verified simulation model was used to evaluate the new proposed infrastructure changes. The results from the simulation model concluded that the newly recommended infrastructure would be able to sustain the increased dewatering demand. In addition, the model was used to ensure that the new infrastructure would adhere to the required redundancy.

The study was validated by investigating the client's request regarding the pre-feasibility of the shaft closure project. As a result, it was determined that it would be feasible to close the C&M shaft. Although the payback period was within six years, the overall LOM savings would benefit the shaft closure project tremendously provided that the gold price remained stable.

Chapter 4: Conclusion

Underground railroad track[20]

The chapter will provide an overview of the study, followed by the shortcomings identified and recommendations for future studies.

[20] P. Müller "Underground rail transport at local mines not being prioritised," *Mining Weekly*, 30 Mar. 2018. [Online]. Available: https://www.miningweekly.com/article/underground-rail-transport-at-local-mines-not-being-prioritised-2018-03-12/rep_id:3650

CHAPTER 4: CONCLUSION

4.1 Preamble

The chapter will provide an oversight of the process followed to solve the objective of this dissertation. The oversight will summarise the literature findings, solution development, and the method's verification and validation on a case study. In addition, it will discuss the shortcomings that were identified in this study, followed by guidelines for future work.

4.2 Study overview

The increasing depth of gold mines causes numerous engineering challenges to ensure both profitability and a safe work environment. These challenges include providing adequate cooling and ventilation for workers, and removing groundwater and service water from the mine to prevent flooding. The focus of this study was directed towards the engineering challenges on the design of a dewatering system. As discussed in Chapter 1, the design of a dewatering system consists of three parts, namely hydrogeological surveys, dewatering system design and feasibility investigation.

Previous studies on dewatering designs either focused on forecasting the dewatering demand that had to be removed or used a simulation-based method to reconfigure the existing water reticulation system. However, the research gap identified was that these studies did not consider evaluating the future dewatering infrastructure using a simulation model. This included the effect of the reconfigurations done on a system for future operations. Therefore, the objective of this study was to develop a method to assist with:

- Evaluating an existing mine's dewatering system capabilities on the simulation model.
- Using the simulation model to evaluate the newly proposed reconfiguration on the system.
- Evaluating the feasibility of the newly proposed reconfigurations.

A methodology was developed in Chapter 2 to address the objectives of the study. The methodology consisted of developing an integrated simulation-based method to assist mines with planning of their dewatering system. The method was verified and validated in a case study. Mine A was in the process of considering the closure of a C&M shaft (Shaft 1), which was a vulnerable asset for ensuring that the neighbouring shafts did not flood.

The methodology developed was applied to the case study to evaluate the newly proposed reconfiguration that entailed diverting the groundwater to a neighbouring shaft (Shaft 2). The only way the capacity of the dewatering infrastructure could be evaluated was by creating a digital twin model of the dewatering system of Shaft 2. The digital twin model (simulation model) was verified against the existing dewatering system to represent the installed dewatering infrastructure accurately. In addition, the newly proposed reconfiguration changes were added to the digital twin to evaluate whether it would be feasible and sustainable to divert the groundwater from Shaft 1 to Shaft 2. The results of the simulations are summarised in Table 26.

Table 26: Summary of the simulations

Pump station	Description	Installed	Required	Required during load shedding	Pump redundancy	Column redundancy
Simulation 1: Evaluating the dewatering infrastructure of Shaft 2						
1	From 2L to surface	7	2	3	Yes	No
2	From 7L to 2L	4	1	2	Yes	No
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes
Simulation 2: Evaluating the capability of Shaft 2 to remove the groundwater from Shaft 1						
1	From 2L to surface	7	5	7	No	Yes
2	From 7L to 2L	4	3	4	No	Yes
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes
Simulation 3: Evaluating the newly proposed dewatering infrastructure to remove the groundwater from Shaft 1						
1	From 2L to surface	7	3	4	Yes	Yes
2	From 7L to 2L	6	3	4	Yes	Yes
3	From 13L to 7L	9	3	3	Yes	Yes
4	From 15L to 13L	4	1	1	Yes	Yes

The existing dewatering infrastructure of Shaft 2 was investigated to ensure that it did have the necessary capacity to remove its service and groundwater during its peak production period. The simulation confirmed that the dewatering infrastructure of Shaft 2 would be able to remove the expected peak water demand. However, an additional dewatering column had to be installed from PS2 up to the surface to ensure the dewatering system adhered to the required redundancy.

The existing dewatering infrastructure of Shaft 2 was investigated to evaluate whether the installed capacity of the system would be capable of handling the additional groundwater from Shaft 1. The results from the simulation indicated that Shaft 2 would only be able to handle the additional groundwater if an additional column was installed from PS2 up to the surface. If an additional column was installed, the dewatering system would remove the groundwater. However, additional dewatering pumps on PS1 and PS2 would need to be installed to adhere to the required redundancy criteria.

The newly proposed dewatering infrastructure to be installed on Shaft 2 was evaluated. The results from the simulation indicated that the infrastructure upgrades would be capable of removing the additional groundwater from Shaft 1 with the required redundancy installed.

The simulation was further used to investigate the redundancy and control strategy of the newly proposed dam on Shaft 1 and the columns diverting the groundwater. The results from the simulation indicated that the dam capacity would be sufficient to handle the required 48-hour emergency storage capacity. The control strategy developed to implement load shifting on Shaft 2 consisted of closing the supply columns from the dam on Shaft 1's side to prevent water from flooding the dams on 7L. As a result, the groundwater will gradually build up in the dam and be removed during the off-peak Eskom tariff times.

The last objective was to evaluate the pre-feasibility of this project. The C&M cost of keeping a shaft open was considered to increase gradually with the inflation rate[21] each year. Therefore, the payback period would be within the year six of project implementation. The results of the pre-feasibility study indicated that it would be feasible to close the shaft considering the LOM. Thereafter, the cost savings would accumulate over the LOM. The gold price could further contribute to the LOM being extended, considering that the gold price would marginally increase as forecasted by Forex Ratings[22] and Trading Economics.[23]

4.3 Shortcomings

The shortcomings of this study and the newly proposed method identified are the following:

- The method is dependent on the mine having a reliable SCADA-type system with a database. If a mine does not have these systems available, the deterioration of pumps and actual water usage will need to be measured manually and interpolated, leading to inaccuracies.

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[21] Inflation rate of 4.5% used [58].

[22] Forex Ratings, "Gold Price forecast & predictions for 2020, 2025 & 2030," 7 Jul. 2020. [Online]. Available:https://www.forex-ratings.com/forex-forecasts/?id=30397.

[23] Trading Economics, "Gold," n.d. [Online]. Available: https://tradingeconomics.com/commodity/gold.

- The method is further dependent on the amount of information the mine is willing to provide. For example, access to production data, underground layouts, and LOM planning data are restricted and confidential.

- The study did not consider each pump's deterioration effect on the overall life expectancy of the pump's performance. The effect thereof could decrease the overall pumping capacity of the dewatering system.

- The study did not focus on the design of the dewatering columns to be used. Instead, the study only focused on evaluating if the suggested infrastructure would be able to remove the groundwater and service water.

- The study only evaluated the newly proposed infrastructure by using a simulation method. The implementation phase of this project is spanned over several years, surpassing the duration of the study.

4.4 Recommendations for future work

The author identified several recommendations for future work:

- Applying the method to the whole dewatering infrastructure on a mine (if it consists of integrated shafts). The dynamic effect of closing one of the shafts can be investigated on all the integrated shafts.

- Applying the same approach on the service water side of the mine to assist and guide the future planning thereof. In addition, this will provide a guideline for mining personnel to determine if the proposed solutions will meet the requirements.

- Using a simulation-based method to evaluate the emergency flood procedures on the dewatering system of deep-level mines. By using a verified digital twin of the mine, the emergency procedure can be evaluated without posing a risk to the mining environment itself.

4.5 Concluding remarks

The study discussed the engineering challenges faced on a deep-level mine. The study identified and developed a method to assist deep-level mines with their dewatering planning. The method aimed to investigate newly proposed projects and reconfiguration changes on a simulation-based model. Thereafter, the feasibility and sustainability of the proposed projects and reconfigurations can be evaluated.

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APPENDIX A: PUMP STATION 1 VERIFICATION

The verification methodology discussed in Section 2.4 was applied to all the pumping stations of Shaft 2. As discussed in Section 3.4, the first step of this verification process was to select a weekday to evaluate the accuracy of the simulation model. The same day was used throughout the verification process of the digital twin.

Water flow

There were seven pumps installed on PS1. On the selected day, only three of the seven pumps were used throughout the day. The same pumps that ran during the day were used for the simulation model to ensure that the simulation was calibrated accurately. Figure 50 illustrates the pump flow results of the simulation model compared with the measured results. The difference between the measured and simulated results was 4.5%, meeting the requirements of less than 5%. The difference can be ascribed to the pump maintenance deterioration, as observed in Figure 34 in Section 3.2.4.

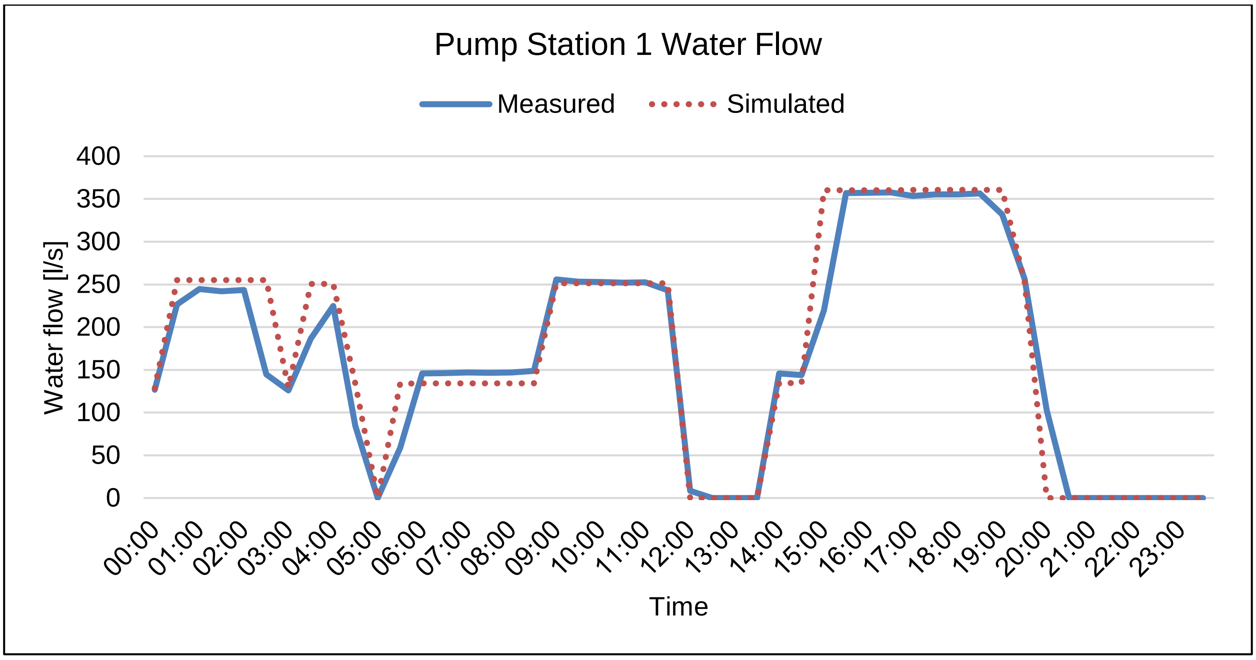

Figure 50: PS1 water flow

Pump power

Plotting the combined measured power usage of all three pumps running on PS1 for the same selected day against the simulation results provided a difference of -4.2%. Figure 51 shows the measured power usage compared with the simulated power usage. Again, the results were within the 5% requirement criteria.

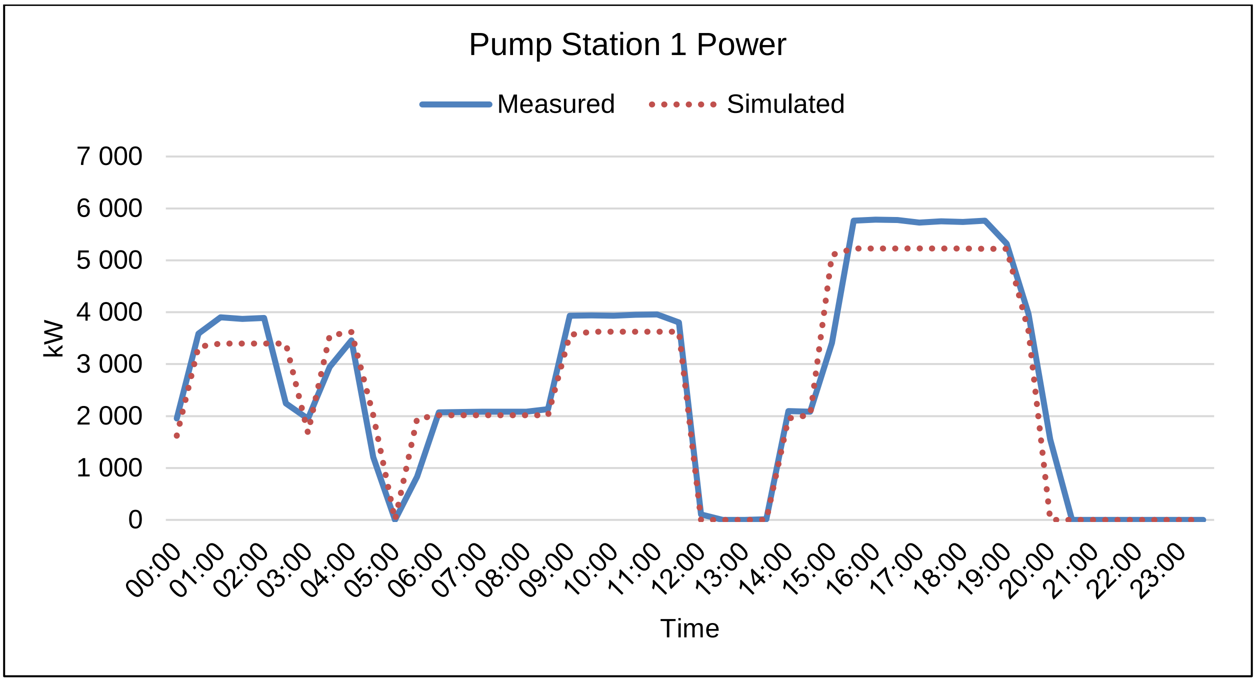

Figure 51: PS1 Measured versus simulated power

Dam level

The measured dam levels for the same day were compared with the simulated dam levels. PS1 had two dewatering dams. On the verification day, both dams were used. The flow distribution between the dams was controlled manually. The same principle discussed in Section 2.4.3 was applied by combining the measured dam levels to compare the measured and simulated results. The same was applied to the simulation model. Figure 52 shows the measured dam levels of PS1 compared with the simulated level. The difference between the results was -0.3%.

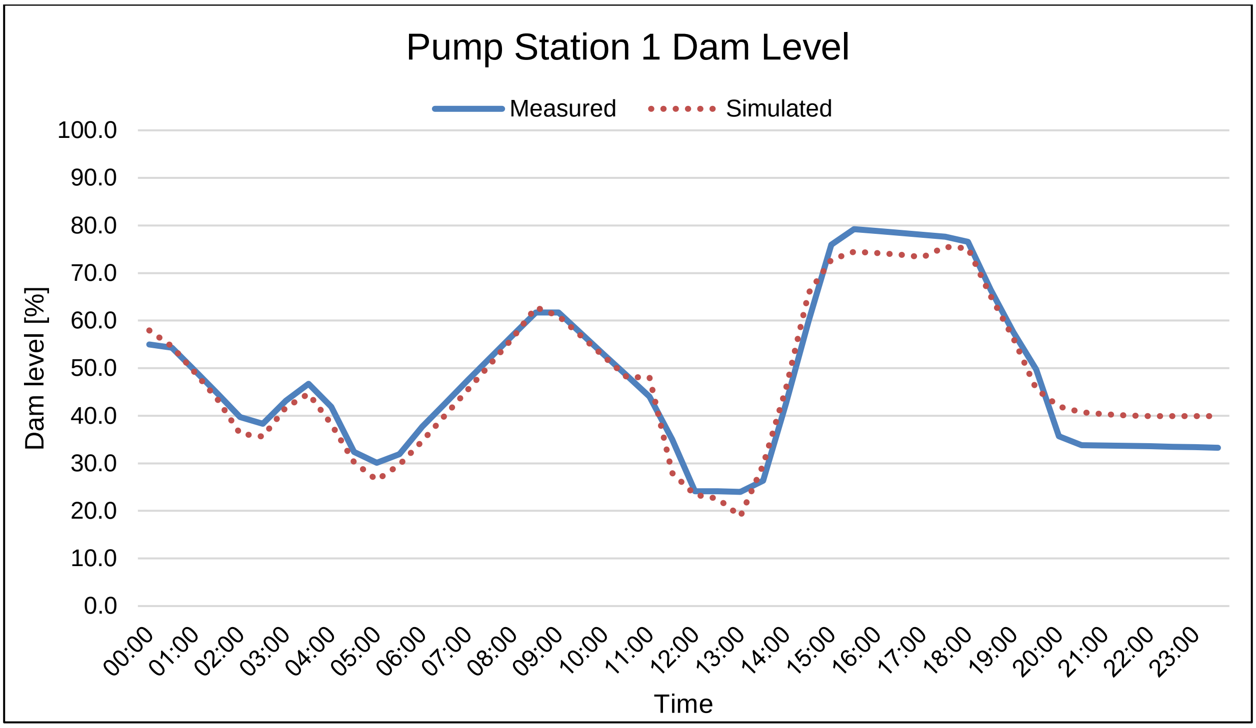

Figure 52: PS1 Dam level verification

APPENDIX B: PUMP STATION 2 VERIFICATION

The verification methodology discussed in Section 2.4 was applied to all the pumping stations of Shaft 2. As discussed in Section 3.4, the first step of this verification process was to select a weekday to evaluate the accuracy of the simulation model. The same day was used throughout the verification process of the digital twin.

Water flow

There were three[24] pumps installed on PS2. On the selected day, only two of the three pumps were used throughout the day. The same pumps that ran during the day were used for the simulation model to ensure that the simulation was calibrated accurately. Figure 53 illustrates the pump flow results of the simulation model compared with the measured results. The difference between the measured and simulated results was 4.6%, meeting the requirements of less than 5%. The difference can be ascribed to the pump maintenance deterioration, as observed in Figure 34 in Section 3.2.4.

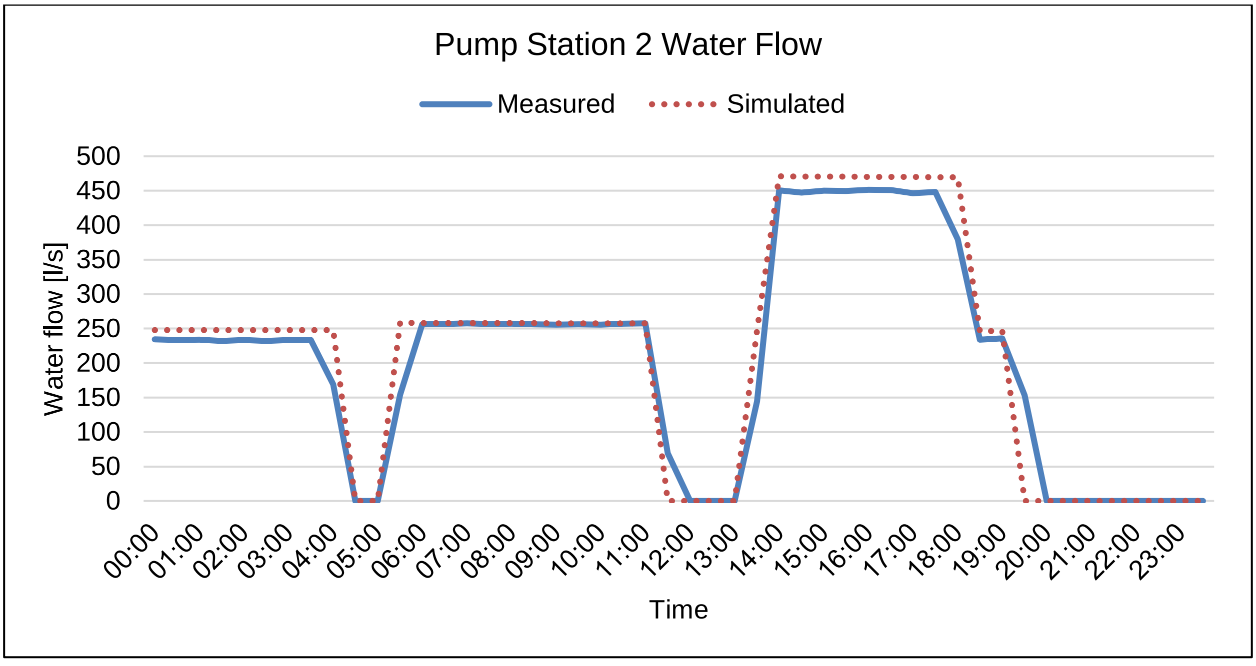

Figure 53: PS2 water flow

[24] As discussed in Section 3.2.1, a fourth pump was being installed and was only included in the validation section.

Pump power

Plotting the combined measured power usage of both the running pumps on PS2 for the same selected day against the simulation results provided a difference of 2.3%. Figure 54 shows the measured power usage compared with the simulated power usage. Again, the results were within the 5% requirement criteria.

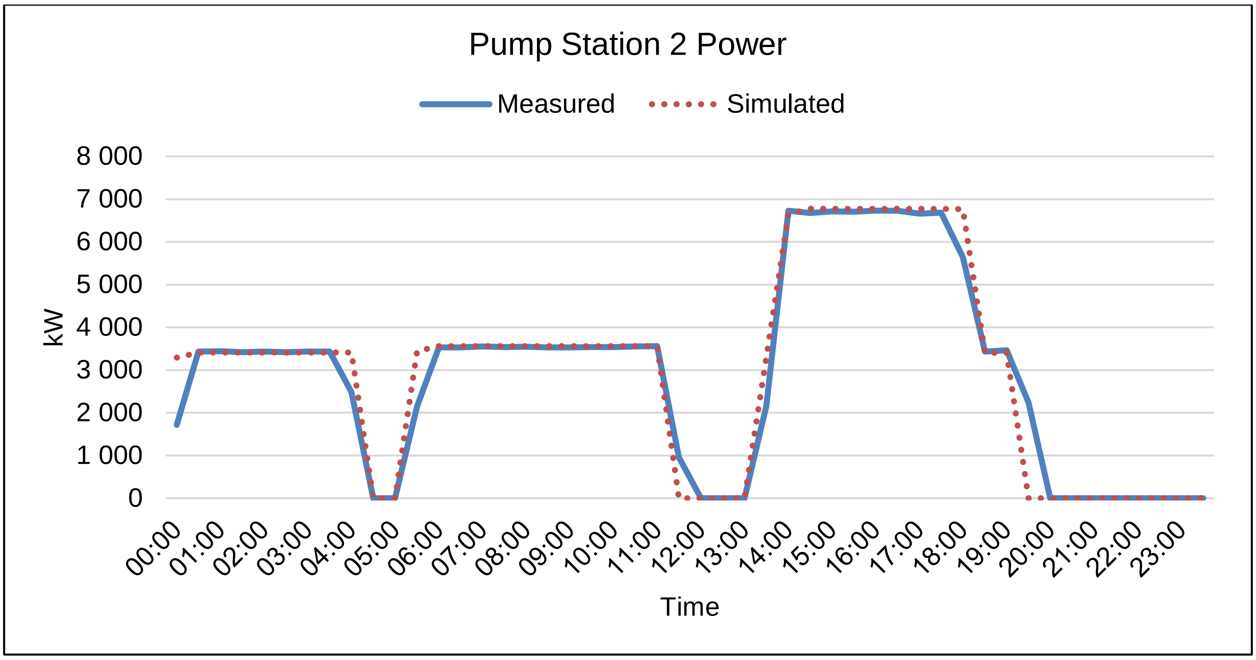

Figure 54: PS2 Measured versus simulated power

Dam level

The measured dam levels for the same day were compared with the simulated dam levels. PS2 had three installed dewatering dams. On the verification day, all three dams were used. The flow distribution between the dams was controlled manually. The same principle discussed in Section 2.4.3 was applied by combining the measured dam levels to compare the measured and simulated results. The same was applied to the simulation model. Figure 55 shows the measured dam levels of PS2 compared with the simulated level. The difference between the results was 2.1%.

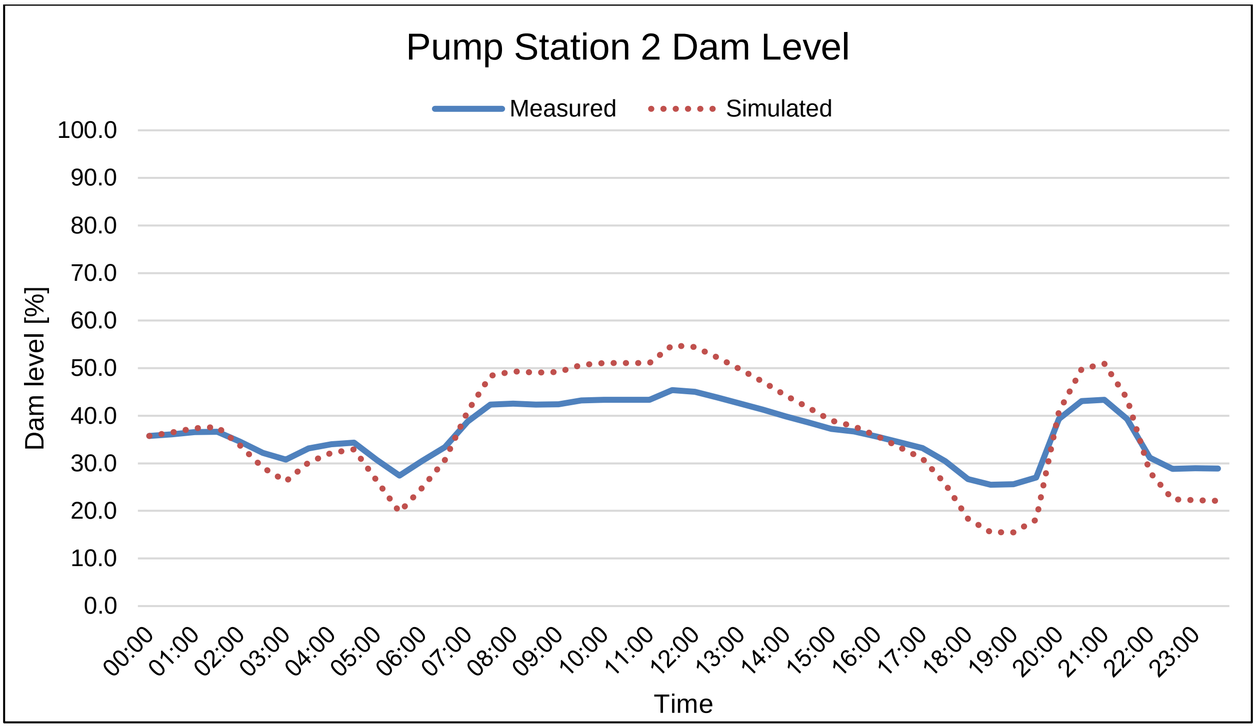

Figure 55: PS2 Dam level verification

APPENDIX C: PUMP STATION 3 VERIFICATION

The verification methodology discussed in Section 2.4 was applied to all the pumping stations of Shaft 2. As discussed in Section 3.4, the first step of this verification process was to select a weekday to evaluate the accuracy of the simulation model. The same day was used throughout the verification process of the digital twin.

Water flow

There were nine pumps installed on PS3. On the selected day, only four of the nine pumps were used throughout the day. The same pumps that ran during the day were used for the simulation model to ensure that the simulation was calibrated accurately. Figure 56 illustrates the pump flow results of the simulation model compared with the measured results. The difference between the measured and simulated results was 4.0%, meeting the requirements of less than 5%. The difference can be ascribed to the pump maintenance deterioration, as observed in Figure 34 in Section 3.2.4.

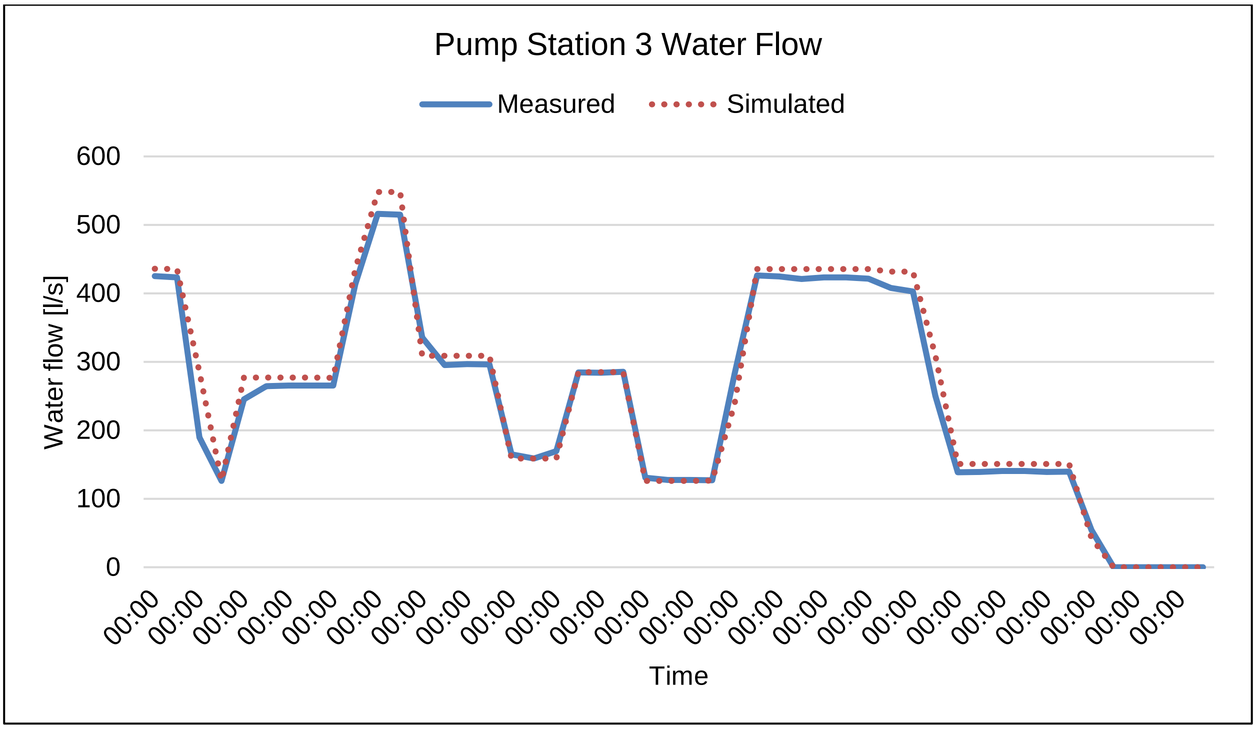

Figure 56: PS3 water flow

Pump power

Plotting the combined measured power usage of both the running pumps on PS3 for the same selected day against the simulation results provided a difference of 1.3%. Figure 57 shows the measured power usage compared with the simulated power usage. Again, the results were within the 5% requirement criteria.

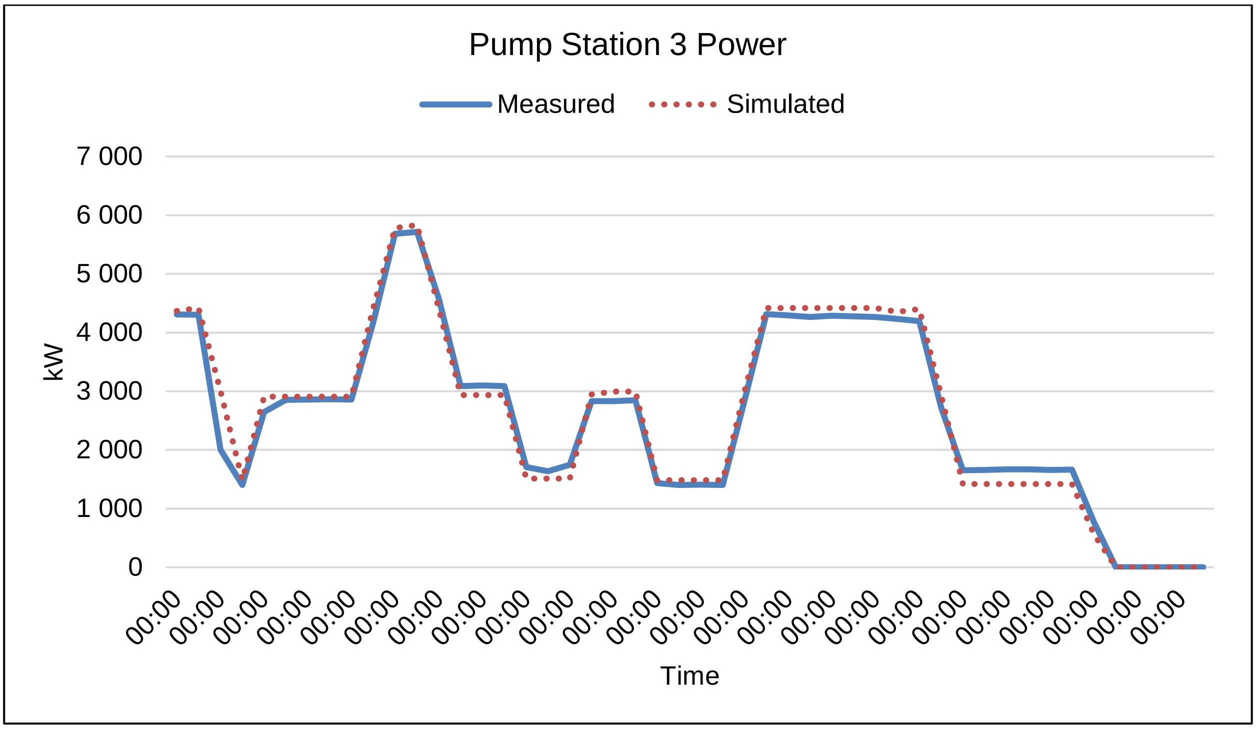

Figure 57: PS3 Measured versus simulated power

Dam level

The measured dam levels for the same day were compared with the simulated dam levels. PS3 had two installed dewatering dams. On the verification day, both the dams were used. The flow distribution between the dams was controlled manually. The same principle discussed in Section 2.4.3 was applied by combining the measured dam levels to compare the measured and simulated results. The same was applied to the simulation model. Figure 58 shows the measured dam levels of PS3 compared with the simulated level. The difference between the results was 2.6%.

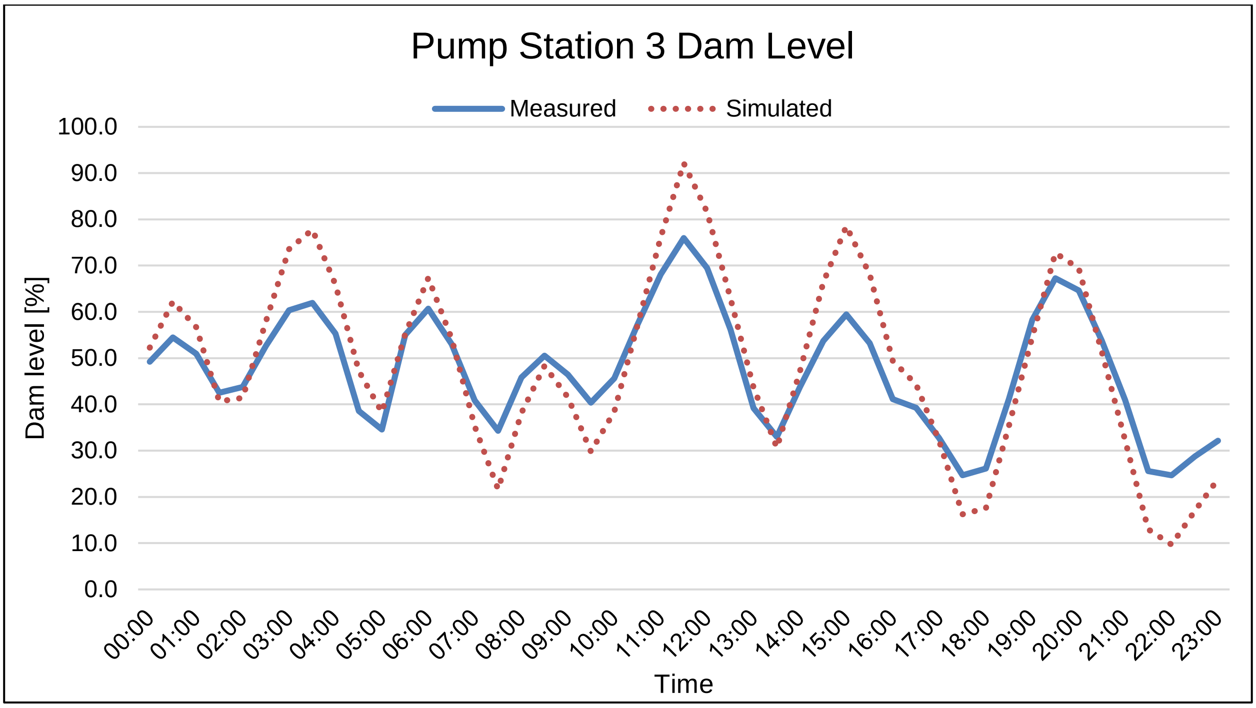

Figure 58: PS3 Dam level verification