

Reducing energy consumption of a deep-level platinum mine dewatering system through infrastructure reconfiguration

HW du Plooy



orcid.org/0000-0003-3297-8452

Dissertation accepted for the degree *Master of Engineering* in
Mechanical Engineering at the North-West University

Supervisor: Dr HJ Groenewald

Co-supervisor: Dr J Marais

Graduation: May 2022

Student number: 27206033

ABSTRACT

Title: Reducing energy consumption of a deep-level platinum mine dewatering system through infrastructure reconfiguration.

Author: HW du Plooy

Supervisor: Dr HJ Groenewald

Keywords: Dewatering, energy efficiency, infrastructural reconfiguration, platinum, water reticulation, load shifting.

South Africa is the largest producer of platinum in the world, accounting for up to 80% of global production. The mining sector contributes significantly to the South African economy, but this contribution is hindered by rising operational costs. A large contributor to rising operational cost is electricity expenditure, with above-inflation annual electricity tariff increases being the norm since 2008. Electricity tariffs have increased far more than the average national inflation rate. These above-inflation electricity tariff increases pose a great threat to the profitability of South African mining companies if not mitigated properly.

South Africa's mining sector is a large consumer of electricity, accounting for up to 14.3% of the national electricity consumption. Dewatering systems consume on average about 14% of a typical mineshaft's total electricity demand. Previous studies have showed that cost savings can be achieved on dewatering systems through load management and supply optimisation. Unfortunately, mines often do not have the correct dewatering infrastructure in place to implement cost-saving measures. Furthermore, research on infrastructure modification to reduce electricity consumption on deep-level platinum mine dewatering systems is limited and focuses on individual sub-systems within the dewatering system.

Therefore, there is a requirement for infrastructure reconfiguration to combine individual sub-systems to reduce the electricity consumption of dewatering systems. Furthermore, there is a need for a methodology to achieve additional cost savings through load management and improvement of underground water recirculation. The main objective of this study was to reduce electricity consumption and costs on the dewatering system of a deep-level platinum mine.

To address the study objective, a five-step methodology was developed to modify the dewatering infrastructure of deep-level platinum mines to achieve electricity cost savings. By

using this methodology, possible solutions were formulated to reduce the electricity consumption of dewatering systems. The different solutions were verified using a simulation model. The solutions were implemented on the case study shaft and validated by comparing the simulation results with the actual results. The simulation results showed that by modifying the dewatering infrastructure, two potential solutions could be implemented, namely load shifting on the dewatering pumps and underground water recirculation.

Underground water recirculation reduced the annual electricity consumption by 1 033 MWh and yielded a cost saving of R1.23 million per annum. A further saving of R300 000 per annum could be achieved through load shifting, i.e., running the dewatering pumps outside the Eskom peak periods. The achieved electricity cost savings bear testimony to the effectiveness of the developed methodology.

ACKNOWLEDGEMENTS

First, and most importantly, I would like to thank the almighty God for blessing me with a wonderful life. Through his love, guidance, and wisdom all things are possible.

He said, "Listen carefully, all Judah and you inhabitants of Jerusalem, and King Jehoshaphat. This is what the LORD says: 'Do not be afraid or discouraged because of this vast number, for the battle is not yours, but God's'". – 2 Chronicles 20:15

I would like to thank my wife, Amy du Plooy. Thank you for the immense support you have provided me. Thank you for your unconditional love throughout the fulfilment of this study. Without you, this would not have been possible.

I would like to thank my parents, Willem and Yvonne du Plooy. Thank you for your years of sacrifice to grant me the opportunity to become the best version of myself.

I would like to my brothers and friends. Your support and patience mean a lot to me.

To my study leader (Dr André Groenewald) and co-study leader (Dr Johan Marais), thank you for your support, insight, and guidance through the fulfilment of this study.

To ETA Operations (Pty) Ltd and its sister companies, thank you for the opportunity to complete this study.

TABLE OF CONTENTS

ABSTRACT	II
ACKNOWLEDGEMENTS.....	IV
LIST OF FIGURES	VIII
LIST OF TABLES	XI
LIST OF ABBREVIATIONS.....	XII
CHAPTER 1: WATER IN DEEP-LEVEL MINES.....	1
1.1 Introduction	1
1.1.1 Platinum mining in South Africa	1
1.1.2 Electricity usage in the mining sector	2
1.2 Deep-level mine water reticulation system.....	4
1.2.1 The use of water in deep-level mining	4
1.2.2 Water reticulation system layout and sub-systems	6
1.3 Potential for dewatering improvements.....	18
1.3.1 Energy management initiatives	18
1.3.2 DSM initiatives	20
1.3.3 Previous studies conducted on DSM initiatives on dewatering systems	23
1.4 Need and objectives of the study	27
1.4.1 Need for the study	27
1.4.2 Problem statement and objectives of the study	28
1.5 Study overview.....	28
CHAPTER 2: DEVELOPMENT OF AN INFRASTRUCTURE MODIFICATION STRATEGY	30
2.1 Introduction	30
2.2 Data acquisition of mine water reticulation systems.....	33
2.2.1 SCADA	34
2.2.2 Layout drawing of WRS	34
2.2.3 Visual audits.....	35

2.2.4	Data quality	35
2.3	Analysis of the dewatering network and infrastructure.....	36
2.3.1	Electric power consumption of a pump.....	37
2.3.2	Pump power.....	38
2.3.3	Fixed variables	39
2.3.4	Water flow management	39
2.3.5	Underground recirculation	40
2.4	Verifying solution through simulation	42
2.4.1	Analyse the dewatering simulation	43
2.4.2	Construct the simulation model.....	45
2.4.3	Calibrate the simulation model	55
2.5	Development of an electricity consumption profile.....	55
2.6	Implementation of solution.....	56
2.7	Conclusion.....	56
CHAPTER 3: IMPLEMENTATION OF THE INFRASTRUCTURE MODIFICATION STRATEGY		58
3.1	Introduction	58
3.2	Data acquisition of the water reticulation system	58
3.2.1	Layout drawings.....	58
3.2.2	SCADA	62
3.2.3	Audit.....	67
3.3	Analysis of dewatering system	68
3.3.1	Power consumption	68
3.3.2	Displacement height	69
3.4	Verification through simulation.....	72
3.4.1	Analysing the dewatering simulation.....	72
3.4.2	Constructing the simulation model	72
3.4.3	Calibrating the simulation model	75
3.4.4	Constructing the electricity consumption baseline for the simulation model	80
3.4.5	Testing possible solution on the simulation model	81

3.5 Construction of the actual electricity consumption baseline.....	88
3.6 Validation through actual implementation.....	91
3.6.1 Implement solution on case study shaft	91
3.6.2 Compare baseline and actual consumption	94
3.7 Conclusion.....	98
CHAPTER 4: CONCLUSION	100
4.1 Summary	100
4.2 Recommendations for future work.....	101
4.3 Conclusion.....	102
REFERENCE LIST	103

LIST OF FIGURES

Figure 1: Geological map of the Bushveld Igneous Complex [4].....	1
Figure 2: Total 2020 Eskom electricity sales in percentage (adapted from [6])	2
Figure 3: Electricity distribution in a typical platinum mine (adapted from [7]).....	3
Figure 4: Profit margin of a platinum mining company in South Africa (2014–2020) (adapted from [9], [10]).....	3
Figure 5: A rock drill operator using a pneumatic drill [18].....	5
Figure 6: Basic refrigeration and ventilation layout of a mine	8
Figure 7: Basic refrigeration process of a deep-level platinum mine	9
Figure 8: Water cascading system of a platinum mine	11
Figure 9: Valve and actuator location	13
Figure 10: Characteristic curve of a parallel pumping configuration (adapted from [38]).....	14
Figure 11: Characteristic curve of a series pumping configuration (adapted from [38]).....	15
Figure 12: Dewatering system and sub-systems of a platinum mine	17
Figure 13: TOU tariff structure for the Megaflex structure 2021/2022 [11]	19
Figure 14: Relationship between water pressure and flow (adapted from [28]).....	22
Figure 15: Methodology used to formulate and implement a solution	32
Figure 16: Data acquisition phase of methodology.....	33
Figure 17: Water pressure boundary component input parameters.....	49
Figure 18: Mass flow component input parameters	50
Figure 19: Water pipe component input parameters	50
Figure 20: Input parameters for the Darcy–Weisberg equation use in PTB	51
Figure 21: Step controller input parameters	52
Figure 22: Dam component input parameters	53
Figure 23: Pump component input parameters	54
Figure 24: WRS vertical section layout.	60
Figure 25: WRS decline section layout.....	61

Figure 26: Underground water consumed by the shaft vs the water pumped out of the shaft by the 21.5L dewatering pumps	63
Figure 27: Decline vs vertical sections' water consumption.....	64
Figure 28: Decline water consumption per level	64
Figure 29: 21.5L dam level control.....	65
Figure 30: 22L dam level control.....	66
Figure 31: 28.5L dam level control.....	66
Figure 32: 21.5L average pump electricity consumption.....	67
Figure 33: Service water flow path for underground recirculation and surface recirculation .	71
Figure 34: Simulation model construction of level water flow.....	73
Figure 35: Decline simulation model used to verify the results.....	74
Figure 36: Power consumption comparison between the actual and simulated 21.5L pumps.	77
Figure 37: Water flow displacement rate comparison between the actual and simulated 21.5L pumps	77
Figure 38: Dam level control between the actual and simulated 21.5L dams	78
Figure 39: Dam level control between the actual and simulated 22L dam	79
Figure 40: Dam level control between the actual and simulated 28.5L dams	79
Figure 41: Simulated baseline for the 21.5L dewatering pumps.....	80
Figure 42: Control philosophy to refill the 22L dam used in the simulation	82
Figure 43: Control philosophy to ensure that the 28.5L dams do not overflow	84
Figure 44: 21.5L load-shifting control philosophy	85
Figure 45: Comparison between the simulated baseline and underground water-recirculation electricity consumption	86
Figure 46: Comparison between simulated baseline and load shifting.....	87
Figure 47: Comparison between the simulated baseline, underground water recirculation and load shifting.....	88
Figure 48: Actual weekday average electricity consumption profile for the 21.5L pumps	89
Figure 49: Actual Saturday average electricity consumption profile for the 21.5L pumps	90
Figure 50: Actual Sunday average electricity consumption profile for the 21.5L pumps	90

Figure 51: Underground recirculation control philosophy implemented by the shaft	93
Figure 52: Recirculation of underground water on the shaft	94
Figure 53: Power consumption comparison between the baseline weekday profile and the current system with underground recirculation implemented.....	95
Figure 54: Power consumption comparison between the baseline Saturday profile and the current system with underground recirculation implemented.....	96
Figure 55: Power consumption comparison between the baseline Sunday profile and the current system with underground recirculation implemented	97
Figure 56: Everyday power consumption comparison between the baseline profile and the current system with underground recirculation implemented.....	98

LIST OF TABLES

Table 1: Cost per kWh excluding VAT for the Megaflex TOU structure 2021/2022 (adapted from [11])	19
Table 2: State-of-the-art matrix	27
Table 3: Required data for PTB components	44
Table 4: Potential sources for required data	45
Table 5: Table used to create the characteristic curves of dewatering pumps on PTB.....	54
Table 6: Depth below surface, pressure and VRT of decline levels	62
Table 7: Manual flow measurements for 28.5L MPS	68
Table 8: Pressure and flow values used to calibrate the 21.5L pumps.....	75
Table 9: Summary of the electricity and cost expenditure and saving per annum for the proposed solutions on the simulation model.....	88

LIST OF ABBREVIATIONS

BAC	Bulk air cooler
DSM	Demand-side management
L	Level
MPS	Main pumping station
PGM	Platinum group metal
PLC	Programmable logic controller
PRV	Pressure-reducing valve
PTB	Process Toolbox
RAW	Return airway
SCADA	Supervisory control and data acquisition
TOU	Time-of-use
VRT	Virgin rock temperature
WRS	Water reticulation system

CHAPTER 1: WATER IN DEEP-LEVEL MINES

1.1 Introduction

1.1.1 Platinum mining in South Africa

The mining sector is one of the largest industries in South Africa. In 2020, the mining industry contributed R362 billion to the gross domestic product of the country and employed roughly 451 000 people [1]. Platinum alone accounted for up to 11% of South Africa's total mineral production value and the industry experienced R171.3 billion in sales [1].

South Africa produces the most platinum and platinum group metals (PGMs) in the world, accounting for up to 80% of the platinum produced and over 60% of newly mined PGMs [2]. The country contains 88% (85 000 metric tonnes) of the total PGM reserves currently known in the world [2], [3]. This large reserve of PGMs is found in the Bushveld Igneous Complex, which is located in the northern part of South Africa [3]. The Bushveld Igneous Complex is divided into four main parts called the northern, eastern, southern and western limbs [4].

Figure 1 shows the geological map of the Bushveld Igneous Complex with the four limbs. The Bushveld Igneous Complex has three reefs where the PGM ore deposits are found, namely the Merensky Reef, Upper Group Chromitite No. 2 reef, and Platreef [3]. Each reef has five layered suites, which are zones that have their own composition of rock and ore. The zones are called the upper, main, critical, lower, and marginal zones [4], [5].

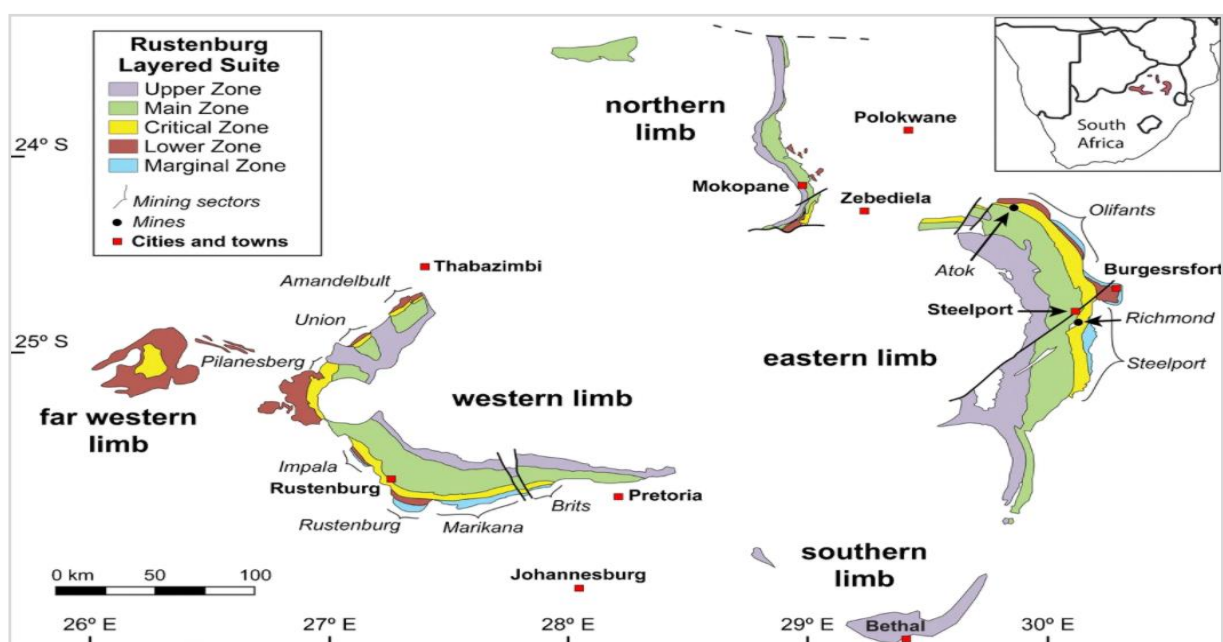


Figure 1: Geological map of the Bushveld Igneous Complex [4]

1.1.2 Electricity usage in the mining sector

Figure 2 shows the distribution of electricity sales in 2020/2021 for Eskom, South Africa's largest electricity producer. The mining industry consumed roughly 14.3% of the total electricity produced in the country, of which approximately 33% was consumed by the platinum mining sector [6], [7].

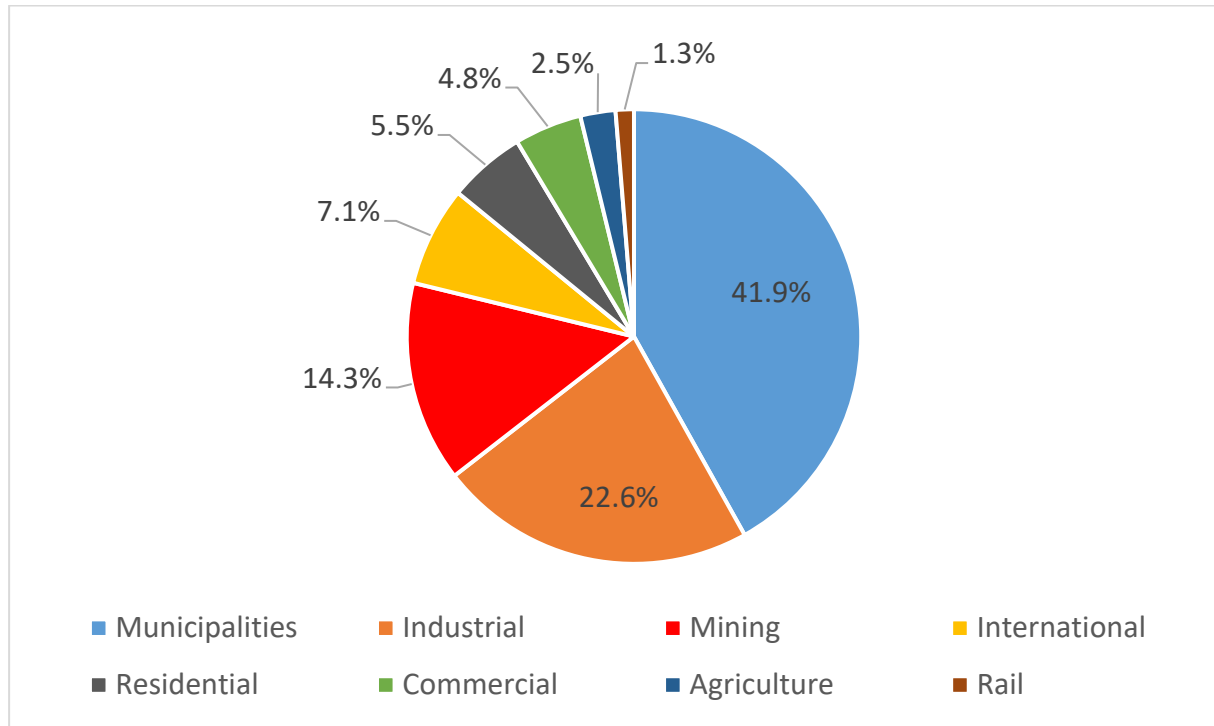


Figure 2: Total 2020 Eskom electricity sales in percentage (adapted from [6])

Deep-level mines are typically at depths between 500 m and 2 000 m under the surface of the earth [8]. Mines exceeding 2 000 m are considered ultra-deep-level mines. Numerous electricity intensive systems exist in deep-level platinum mining. Dewatering systems contribute approximately 14% to the total electricity used in deep-level platinum mining [7]. A dewatering system is an electricity intensive system, which results in substantial electricity costs. Therefore, the opportunity exists to improve these systems and make the use thereof more effective. Figure 3 shows the electricity usage distribution in a typical deep-level platinum mine and the major systems involved.

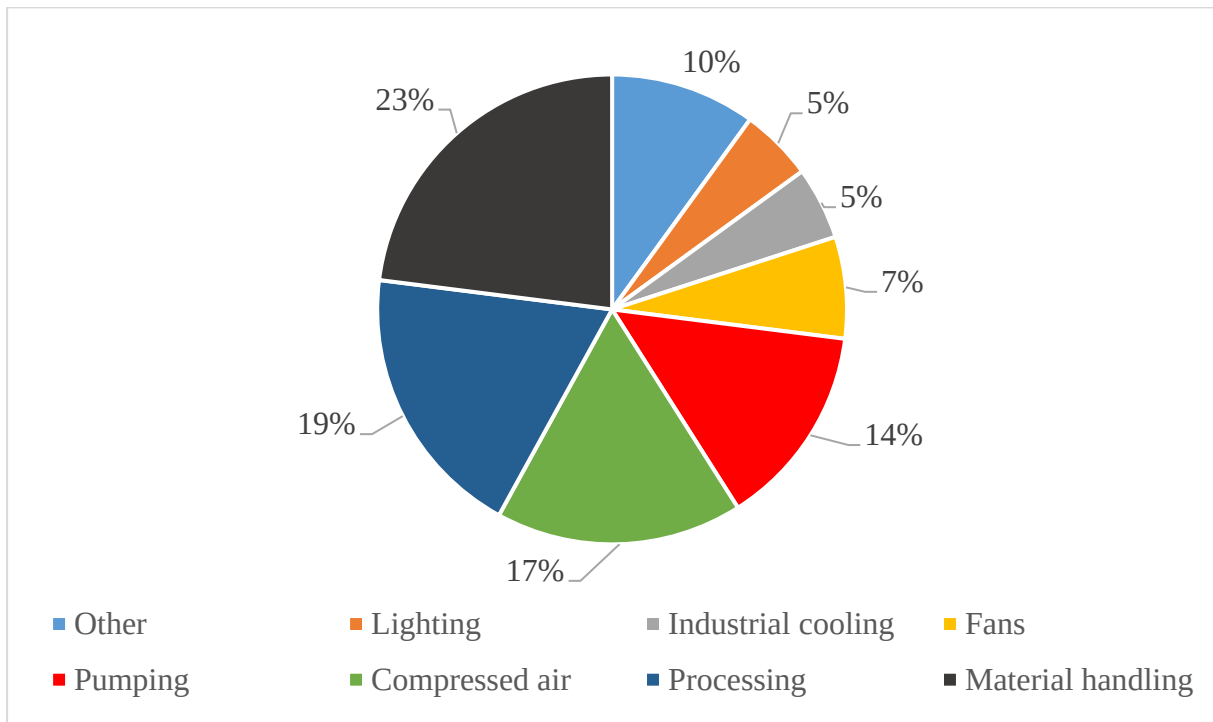


Figure 3: Electricity distribution in a typical platinum mine (adapted from [7])

Some major platinum mining companies in South Africa have been immensely successful in recent years. In 2020, the mines achieved profit margins of up to 49% [9]. However, in past years, these companies have not been as successful and have experienced financial pressure. Figure 4 shows the profit margins over the past seven years for one such company, which had a profit margin of less than 5% between 2015 and 2017 [10].

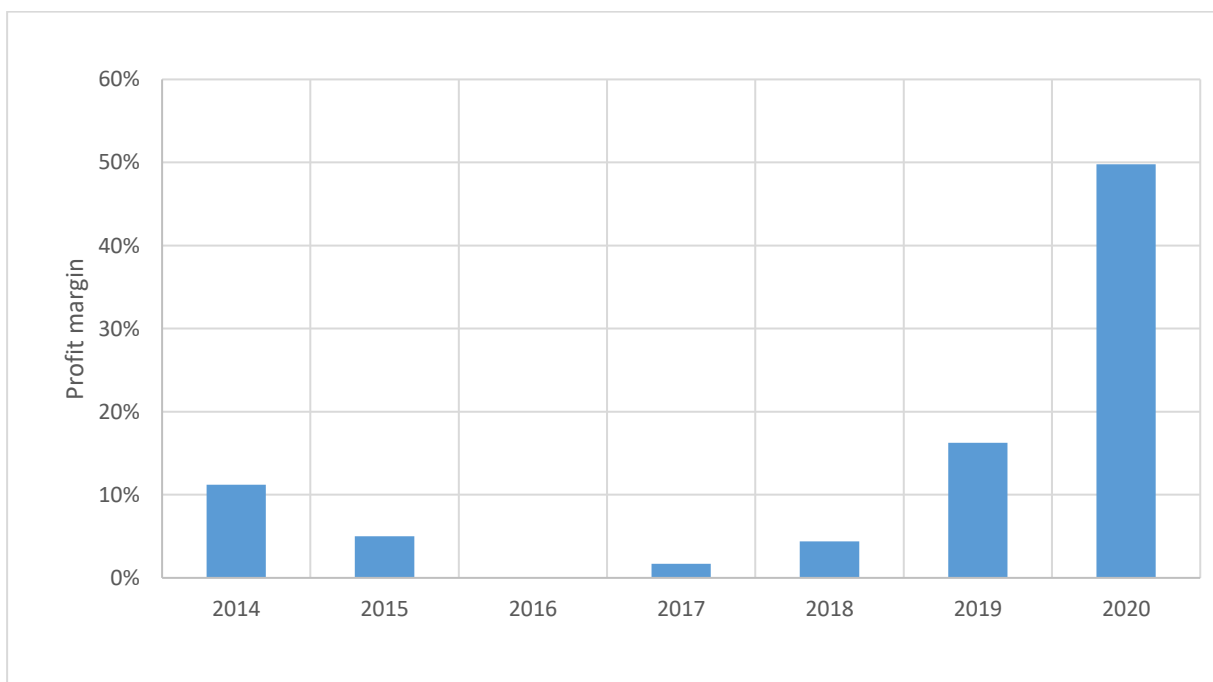


Figure 4: Profit margin of a platinum mining company in South Africa (2014–2020) (adapted from [9], [10])

This financial pressure is largely incited by rising operational costs such as labour and electricity expenditure. Electricity prices have gone up by 15.06% for 2021/2022, which is far more than the average national inflation rate of 3.2% [11], [12]. This above-inflation rate electricity price increase poses a great threat to the profitability of mining companies if not mitigated properly. Within the mining industry, a typical PGM mining group's electricity cost exceeds R1.5 billion per year [13].

1.2 Deep-level mine water reticulation system

1.2.1 The use of water in deep-level mining

A mine's water reticulation system (WRS) describes the entire water system of a mine, including ventilation, refrigeration, and dewatering systems. However, the main purpose of a WRS in a platinum mine is to transport water to various areas in the mine. The water in these areas are used for the following purposes [14], [15]:

- Cooling drilling equipment and virgin rock temperatures (VRTs).
- Suppressing dust.
- Cleaning and flushing stopes in working areas.
- Operating hydraulic equipment.
- Making provision for human consumption.
- Suppressing fires.

Cooling drilling equipment and VRT

To extract ore, holes are drilled into the rockface, explosives are inserted, and the virgin rockface is blown into smaller rock pieces. These pieces are removed, transported, and processed to extract the metal. Although pneumatic drills are normally used to drill holes in deep-level mining, hydraulic or electric drills can also be used [16]. Cool service water is used to cool drill bits and the VRT while rock drill operators are operating the drills. Figure 5 shows a rock drill operator using a pneumatic drill to drill holes in the rockface for blasting.

As mining depth increases, the VRT rises due to the thermal rock gradient. VRTs as high as 70 °C can be experienced in some platinum mines [5]. In these mines, it is necessary to cool down the VRT with service water to create a suitable working environment [17].



Figure 5: A rock drill operator using a pneumatic drill [18]

Supressing dust

A great deal of dust is produced during drilling, which can cause a multitude of health complications and risks when inhaled. Silicosis, pneumoconiosis, and chronic obstructive pulmonary disease are some of the diseases that can be brought on by dust inhalation [19]. Thus, it is important that dust suppression methods are used. Dust is supressed by spraying service water into drilling areas called stopes. Service water settles the dust and hardens it to a solid or slurry. Wearing the correct personal protective equipment such as dust masks further mitigates dust inhalation.

Cleaning and flushing working areas

During the drilling shift, compressed air is used to drive the drill bit forward to crush the rock and create a hole. As drilling continues, small flakes of rock break of and fill the hole. Service water is used to flush out the flakes to avoid the drill bit from seizing [20]. As the water flushes out the fine rock flakes, it creates a slurry containing the flakes of ore. To be as profitable as possible, it is thus necessary to flush out the working areas and pump out the slurry mixture.

After blasting, the ore is removed from the stopes. Large rocks are usually moved by hand or with a loader. Smaller rocks are washed away into the loader boxes using pressurised water

from a water cannon or hose. Service water is further used underground for general workplace and equipment cleaning.

Operating hydraulic equipment

Compressed air is normally used to operate rock drills, but water can also be used [16]. Hydro-electric drills exist that can drill rock by using water as driving force. They are alternatives to pneumatic drills with their own advantages, such as low energy consumption, less noise output, and higher drilling efficiency than pneumatic drills [21]. Hydraulic equipment is also found in loaders and other mining equipment.

Providing for human consumption

Potable water is water that is safe for human consumption. It is requirement that potable water is available for consumption in underground working areas. A healthy hydration level is a necessity to regulate body temperature and promote healthy brain function [22].

Supressing fire

Water is used in fire suppression systems in case of accidental fires. These systems are often automated and work through smoke detection or manual activation. It is thus important for the system to always have water on standby in case of an emergency.

1.2.2 Water reticulation system layout and sub-systems

1.2.2.1 Ventilation and refrigeration system

Underground temperatures are crucial to the productivity of deep-level mining. Productivity is directly affected by underground temperatures, which must be regulated [23]. A safe underground temperature is not only important for good production levels, but also a necessity for a suitable mining environment. Underground temperatures may not exceed the legal limit of 32.5 °C wet bulb or 37 °C dry bulb [24].

As mining depth increases, the earth's temperature rises, which is called the geothermal gradient of the earth [23]. The geothermal gradient is specific to the rock composition of a specific area. Most platinum mines are in the Bushveld Ingenious Complex. Here, the geothermal gradient is between 20.7 ± 1.3 K/km and 16.4 ± 2.4 K/km [5]. The underground temperature increase is not only caused by the geothermal gradient, but also explosives,

underground machinery, and the auto-compression of air [25]. A supply of fresh air and water is thus required to keep temperatures from rising above the legal limit.

Large industrial cooling devices such as bulk air coolers (BACs), fridge plants, and cooling towers are responsible for supplying fresh cool air [26]. BACs located on surface are normally used as the primary cooling method alongside fridge plants to cool incoming air. Fridge plants cool down water on the principle of the vapour compression cycle. The cool water is sprayed over incoming warm air to reduce the temperature of the air molecules. The BACs force this cool air into the main shaft using high pressure fans. The cool air produced by the cooling systems picks up heat from within the mine. Surface ventilation fans extract the hot air through the return airway (RAW) of the shaft.

Cooling methods are chosen based on each mine's specific cooling requirements, which are influenced by the shaft depth and geothermal gradient. Different mines may have different properties and thus different requirements. Figure 6 depicts a simplified layout of a deep-level mine's ventilation and refrigeration system. The figure shows the approximate location of the cooling devices as mentioned previously.

Return water from underground areas are cooled using cooling towers, then fed through the refrigeration plants to be sent underground and reused as service water for mining operations [27]. After the cool water has been used in mining operations, it is pumped to hot water holding dams where it is cooled, filtered, treated, and recirculated.

Hot water is pumped from underground to surface hot water dams that normally have temperatures of between 25 °C and 30 °C. From these dams, the water is pre-cooled in cooling towers to between 15 °C and 20 °C [15], [28]. Cooling towers use ambient air to cool water from underground. Cooling towers are thus only effective if the ambient air temperature is below the underground water temperature. The use of cold water and the water-cooling requirements are shaft specific and depend on the underground temperature.

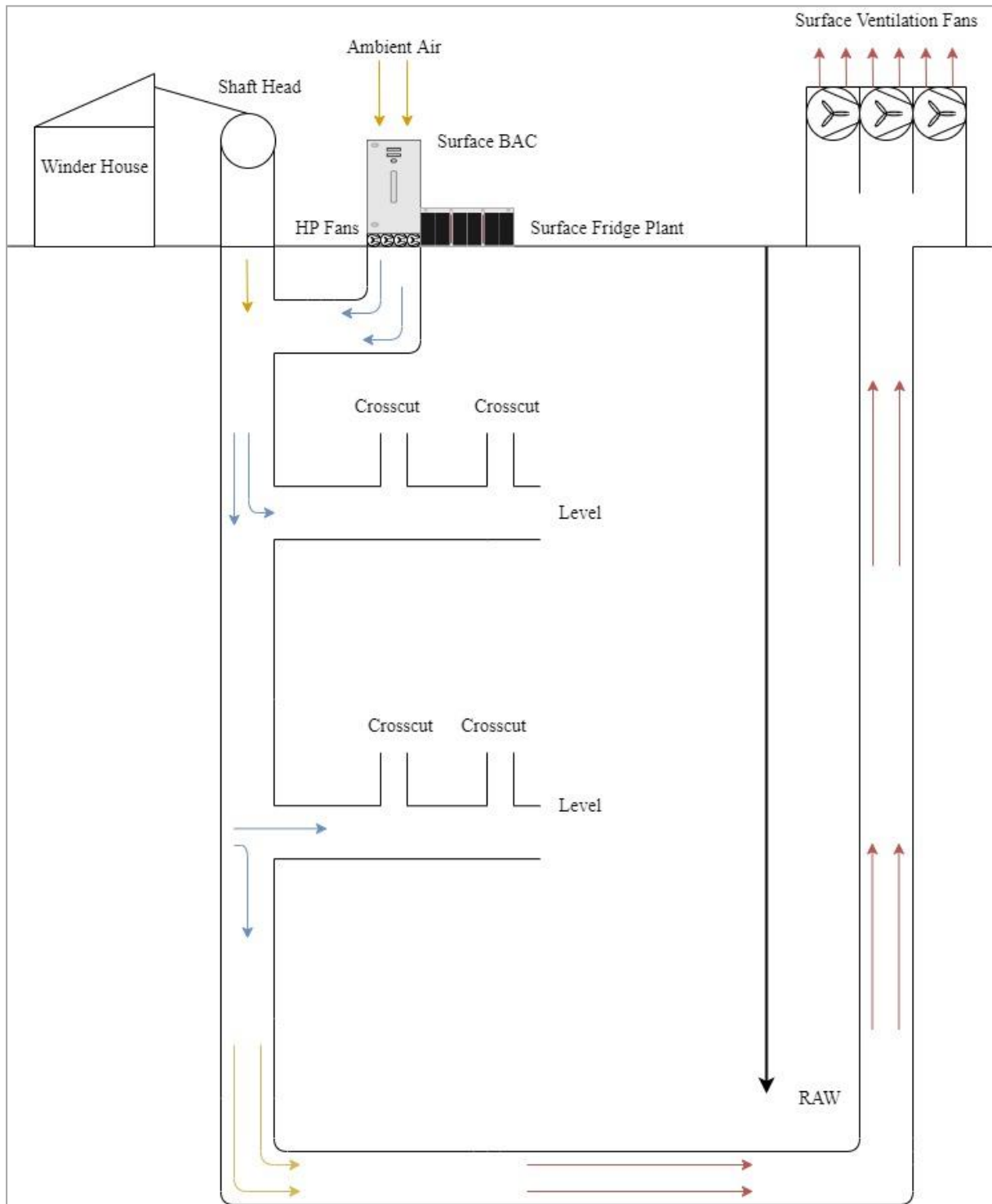


Figure 6: Basic refrigeration and ventilation layout of a mine

Figure 7 shows a basic refrigeration process typically found on a deep-level platinum mine. Different configurations of this setup exist depending on the specific cooling requirements.

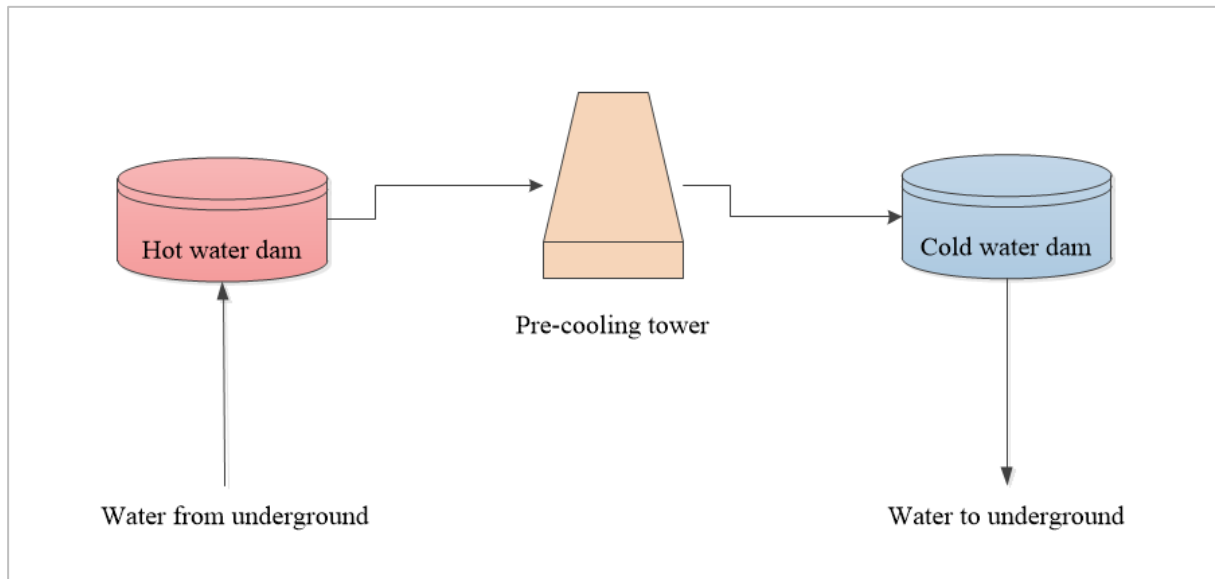


Figure 7: Basic refrigeration process of a deep-level platinum mine

1.2.2.2 Dewatering system

The dewatering system is responsible for supplying and extracting water from the mine. Numerous sub-systems exist that contribute to the interconnectivity of this system. The main components in the systems are [28]:

- Dams.
- Piping network.
- Valves.
- Pumps.
- Settlers.

Dams

Dams store large quantities of water and supply working areas with water – either underground or on surface. They can be very large and hold as much as 5.0 Ml water. Dams can either be hot dams containing used warm water from underground or cold dams containing cool water ready to be used underground [17]. These dams can also be sludge dams that contain mud.

After the water has been cooled on surface using cooling towers and fridge plants, it is pumped to a surface cold water holding dam. From the surface dam, the water is gravity-fed to the levels in the mine. With mines exceeding depths of 1 000 m, water pressure can build up significantly.

Since highly pressurised water can become dangerous, it is necessary to reduce the pressure before supplying the water to the working areas. Water breaker dams reduce the pressure of the water by exposing it to ambient conditions [29]. The water breaker dams supply the level dams with water through a cascading system [29], [30], [31]. Thereafter, the level dams safely supply service water to working areas.

After the water has been used in the working areas of each level, the water flows out of the level in the return piping or trench network. From there, the water cascades down level per level until the water reaches the pump station. The water can either flow straight into warm holding dams or go through settlers. The settlers filter the water to separate the contaminants from the water. After passing through the settlers, the clean water flows into clean water dams while the sludge flows into sludge dams. Although multistage dewatering pumps can pump dirty water, it is not advisable as this causes degradation and premature failure on pumps [32]. A series of pumps pump the water out of the shaft into warm water holding dams on surface.

Figure 8 shows a typical water cascading system of a deep-level platinum mine. A cascading system works by overflowing each dam except the last dam in the sequence. One valve, which is situated just before the inlet of the first dam, regulates the entire flow of the system. When the first dam is full, the water will cascade down a pipe into the second dam. The second dam will fill and cascade to the next. This happens until the last dam is full. When the last dam is full, the inlet valve will close. When any of the dams' water levels drop, float switches will signal the inlet valve to open, thereby cascading the water down into the required dam.

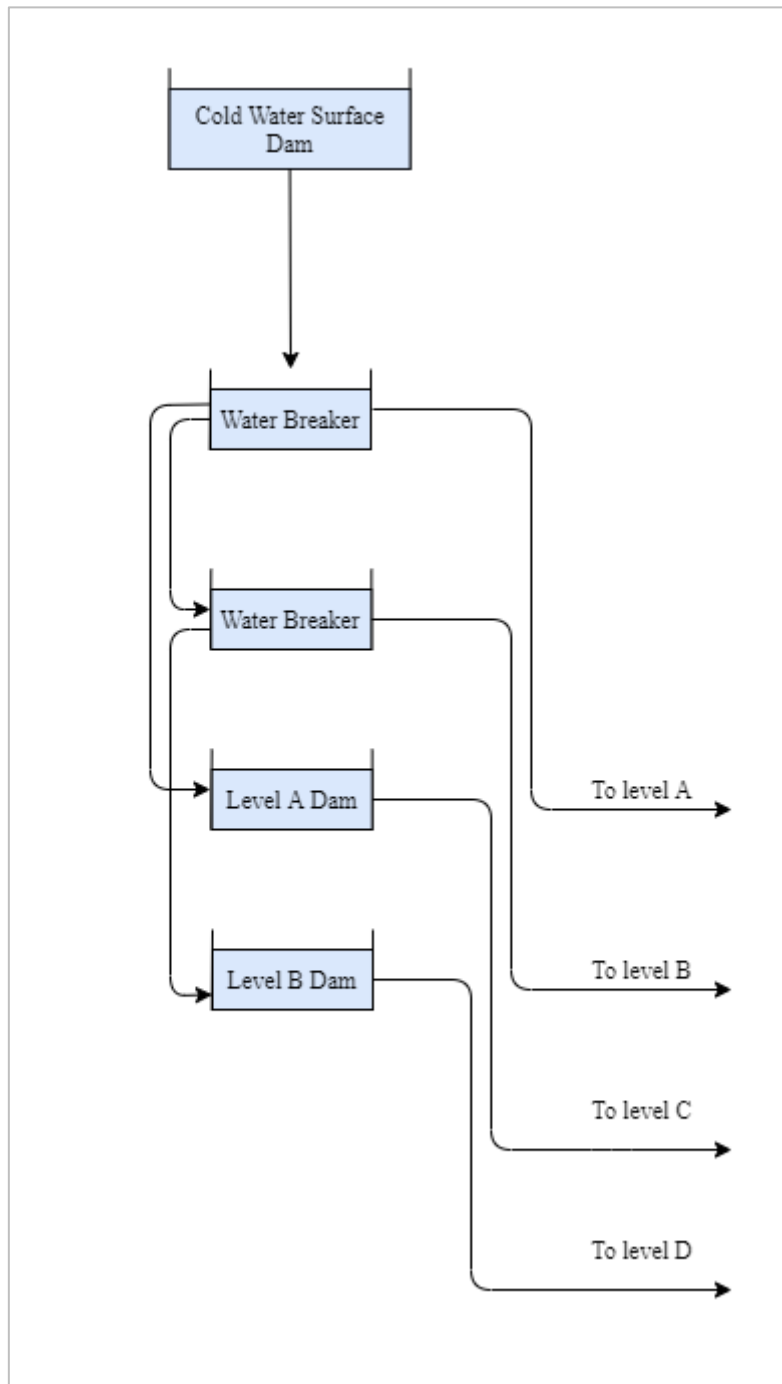


Figure 8: Water cascading system of a platinum mine

Piping network

The piping system of a mine is an intricate network of pipes of different sizes and shapes. The main purpose of these pipes is containing the water while transporting it from one section to another. Due to the immense depth that some mines reach, water pressure can build up significantly. Water hammer, also known as hydraulic shock, is an oscillating pressure resulting from a rapid increase or decrease of flow [33]. These shockwaves are normally caused by sudden opening or closing of valves or pump starting or stopping, and they can cause serious

mechanical damage on pipes. The pipes should be able to withstand the pressures caused by the hydrostatic head and pump outlet pressures. To mitigate the damage caused by water pressure, pipes are usually fitted with pressure relief valves and pump outlet pipes are supported by thrust blocks to prevent movement.

Valves

The purpose of a valve is to control the passage of a fluid. A valve can be a manual, or actuated valve. Manual valves typically require personnel to adjust the state of the valve by hand by either turning a wheel or a hand lever on the valve. Actuated valves are normally connected to electric, pneumatic, or hydraulic actuators, which allow for remote control and automation. Automatic valves can be controlled to achieve certain conditions, such as flow or pressure control [34].

Different valve types feature a range of applications and characteristics [31], [35]. Valves used most often in mines include ball, butterfly, and gate valves. These valves typically control the pressure or flow of water or compressed air into the mining levels. Pressure-reducing valves (PRVs) reduce water pressure, to supply safe pressures to the mining levels. Figure 9 shows the typical location of valves in the dewatering system. Surge valves are fitted to pipes that experience severe hydraulic shock. Isolation valves are used to isolate certain areas for maintenance purpose or to prevent water wastage on levels where no mining activities take place.

Valves are further used to limit the flow based on the percentage that the valve is open. Hasan *et al.* [17] conducted a study to determine the characteristics of a plug valve in terms of water flow and valve percentage open. The curve established in their study showed a rapid increase in flow until a valve opening of 30%, at which point the maximum flow is achieved through the pipe. It is important to note that the control of these valves is not linear and that flow increases exponentially.

Due to the harsh environment in mines, valves are often operated remotely from surface. A control system is thus required to enable remote monitoring and operation. Programmable logic controllers (PLCs) are often used as rugged industrial computers. They are adapted to control any activity that requires reliable, ease-of-use programming. PLCs are thus ideal for programming and controlling valves from surface [36].

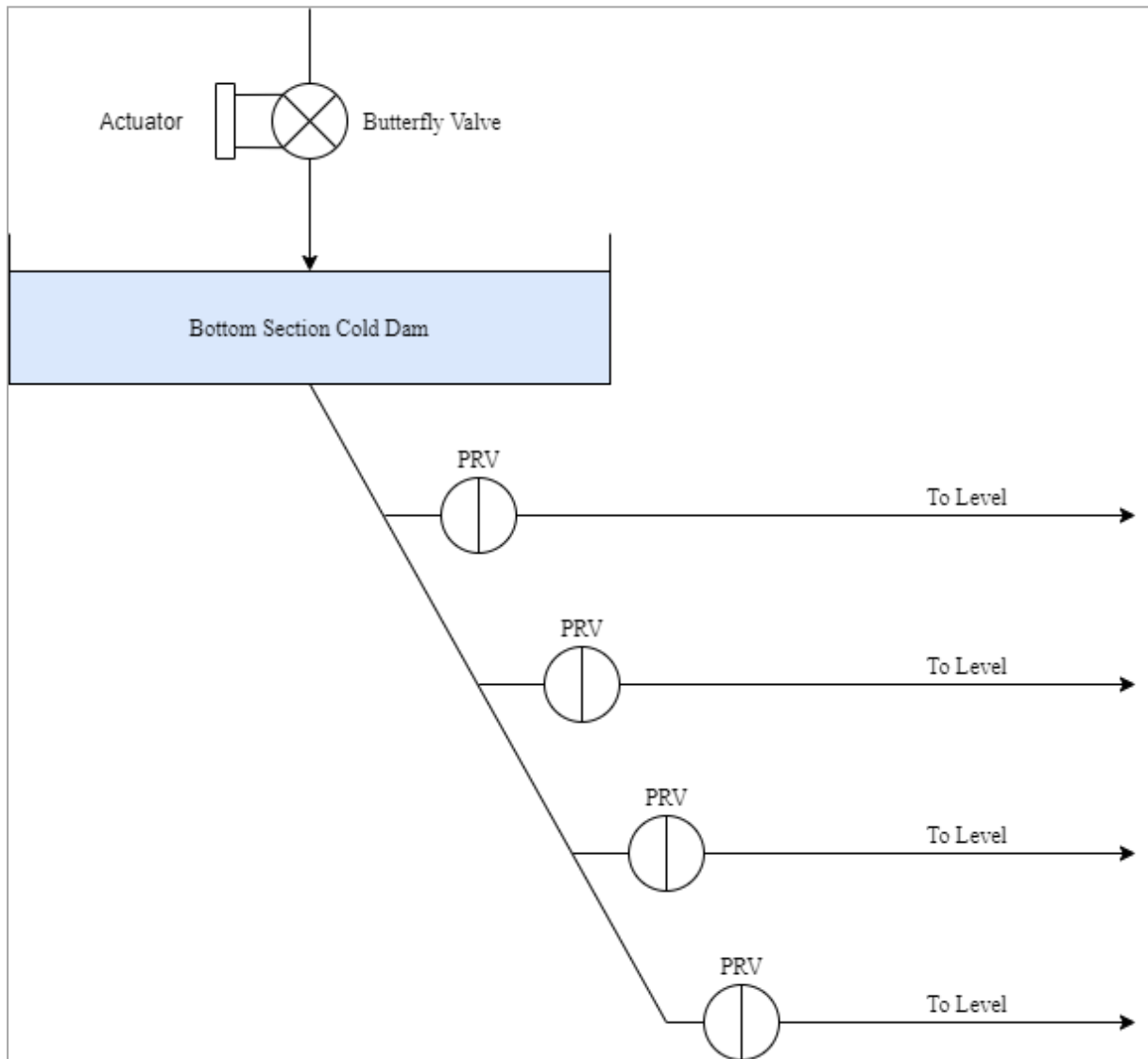


Figure 9: Valve and actuator location

Pumps

Dewatering pumps are the main component and electricity consumer in a dewatering system. The purpose of dewatering pumps is to increase the pressure of the fluid to displace it out of the shaft or to other working areas. This is important to prevent flooding of shafts and opencast mining pits. Different types of pumps have different characteristics and operating conditions.

Centrifugal pumps are used most often. These pumps have rotating blades to create suction, which then moves the fluid through the pipes [37]. Different variations of centrifugal pumps are used in the mining environment. Clear water pumps are used to pump relatively clean water while slurry pumps are used to pump mud.

Variations of these pumps exist that operate in combination. When two or more pumps are used, they can be in a series or parallel configuration, or a combination of both [38]. Mining

operations normally require more than a single pump. It is thus important to configure the system to the mine's requirements.

In parallel pumping, two or more pumps receive and discharge fluid in one common manifold. Pumps in parallel are normally used to increase the amount of flow discarded [38]. They can be operated independently of one another to avoid redundancy. Thus, pumps running in parallel are ideal for constant operations. Only one pump can be operational while the other pumps are under maintenance or used for backup pumping purposes. Figure 10 shows a typical pumping characteristic curve of a parallel pumping configuration.

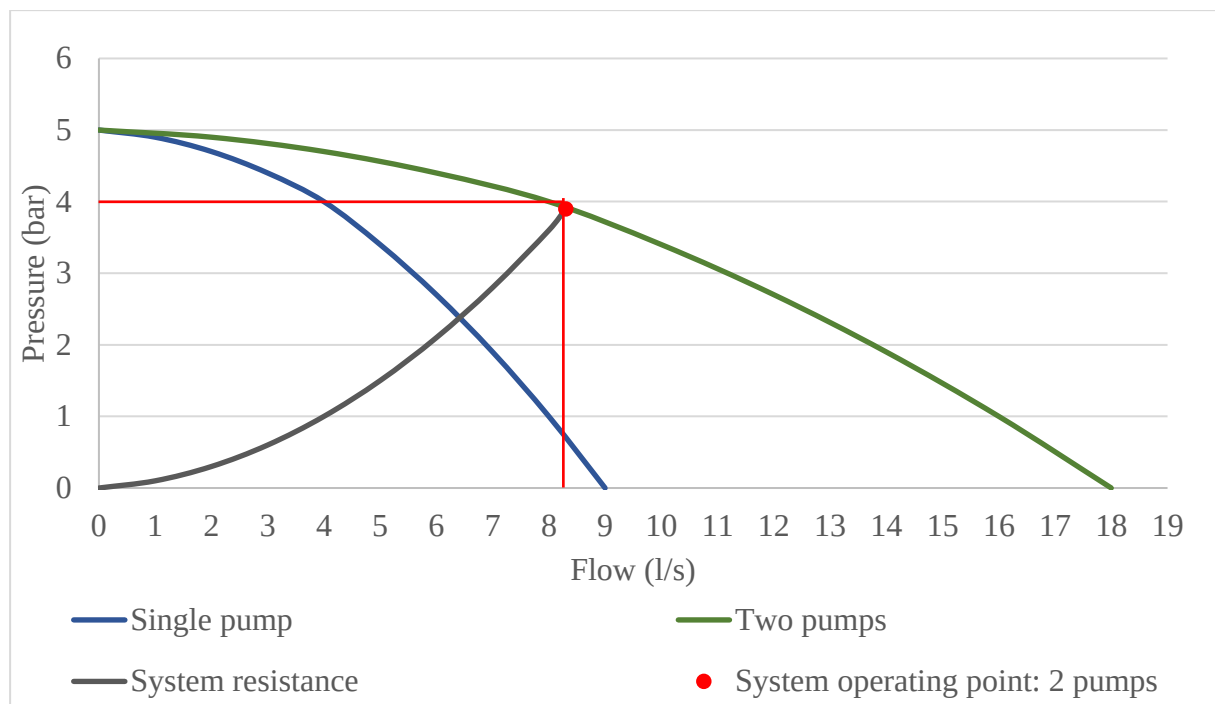


Figure 10: Characteristic curve of a parallel pumping configuration (adapted from [38])

In series pumping, one pump discharges into the next pump's inlet. Pumps are normally used in series to increase the final discharge pressure of the fluid [38]. A series configuration either reduces the strain on a single pump or displaces fluid at extreme depths. However, a single series pumping configuration is normally avoided in deep-level mining because when one pump breaks, the pumping system is not operational until the broken pump is repaired. Therefore, when series pumping is required, a combination of parallel and series pumping is installed. Figure 11 shows a typical pumping characteristic curve of a series pumping configuration.

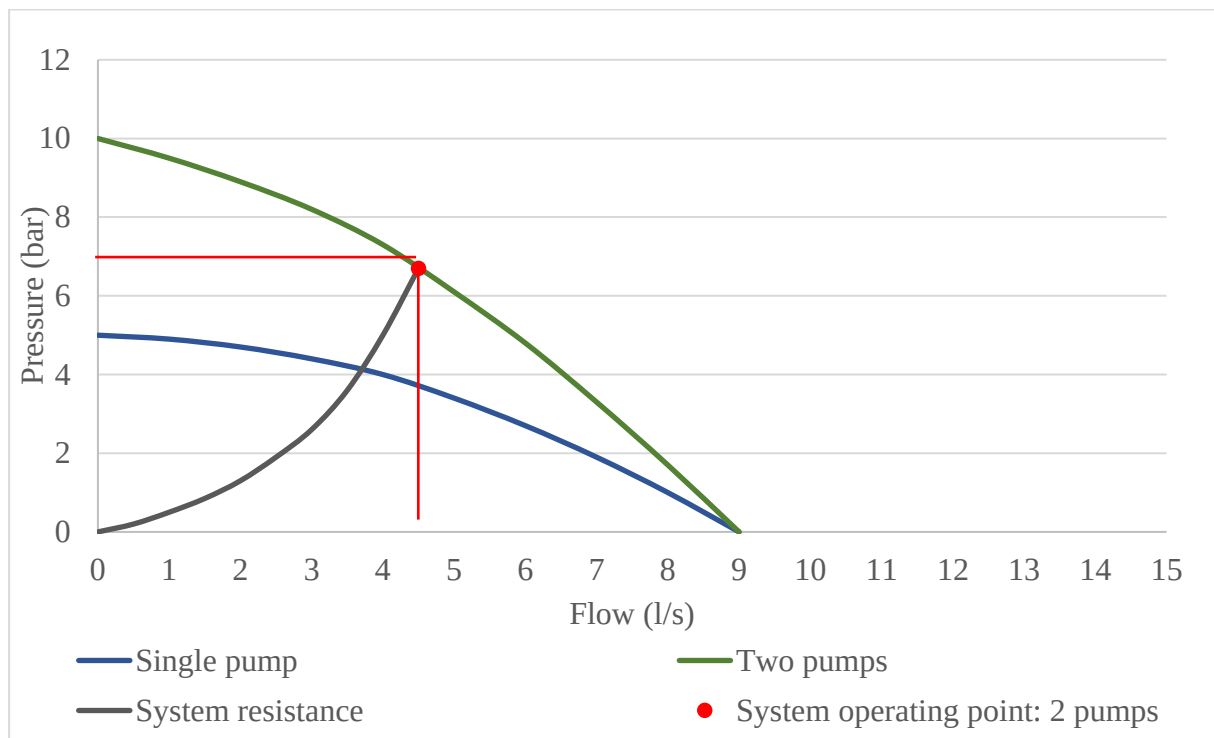


Figure 11: Characteristic curve of a series pumping configuration (adapted from [38])

Settlers

Clean service water is required for equipment to prevent premature degradation and unexpected maintenance. Service water must be safe for accidental human consumption. Furthermore, dewatering pumps operate more efficiently and require less maintenance when pumping clean water [32]. It is thus important that water treatment is applied.

Settlers are devices that filter contaminants from service water using a chemical called flocculant [39]. Flocculant gel blocks are added to the water and slowly dissolve and mix with the water. The flocculant causes the suspended solids to bind together and form heavier particles. The heavier particles settle to the bottom of the settler while the clean water is drained to the clear water dams [40]. The flocculant and solid mixture form a slurry, which is drained to mud dams where mud pumps will pump it to surface. The slurry contains ore and will be processed.

1.2.2.3 Water treatment

The circulation of mine water can change the quality of the water due to the mixing of fissure water and water used in actual mining operations. The main underground water quality problem contributors are the following [39], [41]:

- Dissolved salts – Normally caused by water leaching from the stopes into the water circuit. These salts cause scaling on heat exchanger surfaces and increase corrosion on steel pipes. Corrosion can lead to problems such as thinning of pipes and increased friction losses.
- Nitrogen compounds – Nitrate from nitrate-based explosives and ammonia from ammonium-based explosives are common in mine water. Ammonia reacts with chlorine and impairs its disinfection properties.
- Water pH – Acidic and alkaline water emanates from drainage in the mine. Acidic water increases corrosion while alkalinity increases scaling.
- Suspended solids – Suspended solids emanate from mining operations such as drilling. Suspended solids cause rapid wear in the WRS.
- Microbial quality – Underground service water is often contaminated with human faeces and urine. In case of accidental consumption, it is thus important to treat water when recirculating water underground. Contaminated water causes health problems such as cholera, typhoid, and dysentery when ingested.
- Oils and greases – Machinery that uses fuels, oils and greases often spill these substances into the underground water circuit, which can cause health problems and inefficient water filtering.

Treatment of service water is thus important for ensuring a safe supply of water and the effective use of the WRS components. As previously discussed, settlers are used to filter out suspended solids. Neutralising agents are used to neutralise dissolved salts, nitrogen, and acidic compounds. Brominators can be used to sanitise service water by keeping the water clear from algae. Brominators use bromo chloro-dimethyl hydantoin to treat the water [42].

1.2.2.4 Pump stations

Pump stations are areas in the mine where pumping takes place. These areas normally have all the main components of a dewatering system. Different types of pumping stations perform different functions. Main pumping stations (MPSs) are stations equipped for water treatment and thus have settlers and dosing areas [43]. Intermediate pumping stations are not equipped with water treatment facilities and only function as a relay between the bottom dams and surface dams. Temporary pumping stations are temporary intermediate pumping stations or temporary MPSs. They function only as temporary stations until permanent MPSs can be built. Generally,

temporary pumping stations are high maintenance, but can still be used as backup stations once the MPSs have been built.

1.2.2.5 General layout of dewatering system

Figure 12 depicts the entire dewatering system of a deep-level platinum mine.

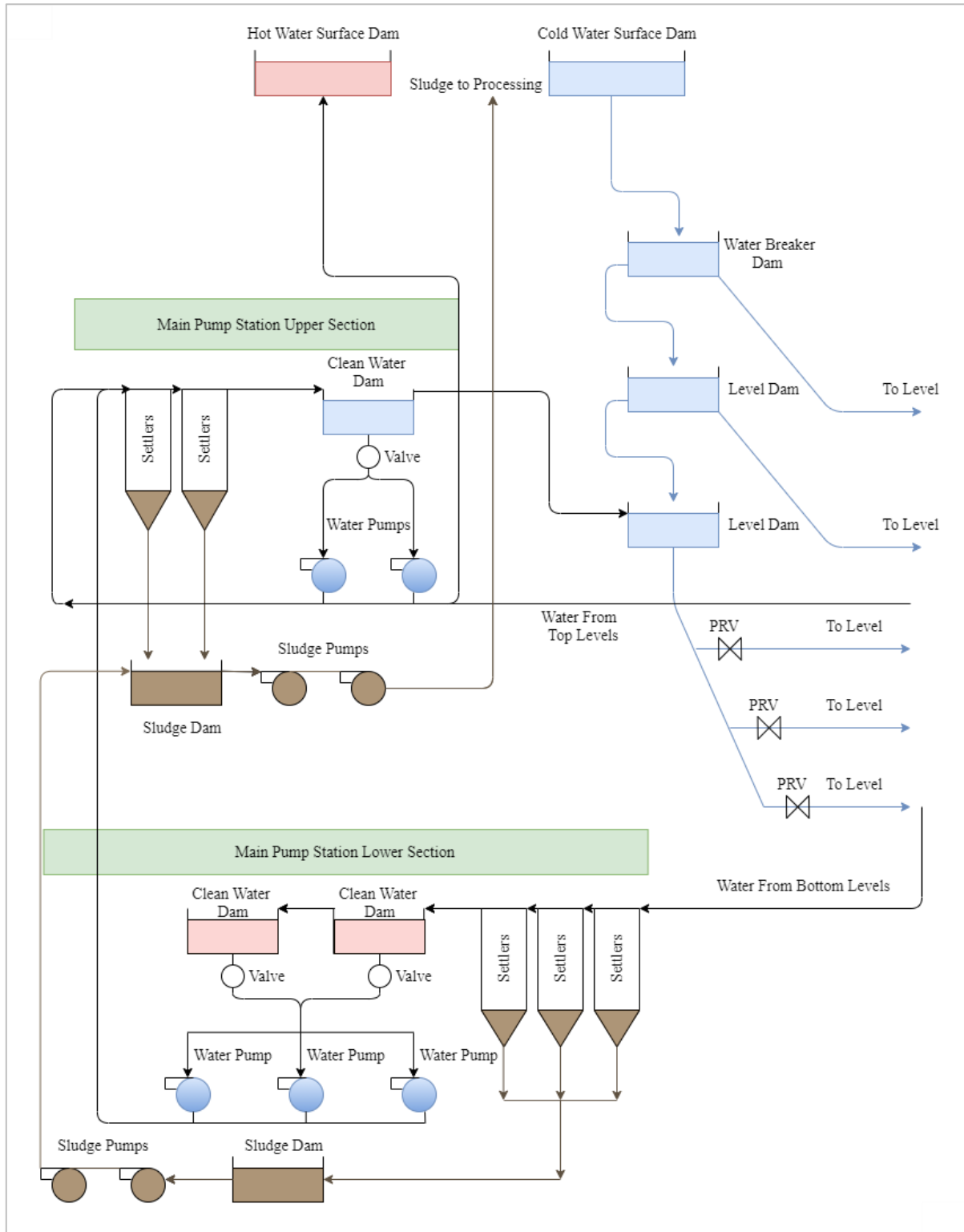


Figure 12: Dewatering system and sub-systems of a platinum mine

The cold service water cascades down into level dams where the water will be used. From the working areas, the water gravity-feeds to the settlers where it is filtered. The clean water flows into clean water dams, whereas the slurry feeds into mud dams. The mud is pumped to surface and the water is relayed to another pump station and finally to surface. The water is cooled on surface and placed back into circulation.

1.3 Potential for dewatering improvements

1.3.1 Energy management initiatives

Energy management focuses on improving the energy efficiency of electricity consumers. Energy management techniques increase the reliability of the power supply in an electricity network [44]. The success of energy management initiatives is predominantly measured using the amount of electricity cost saved. Demand-side management (DSM) initiatives focus on reducing the amount of water used by the end user. In turn, this reduces the amount of time that pumps are active, which reduces the overall electricity consumption.

Energy management improves the efficiency of electricity systems when consumers are active, thereby using less power and reducing the overall cost for the same outcome. On the WRS, the primary electricity consumer is dewatering pumps. Improving the efficiency of the pumps will result in significant electricity and cost savings. Load-shifting, peak-clipping and energy efficiency initiatives can be implemented to reduce the electricity expenditure of dewatering pumps.

1.3.1.1 Tariff structure

The mining sector in South Africa uses a large amount of electricity. Eskom, which is the main electricity provider in the country, includes a time-of-use (TOU) electricity tariff in their tariff structure [11]. This ensures that large electricity consumers are penalised when they syphon electricity during peak times and are rewarded when they use electricity during off-peak times. Therefore, Eskom's TOU structure bills customers different amounts for electricity used during different times of the day throughout the year. Variations of the TOU tariff structure exist depending on the consumer's electrical load. Consumers with a notified maximum demand of more than 1 MVA are billed according to the Megaflex tariff structure. Most deep-level mines fall under this tariff structure [11].

Figure 13 shows the TOU tariffs according to the Megaflex structure. The structure is divided into two main sections, namely the high demand and low demand seasons. The high demand season is from 1 June until 31 August and the low demand season from 1 September to 31 May each year. Each season has different periods in the day starting and ending at certain times. Table 1 shows the hourly tariff four for each season and period.

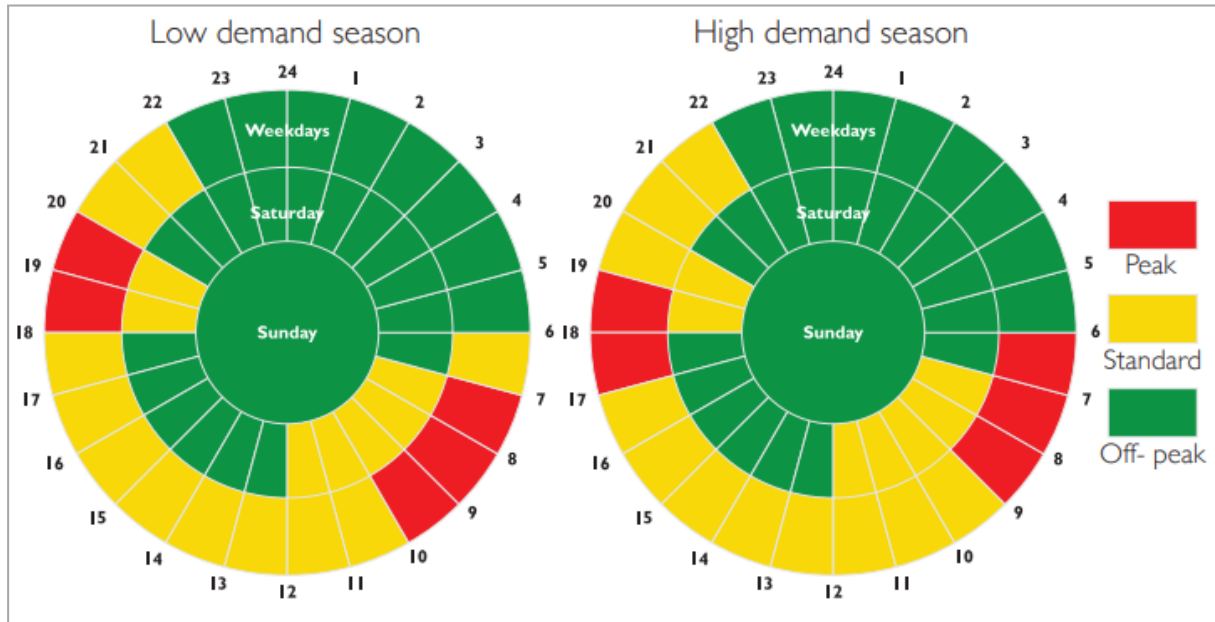


Figure 13: TOU tariff structure for the Megaflex structure 2021/2022 [11]

Table 1: Cost per kWh excluding VAT for the Megaflex TOU structure 2021/2022 (adapted from [11])

Active energy charge [c/kWh]							
		High demand season			Low demand season		
Zone	Voltage	Peak	Standard	Off-peak	Peak	Standard	Off-peak
≤ 300 km	< 500 V	437.10	133.01	72.58	143.1	98.76	62.95
	≥ 500 V & < 66 kV	430.21	130.35	70.79	140.34	96.58	61.29
	≥ 66 kV & < 132 kV	416.64	126.21	68.55	135.92	93.56	59.34
	> 132 kV	392.65	118.95	64.59	128.08	88.15	55.92

1.3.1.2 Load shifting

Load shifting is a technique that can only be used if a TOU tariff structure is available. The TOU structure charges different electricity prices based on the time of the day and normally has a peak and off-peak period. Load shifting aims to avoid electricity consumers operating in peak periods and instead incentivising them to operate in off-peak periods [45]. This ensures that the high operating cost of running electricity consumers in peak periods is avoided without influencing production. This technique does not reduce the total electric power consumed, but only reduces the overall cost. An example of load shifting is a dewatering pump and a dam. By pumping most of the water out of the dam before the Eskom peak period, the dam has time to fill back up in the peak period without the need to pump. When the peak period is over, pumping from the dam can commence again [43], [46].

1.3.1.3 Peak clipping

Peak clipping is a technique that reduces power consumption by switching off devices in peak periods [45], [43]. These devices are usually not necessary to be switched on or can be scaled back during peak times. Not only does peak clipping reduce the overall power consumption without influencing production, but it also lowers the electricity expense. An example is an air conditioner that operates the entire day. Using the peak-clipping technique, the air conditioner will typically be switched off during periods when nobody is in the building or be scaled back on cooling when only half the personnel are present.

1.3.1.4 Energy efficiency

Energy efficiency focuses on using power more efficiently to reach the same outcome, which includes changing the operating conditions of an electric device. For example, the power consumption can be reduced by replacing old pumps with pumps that have higher efficiency ratings. By reducing the pumping height or amount of water being displaced, electricity consumption can further be reduced [47].

1.3.2 DSM initiatives

DSM on the dewatering system of a mine focuses on reducing the amount of water in the WRS. Reducing the amount of water being used in a mine will reduce the electricity consumption of the dewatering pumps. Monitoring and supplying the correct demand are thus important to the overall effectiveness and profitability of the mine. DSM initiatives are required to reduce the water supplied to underground working areas. Initiatives such as stope isolation valves, pressure

set-point control, leak management, and infrastructure reconfiguration are implemented to reduce the demand for water.

1.3.2.1 Isolation valve

During the drilling and sweeping shift, water is used in working areas of the mine, especially inside stoping areas. There are usually numerous water leaks in stoping areas caused by damaged infrastructure such as rusted pipes and water hoses that are left open. After the drilling and sweeping shift is completed, service water is no longer required in the stopes. Level isolation valves are used to isolate the supply of water to specific areas of the mine [31]. These valves prevent unnecessary water from leaking into the stopes outside the drilling and cleaning shift. This reduces the load on the dewatering system and prevents the pumps from operating unnecessarily.

Isolation valves are installed on certain key areas of the mine to prevent water wastage. Section isolation valves isolate the supply to multiple levels. Level and half-level isolation valves isolate the supply to an entire level, while stope isolation valves isolate the supply to individual stopes in a level. Installation of section, level and stope isolation valves creates redundancy in the system. If a stope valve is not closed, half-level valves will cut off the supply. The same applies to level and section valves.

1.3.2.2 Water pressure set-point control

Vosloo [28] conducted a test involving the pressure and flow of water to determine leak severity. Figure 14 shows the results from the test conducted by Vosloo regarding the relationship. As the pressure increased inside the pipe, the flow rate out of the leak also increased. Initially the flow rate increased rapidly with a rise in pressure until the flow settles as it reaches a plateau point.

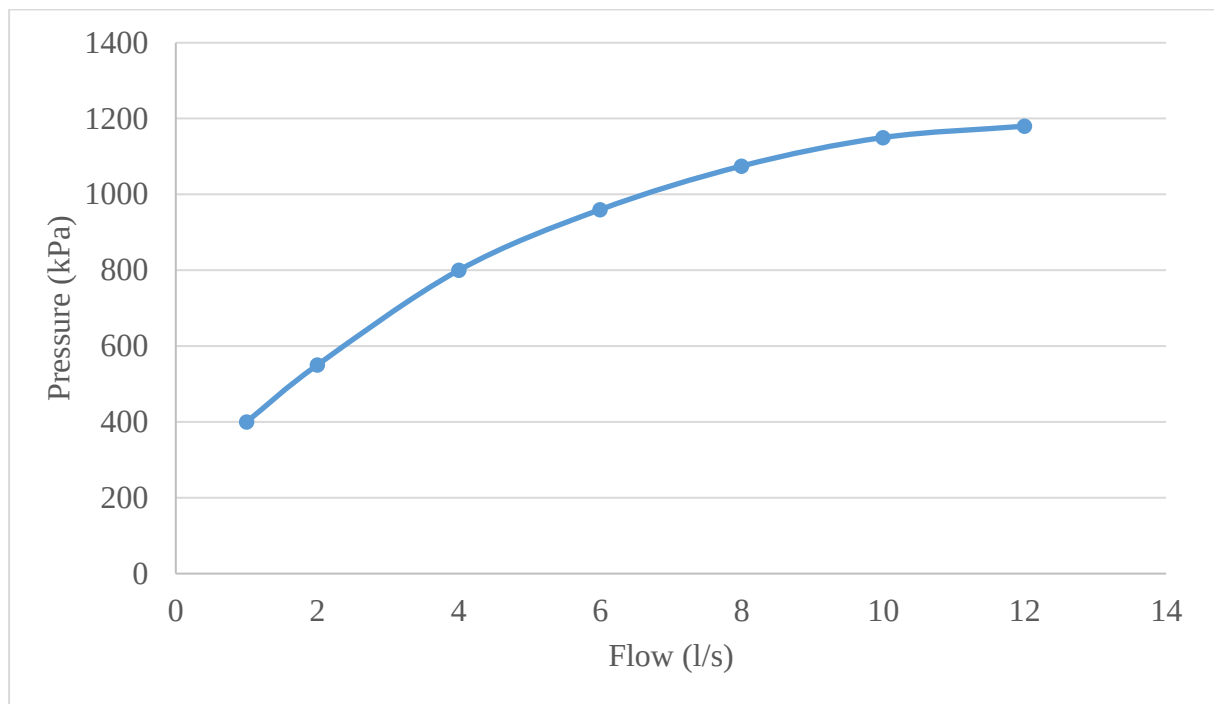


Figure 14: Relationship between water pressure and flow (adapted from [28])

Water pressure set-point control involves adjusting the PRVs to meet a desired pressure. By controlling the pressure, the flow rate can also be controlled. This action limits flow, which results in less water wastage from open-end hoses and pipe leaks. Furthermore, different flow rates are required during different shifts [28]. The water flow can be tailored to meet the demands of each shift to reduce water wastage. Extreme water pressures deep underground can be dangerous and unnecessarily high. Reducing the pressure will result in safer working environment with less water wastage.

1.3.2.3 Leak management

A large contributor to underground water wastage is leaks in pipes as well as water pipes that are left open. These water leakages must be pumped out of the shaft, which causes the dewatering pumps to use power unnecessarily [28]. Electricity is further wasted unnecessarily in the refrigeration process to cool down the service water that is leaked. These pipes are normally made from steel that rusts or plastic that cracks easily. Due to negligence and a lack of maintenance these faults progressively become worse, wasting more water.

Tracking the water usage on the mine is crucial as it gives an indication of water wastage. Levels are normally equipped with water flow sensors that measure the amount of water consumed in the level. If the flow meters record an abnormal amount of water on a level, this could mean that there are large water leaks present in the level. A visual audit must be

performed to verify if leaks are present. Auditing a level involves walking alongside pipelines to search for any faults. These faults are recorded together with their approximate locations and distances. Typical faults found on levels normally involve leaking flanges, broken valves, and water hoses that are left open.

1.3.2.4 Infrastructure reconfiguration

The required infrastructure to enable certain electricity-saving initiatives is often not found in mines. It is thus important to first introduce these modifications before initiatives can be implemented. Integrating various infrastructural modification does not only enable individual cost-saving initiatives, but also initiate integrated cost and electricity-saving initiatives.

As simulated by Stols [46], larger dam sizes enable longer load-shifting periods. Introducing control valves to the dewatering system, as investigated by Taljaard [31], further reduces energy consumption through leak management and pressure control. Installing water treatment stations underground leads to cleaner water, thereby prolonging the lifetime of the dewatering pumps. Recirculating service water further reduces the electricity consumption of dewatering pumps, although an integrated infrastructure approach will be required.

1.3.3 Previous studies conducted on DSM initiatives on dewatering systems

The previous section highlighted the impact that underground dewatering systems have on energy usage. In this section, existing literature will be reviewed to identify possible solutions to reduce the electricity usage of deep-level mine dewatering systems.

In 2012, Taljaard [31] conducted a study on control valve selection for WRSs. This study mainly focused on reducing the amount of water sent underground and therefore reducing the electricity consumption of dewatering pumps by using control valves. This study discussed infrastructure modifications to the dewatering infrastructure of a mine by considering different types of valves. Although the author mentioned several methods of energy reduction such as load shifting on a mine's dewatering pumps, recirculation of service water in deep-level mining without cooling was not mentioned. This study did, however, give adequate information regarding valves on the dewatering system of a gold mine.

In 2016, Stols [46] studied infrastructure constraints in dewatering systems. This study was conducted at a gold mine and focused primarily on reducing electricity consumption of the dewatering system by introducing energy efficiency methods. Although this study did mention the effects of infrastructural modifications, they were limited to changes to the pump

availability and dam size in gold mines. The author did not discuss the possibility of underground recirculation without cooling. This is of importance because mines encounter extraordinarily high electricity expenditures and are required to mitigate the costs using various energy efficiency initiatives [6]. Additional research should be conducted to reduce the electricity consumption of dewatering systems on platinum mines. Stols's study showed that the electricity consumption could be reduced by modifying certain infrastructural parameters on the dewatering system of a deep-level gold mine. Stols further showed that simulation could be used to predict the effects that certain energy efficiency initiatives would have on the electricity consumption and costs of dewatering systems [46].

In 2020, Du Plessis [48] conducted a study on possible energy savings of an open-pit mine. This study mainly focused on energy reduction through load shifting by using existing infrastructure. The study did not mention the effects of infrastructure modification on electricity use. Mines have large electricity expenditures that should be reduced through different energy efficiency initiatives and methods [6]. However, load shifting was the only energy efficiency method that the author considered. Thus, additional research is required to identify alternative solutions for reducing electricity use.

In 2018, Van der Wateren [49] conducted a study on energy recovery on mine dewatering systems. This study mainly focused on reducing the electricity consumption of mines' dewatering systems by integrating them with energy recovery devices. Van der Wateren's study included energy efficiency methods on the dewatering system of a gold mine. However, the study did not focus on the effect of infrastructure modification on the electricity consumption of dewatering systems. Dewatering systems are often limited by their infrastructure, which is a problem as energy efficiency methods rely greatly on existing infrastructure [48]. Alternative methods for reducing the electricity consumption of dewatering systems should be investigated by focusing on infrastructure modifications. However, this study did show that electricity consumption can be reduced by integrating existing systems with energy recovery devices [49].

In 2010, Mackay, Bluhm and Van Rensburg [50] conducted a study on refrigeration and cooling concepts for ultra-deep platinum mines. This study mainly focused on supplementary refrigeration technologies required at certain depths of a platinum mine, and it did not address any dewatering aspects or energy efficiency initiatives. This is of concern as mining operations are under great pressure to reduce electricity consumption due to increasing electricity rates [11]. However, this study did include specifying cooling infrastructural parameters that had to be in place at certain depths of a platinum mine. Nonetheless, further research must be

done to verify if the prescribed cooling methods of Mackay *et al.* would suffice for underground water cooling. This study provided ample information on cooling methods at certain depths of a platinum mine [50].

In 2020, Venter [43] conducted a study on reconfiguring a mine's dewatering system for increased water volumes. This study mainly focused on possible solutions for dewatering systems to compensate for excess water. Although the study mentioned infrastructure modification on the dewatering system, the author did not implement changes to the system. The electricity consumption was reduced by means of system automation and load shifting. The study did not mention water recirculation of underground service water without cooling or infrastructure modifications on platinum mines. Research should be done to find additional methods for reducing the electricity consumption of platinum mines dewatering systems.

In 2014, Schoeman [51] conducted a study on the integrated effects of DSM on mine chilled water systems. This study mainly focused on improving the efficiency of certain components in a deep-level gold mine. The study did, however, mention increasing underground water recirculation to reduce the electricity consumption of the dewatering system. By pumping less water up to surface, the electricity consumption could be reduced.

In 2018, Pascoe [52] conducted a study on improving control processes to sustain electricity cost savings on a mine WRS. This study principally focused on mitigating the reduction of load demand shifting when a critical component failure occurs on a mine WRS. The author did mention methods for decreasing the electricity consumption of the dewatering system. However, these methods were specified at a gold mine and did not mention an improvement in underground water recirculation. These improved control processes were also implemented on the existing infrastructure already in place. Additional research should be done on methods to reduce the electricity consumption of platinum mines' dewatering systems by either using new or existing infrastructure.

In 2015 Deysel [53] conducted a study on DSM strategies to reduce electricity consumption on platinum mines. This study mainly focused on plausible DSM strategies on three major systems, including a platinum mine's dewatering system. The author mentioned several strategies for reducing the electricity consumption but failed to evaluate the feasibility of increased underground water recirculation and the required accompanying infrastructure modifications. Additional methods for reducing electricity consumption of the dewatering systems should be

investigated by focusing on infrastructure modifications. However, the study did cover ample DSM strategies for reducing a dewatering system's electricity consumption.

In 2012, Louwinger [54] conducted a study on two pumped storage scheme power stations. This case study focused primarily on planning the capacity expansion of an electricity supply system that enables Eskom to meet future power and energy demands as economically as possible. In this case study, infrastructure modification was considered. The author explained the necessity of power stations and the basic working thereof. Power stations work on the same concept as load shifting in the studies mentioned above. They generate less electricity during peak hours than consumed during off-peak hours, resulting in less fuel being consumed overall from the electricity grid. However, this case study was not conducted on a mine and did not give additional methods for energy efficiency initiatives. Thus, additional methods for reducing electricity consumption of the dewatering systems should be investigated by focusing on infrastructure modifications. This case study did, however, show the need for proper infrastructure evaluation in industries other than mines.

In 2014, Hasan *et al.* [17] conducted a study on the optimisation of energy usage on South African mines. This study focused on implementing DSM strategies on compressed air networks and water pumping systems. DSM strategies, such as load shifting, were implemented on dewatering pumps and resulted in a 7.9 MW load being shifted. The authors provided good explanations on the control of valve fractions and the rate of flow. Recirculation of service water underground was not discussed in this study, although infrastructure was mentioned briefly. These case studies were also conducted on a gold mine.

In 2016, Meyer [29] conducted a study on the improved control of clear water underground pumping systems for DSM. This study compared automated pumping control systems with manual load-shifting results from a case study done on interconnected gold mines. The study sufficiently explained the infrastructure that is required to fully automate the pumping system of a deep-level mine. The study did not, however, mention dealing with water that is pumped to surface unnecessarily or increasing underground water recirculation.

After the literature review, a state-of-the-art matrix was created based on the studies mentioned above. A state-of-the-art matrix is simply a summary of the above studies with the key aspects highlighted. The following key aspects were chosen as they had relevance to this specific study:

- Dewatering.
- Infrastructure.

- Energy efficiency.
- Platinum mines.
- Water recirculation.

Table 2 shows the studies mentioned above and the aspects relevant to this study. Green blocks indicate that the author did do research about the associated aspects, while orange blocks indicate that the author did not.

Table 2: State-of-the-art matrix

Source	Dewatering	Infrastructure reconfiguration	Energy efficiency	Platinum mines	Underground water recirculation
[46]					
[48]					
[49]					
[50]					
[43]					
[51]					
[52]					
[53]					
[54]					
[17]					
[29]					

1.4 Need and objectives of the study

1.4.1 Need for the study

In the preceding section, past studies were reviewed to identify possible solutions for reducing electricity usage of deep-level mines' dewatering systems. Most research regarding energy efficiency improvements to dewatering systems has been done on individual sub-systems. However, limited research has been done on integrated infrastructure changes that can improve the energy efficiency of dewatering systems by recirculating water underground. Therefore, a need exists to reduce the electricity consumption of deep-level platinum mines through infrastructural improvements to the dewatering system.

1.4.2 Problem statement and objectives of the study

Water has many uses in mines. After water has been used, it flows through numerous sub-systems into large underground holding dams. The water in these dams are pumped to surface for cooling and treatment [28]. Thereafter, the water is placed back into circulation for use by mining personnel and equipment.

A problem for platinum mines is that incorrect or lacking infrastructure is keeping them from realising cost-saving opportunities. Service water is pumped to surface unnecessarily and TOU periods are not considered when using dewatering pumps.

The main objective of this study is therefore to reduce the electricity consumption and cost of the dewatering system of a deep-level platinum mine. The secondary objectives of this study are the following:

- Identify a problem in the dewatering system.
- Formulate a possible solution.
- Verify the solution using a simulation model.
- Validate the solution through actual results.

1.5 Study overview

This section provides a brief overview of each chapter and its expected contents.

Chapter 1

Chapter 1 described the background of the environment the study was conducted in and discussed the components involved. This section further provided literature relevant to the study. From this background and literature, a problem was identified and the need for this study was ascertained.

Chapter 2

Chapter 2 describes a universal five-step method for improving the dewatering systems of deep-level platinum mines for electricity and cost-saving opportunities. The five steps are as follows:

- Acquire data of a mine's WRS.
- Analyse the dewatering system's infrastructure.
- Verify the proposed solution.

- Develop an electricity baseline.
- Implement the solution.

The five steps are discussed in detail and the chapter gives a universal solution for reducing the energy consumption of a deep-level platinum mine's dewatering system.

Chapter 3

Chapter 3 describes how the five-step methodology developed in Chapter 2 was applied to one case study. The process and main finding of the case study are discussed in detail in this chapter. This chapter serves as the results section of the study.

Chapter 4

Chapter 4 summarises the study and gives recommendations for future work and study fields. This chapter serves as the conclusion of the study.

CHAPTER 2: DEVELOPMENT OF AN INFRASTRUCTURE MODIFICATION STRATEGY

2.1 Introduction

This section describes how a methodology was developed to reduce the electricity consumption and expenditure of a deep-level platinum mine's dewatering system through infrastructure reconfiguration. The methodology was developed to not only improve the mine's electricity consumption, but also to include cost avoidance. The method followed a five-step process that allowed for a generic approach to infrastructural modification for cost and electricity avoidance. The process was derived and adapted from infrastructure modification processes and initiatives described in multiple previous studies. The infrastructure modification strategy followed a five-step process, and each step is discussed in depth in this section.

Step 1: Acquire data of mine water reticulation systems

Gathering data on a system is an important step for understanding the system and associated problems. This step focuses on acquiring data through various methods such as monitoring existing systems, doing visual inspections, and using drawing layouts. Analysis of the acquired data improves familiarity with the WRS and the problems at hand.

Step 2: Analyse the dewatering system

From the data acquired in Step 1, possible problems in the WRS are identified and solutions formulated. Within this step, the high-level feasibility of the solution is tested while focusing on infrastructure modifications. The solution can either be energy reduction or cost avoidance.

Step 3: Verify the solution

After the problem and a possible solution have been identified, the solution's feasibility is verified. Simulation is used to aid in the verification of the solution. The simulation model is constructed and calibrated from the data obtained in Step 1.

Step 4: Develop the baseline

After a possible solution has been formulated and verified through simulation, a baseline is developed to measure its performance. The baseline is constructed from data obtained in Step 1. The key aspect of the performance evaluation is electricity consumption. Other aspects such as

water flow can also be monitored to aid the true effect of the implemented solution. A baseline is developed before the solution is implemented.

Step 5: Implement the proposed solution

After data has been acquired, the problem identified, a possible solution identified and verified, and a baseline developed, the solution is implemented. The baseline developed in Step 4 is used to evaluate the performance of the implemented solution. The results are used to validate the solution. Further monitoring ensures the stability of the infrastructure modification solution.

Figure 15 shows the methodology that was used in this study in the form of a flow diagram.

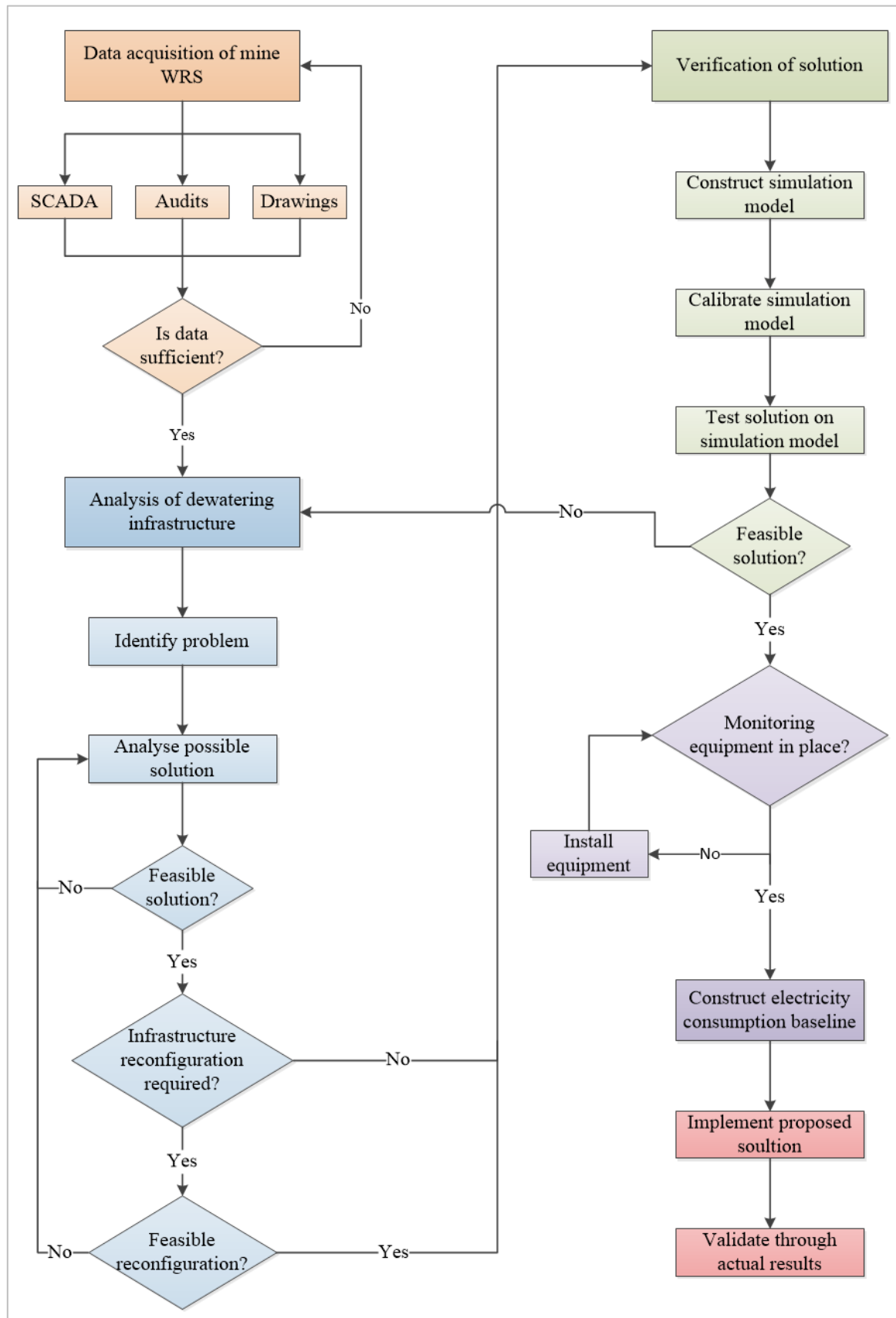


Figure 15: Methodology used to formulate and implement a solution

2.2 Data acquisition of mine water reticulation systems

Data acquisition of the case study mine's WRSs involves procuring information regarding its water network. Acquiring and analysing this data aids in understanding the mine's WRS in greater detail. After this analysis, the current operation of the system can be evaluated better to identify problematic areas and potential solutions. Important factors are the water flow data, existing infrastructure, and electricity consumption of the dewatering pumps. Using this data, problems inside the WRS can be identified and possible solutions be formulated. Figure 16 shows the process of acquiring the data for the WRS of the mine.

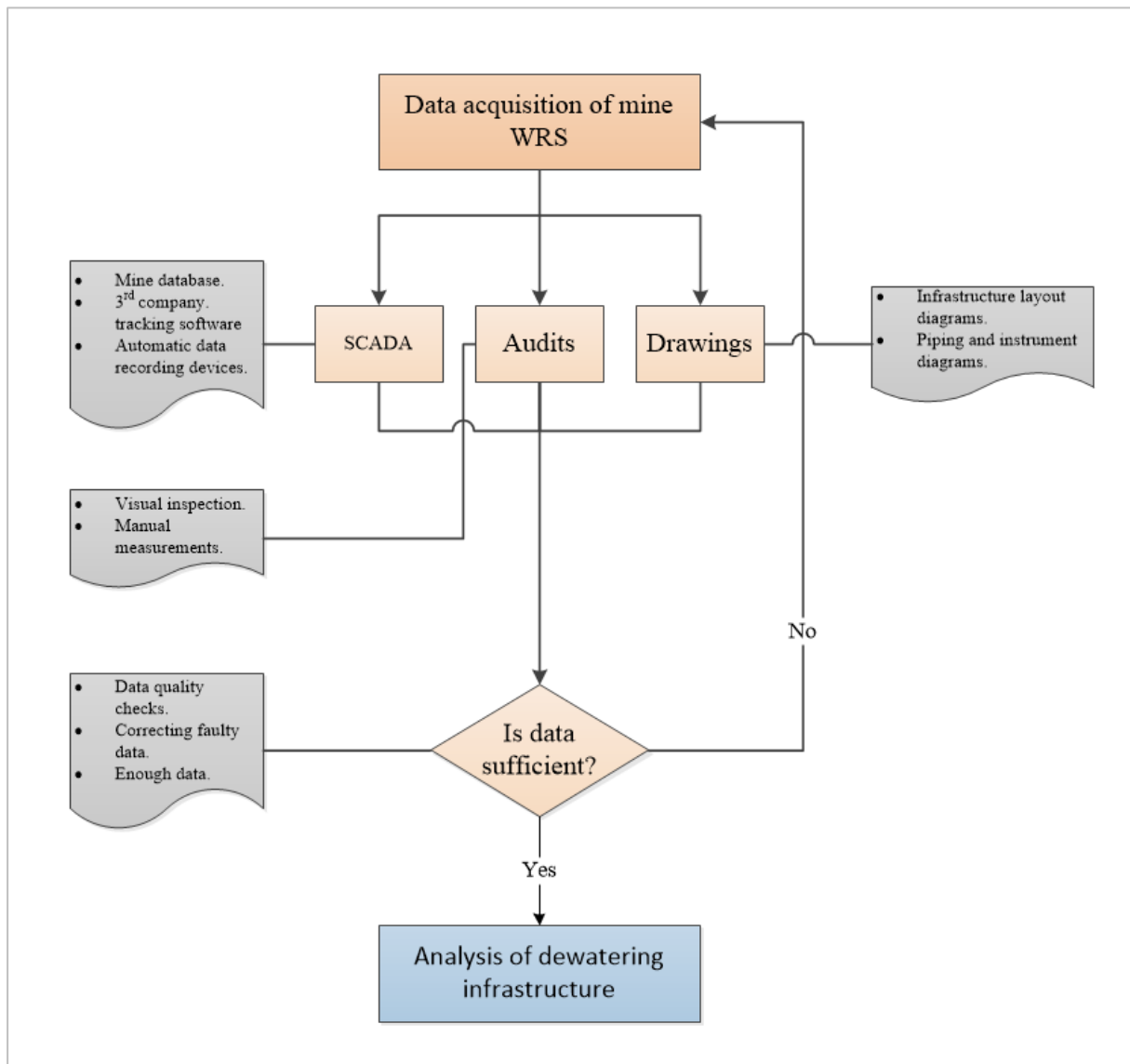


Figure 16: Data acquisition phase of methodology

2.2.1 SCADA

A supervisory control and data acquisition (SCADA) system is a control system that consists of various computers, networked data communications, and graphical user interfaces (GUIs). SCADA systems are used for high-level process control and data acquisition [55]. They are further used to control processes remotely by interacting with the GUIs.

Subordinate operations are performed by the various modules connected to field devices [55]. These field devices are normally data recording devices such as flow and pressure sensors that are controlled via a PLC. The PLC logs data and sends it through to surface where it is stored and displayed on the SCADA. On the SCADA, various measurements and equipment statuses should be present. These measurements are identified as tags. Tags are used to pull historical data for the specific component over a specified period. Measurements important for analysing the WRS of a mine include the following:

- Water flow rate.
- Water pressure.
- Dam levels.
- Valve position.
- Run statuses of dewatering pumps.
- Water and equipment temperatures.
- Electricity consumption.

If the required data is not present on the SCADA or if the mine does not have a SCADA system, data is retrieved manually directly from the installed equipment or using hand-written logs.

2.2.2 Layout drawing of WRS

A layout drawing of the WRS can also be used for data acquisition purposes if the SCADA does not contain sufficient data about the infrastructure. The drawings contain the entire WRS network and infrastructure specifications and locations. Typical information found on these drawings includes the water flow system, dewatering infrastructure on each level, and depths of these levels. It is important to note whether the drawings are up to date and signed off by the shaft. Each shaft will have its own set of drawings and infrastructure specifications.

2.2.3 Visual audits

Using the SCADA and layout drawing of the mine may not always provide sufficient data to formulate a good understanding of the WRS. It is good practice to verify the location and existence of the current WRS infrastructure of the shaft. Visual auditing involves the physical act of confirming the known information based on the theoretical data. Leaks and infrastructural mismanagement data are often not present on the SCADA, thus making auditing the water reticulation network essential for identifying problems. Leak audits involve walking the water pipeline to search for leaks that are present in the system. Infrastructure audits entail confirming the condition of the current infrastructure and verifying future infrastructure installation sites.

Sufficient data should be acquired by using the above-mentioned sources. If the data is still insufficient, the process should be repeated to solidify the understanding of the WRS. Third parties can also be used as a source during data acquisition as their hardware and measurements do not always appear on the SCADA. If the data is sufficient, analysis of the WRS commences to identify the problems with the system.

2.2.4 Data quality

Using high quality data is vital for ensuring that the simulation model is as accurate as possible. The simulation model can only be representative of the actual system if accurate data has been used [56]. Since mining systems are often in operation for long periods of time, the accuracy of certain measurements deteriorates over time. Factors that influence data accuracy and integrity must be inspected, which can be summarised as follows [56]:

- Conversion of measurement value.
- Storage and collection of the system.
- Traceability of measurement sources.
- Measuring equipment accuracy and malfunctions.
- Data abnormalities.

It is therefore important to verify the accuracy of the data before use. To ensure that the data is of high quality, checks are performed. If a check is not passed, the data should be corrected if possible or an explanation must be provided why the check was not passed. Checks include (adapted from [56]):

- Is there missing data in the sequence?
- Are there fluctuations in the data?

- Is the data stagnating beyond reasonable expectation? For example, a pump is not operational, but the hot water holding dam's level is decreasing. If the pumps are working but the data does not reflect this, it means that the data is of low quality.
- Do the data points exist in the expected range and follow the typical trend associated with historical data? For example, a 1 MW dewatering pump should consume between 0.9 and 1.1 MW when operational. Values outside this range indicate inaccurate readings.
- Do related parameters or variables follow the same data trend? For example, if the water consumption in a dewatering system increases, does the power consumption of the pumps also increase? According to Equation 3, this should be the case.
- Do values from independent measuring devices correlate with one another? For example, a water flow meter for a section should equate to the sum of each level assuming there are not losses between the flow sensors. Even if there are losses between the measuring devices, they should still follow the same trend.

2.2.4.1 *Correcting faulty data*

Faulty data should be corrected as far as possible. Manual verification should be done to rectify the data, including doing spot measurements, checking personnel's logged operational notes, and doing manual inspections. However, it will not always be possible to rectify or correct the data. In this case, assumptions must be made to account for missing or inaccurate data. For example, to determine the amount of fissure water of a level, the total water pumped up must be subtracted from the amount of water sent down, which will give an approximation of the total amount of fissure water in the system.

2.3 **Analysis of the dewatering network and infrastructure**

The objective of this study is not only to reduce electricity usage, but also the electricity expenditure of the dewatering system in a platinum mine. A key focus point is reconfiguring the infrastructure of the dewatering system to enable cost-saving opportunities. Once the problem has been identified, a solution will be formulated. The feasibility thereof will be tested briefly by using a theoretical approach. The current system together with the proposed solution

will be tested using simulation software. Figure 15 shows the methodical approach that will be followed to identify a problem and derive a solution.

2.3.1 Electric power consumption of a pump

From the data acquired in the data acquisition phase, a possible problem in the dewatering system can be identified and a solution formulated. The first step in identifying a problem is to identify the power-intensive devices in the dewatering system, such as electric pumps, which are highly intensive electricity consumers. By reducing the work done by the pumps, less electricity will be consumed by the system. Equation 1 is used to calculate the hydraulic power of an electric pump is as follows:

Equation 1: Equation used to calculate hydraulic power

$$P_h(kW) = \frac{\rho g (Q \times 3.6) H}{1\,000 \times 60 \times 60} \quad [1]$$

For the above-mentioned equation, the following holds:

- P_h = hydraulic power (kW).
- ρ = density of the fluid (kg/m³).
- g = acceleration of gravity (9.81 m/s²).
- Q = fluid flow rate (ℓ/s).
- H = fluid displacement height (m).

To calculate the power a pump must exert to displace water, Equation 2 is used:

Equation 2: Equation used to calculate pump power

$$P_s(kW) = \frac{P_h}{\eta} \quad [2]$$

Where:

- P_s = shaft pump power (kW).
- η = pump and electrical motor's combined efficiency.

Combing Equation 1 and 2 results in Equation 3, which will be used to theoretically calculate the power exerted by the dewatering pumps:

Equation 3: Combined equation used to calculate power of a hydraulic pump

$$P_s(kW) = \frac{\rho g(Q \times 3.6)H}{\eta \times 3.6 \times 10^6} \quad [3]$$

Equation 3 contains the variables that govern the amount of power an electric pump consumes. By analysing each variable separately, a thorough approach is applied to reduce the electricity consumption and cost of the dewatering system. Using this approach highlights key areas where a problem in the dewatering system may occur. Methods used in previous studies on dewatering systems will be used as potential energy saving initiatives that can be applied on the dewatering pumps.

2.3.2 Pump power

The first term in Equation 3 is shaft power (P_s), which is the amount of electricity the pumps are consuming at any given instance depending on the other independent variables. As this variable is dependent on other variables in the equation, shaft power is fixed based on the current conditions. However, electricity cost is dependent on both the amount of power being consumed and the TOU tariff, making the shaft power an independent variable in the Eskom Megaflex structure. Different electricity tariffs apply to different TOU periods in this structure. The tariffs are shown in Table 1 and the different TOU periods are displayed in Figure 13.

Stols [46], Deysel [53], Hasan *et al.* [17] and Venter [43] conducted studies to investigate the possibility of reducing electricity expenditure through load shifting and peak clipping. The initiatives from their studies had great success and managed to reduce the electricity expenditure. Load shifting involves operating electricity consumers outside of Eskom peak TOU periods. This moves the power usage from the expensive peak periods to less expensive off-peak periods. Load shifting does not reduce the electricity consumption, but only the electricity expenditure. Peak clipping involves reducing the amount of use from non-essential devices in peak periods.

Dam water capacity was identified by Stols [46] as one of the most important aspects to account for when considering load shifting. To stop dewatering pumps from operating during peak periods (low demand period is 07:00–10:00 and 18:00–20:00, and high demand period is 06:00–09:00 and 17:00–19:00), hot water service dams must have the capacity to hold the water until the period is over in order to not exceed its maximum limit. Furthermore, the pump rate should exceed that of the incoming flow of service water to avoid flooding the dam and shaft.

In terms of infrastructure, Stols [46] noted that a larger dam capacity leads to better load-shifting capabilities. Meyer [29] demonstrated that load shifting can either be done manually or be automated.

2.3.3 Fixed variables

The second term in Equation 3 is the density (ρ) of the fluid being pumped. For the pumps found in deep-level mining, this fluid is water. The density of water is dependent on temperature and pressure. The pressure in the mine is assumed to be atmospheric pressure, while the density of water can vary between 1 000 kg/m³ at 4 °C and 958 kg/m³ at 100 °C [57]. For this study, the temperature of water will only be considered in terms of not exceeding the legal wet-bulb limit of 32.5 °C.

The third term in the equation is the acceleration of gravity (g), which will be assumed constant at 9.81 m/s².

2.3.4 Water flow management

Water flow management is one of the most essential aspects to consider when attempting to reduce the electricity consumption of a pump. Although most terms in the hydraulic pump equation are either constants or kept constant, flow rate (Q) can change irrespective of the other variables. Pumping less water directly leads to less electricity being consumed by the pumps. Water management strategies are thus important to save water and reduce unnecessary pumping cost. Water mismanagement can be from pipe leaks that occur due to damaged infrastructure or water hoses that are left open. To determine the amount of water that is wasted, Bernoulli theorem is applied. The theorem is as follows:

Equation 4: Bernoulli's theorem

$$Q = C_c A_c \sqrt{\frac{2 \times \Delta P}{\rho \left[1 - \left(\frac{A_2}{A_1} \right)^2 \right]}} \quad [4]$$

For the above equation, the following holds:

- C_c = contraction coefficient.
- A_c = leak area (m²).
- ΔP = leak pressure – inside pipe pressure (kPa).

- A_1 = pipe area (m^2).
- A_2 = hole area (m^2).

Measuring equipment is used to quantify the amount of water wasted when certain variables are unknown. Water flow sensors measure before and after leaks. A simple mass balance is performed to determine the amount of water wasted.

Water leak management is implemented by using valves and identifying leaks caused by faulty infrastructure. To manage leaks caused by damaged infrastructure, such as holes and cracks in water piping, active knowledge on where the leaks are is important. Monitoring the water usage on the SCADA can give an idea of the water usage per level. If the water consumption has increased significantly, leaks might be present. Performing a visual audit of the problematic areas may highlight the locations of these leaks. After a leak has been identified, the location and intensity are recorded. The intensity can be approximated based on a numbering system or be calculated. The intensity of these leaks can either be calculated by using Equation 4 and Equation 3 or by using measuring equipment.

Valves control the flow of water to certain areas. They are used to control pressure and thereby control the flow rate to working areas as explained by Vosloo [28]. Valve opening percentages can also control the flow rate as shown by Hasan *et al.* [17]. Valves can thus be used to manage the amount of flowing water. Studies conducted by Deysel [53] and Taljaard [31] demonstrated the success that PRVs and isolation valves have in reducing the power consumption of dewatering pumps. Valves can be automated to improve cost and reduce electricity on the dewatering system as shown by Meyer [29].

PRVs can be used to limit the water flow to sections and areas in the mine. Control valves limit the flow by changing the valve position. Isolation valves limit flow by reducing the flow for stopes or entire levels. To confirm if valves are present, a visual audit should be performed. If valves are present on the SCADA, the condition of the valves must be verified.

2.3.5 Underground recirculation

The next variable in Equation 3 is the height (H) of the fluid the pumps must displace. Lowering the height reduces the electricity consumption of pumps. As mines recirculate water from surface to underground, the possibility exists to reduce the displacement height by recirculating the water underground as mentioned by Schoeman [51]. This, however, requires the correct conditions and infrastructure.

To ensure that the recirculation of service water underground is feasible, the conditions and infrastructure should be suitable. Service water on most platinum mines is recirculated by pumping it to surface dams where cooling and treatment take place. It is further necessary to displace the water to surface dams so that levels closer to surface can be supplied with water from these dams. For the underground recirculation of service water to be feasible, the underground service water condition should be similar to surface water conditions.

As previously mentioned, a primary reason for pumping water to surface is to cool the water before placing it back into circulation. Cooling requirements for the specific shaft should be investigated first to determine whether the possibility exists to recirculate water underground. A study conducted by Mackay *et al.* [50] showed the depth at which certain cooling devices are required for platinum mines. This study was conducted on mine ventilation requirements. However, some heat exchange with water from these cooling devices takes place in the shaft. Determining the VRT gradient of the specific shaft gives an indication of the depth limit the mine can reach before additional cooling is required. Additionally, measuring the temperature of the return water and comparing it with the supply water's temperature provides the cooling duty of surface operations. The mine wet-bulb heat tolerance is 32.5 °C. If the temperature of the service water is below the legal limit, cooling requirements can be assumed to be sufficient.

After service water is used in working places, the water is contaminated due to mining operations as explained by the Department of Water Affairs and Forestry [39]. To remove these contaminants, filtering and treatment stations are installed on and in the shaft. The service water supplied to levels should be cleaned before re-entering the level. Recirculating the water underground thus requires these stations to be located underground in the shaft. Without treatment and filtration, contaminated water does not only cause damage to dewatering pumps and equipment, but also cause health risks to mining personnel. Settlers are normally installed to filter contaminants from the water. By using flocculant, impurities cling together and sink to the bottom of the settler into sludge dams. From the sludge dams, mud pumps displace the sludge to surface. It is thus important that the applicable shaft is equipped with mud-handling infrastructure.

For underground water recirculation to be feasible, the correct dewatering infrastructure should be in place. This includes the required piping network necessary to reroute the water to the levels and areas where it will be used. This pipeline should have valves installed to control the flow of water. This is a crucial part of recirculating water underground. Most shafts have two main water columns flowing into a level, namely a service and potable water column. However,

the water flowing out of a level is a mixture of service and fissure water. Thus, if water is recirculated underground, the cold-water supply dams will eventually overflow, and the shaft will be flooded. Since hot water dams are equipped with dewatering capabilities, it is essential to switch the flow of water between cold and hot water dams. Valves make it possible to change the flow path of water in pipes [31]. However, hydraulic shock is an important factor to consider when switching between dams. Hydraulic shock normally occurs when the flow of water is stopped too quickly [33]. This can be prevented by slowly closing the valve, which gives the water pressure time to stabilise.

2.4 Verifying solution through simulation

A simulation model will be used to verify the proposed solution. The simulation model together with the implemented solution will give an indication of the effects that the proposed solution will have on the dewatering system. It is important to understand what is expected of a simulation model. A simulation model does not give a perfect flawless representation of the actual results and effects of the system, but rather indicates whether the proposed solution can deliver the desired results.

In this study, a simulation model will only be used to test if the proposed solutions can reduce electricity consumption and expenditure, thereby verifying Equation 3. The simulation software that will be used to verify the proposed solution is Process Toolbox (PTB). De Jager [58] used simulation to prioritise the implementation of platinum mine compressed air efficiency solutions. De Jager created a thorough methodology for accurately constructing a simulation model for compressed air systems. A similar methodology will be constructed in this study by adapting De Jager's methodology to dewatering systems.

Accurate data is required to calibrate the simulation model to ensure the simulation is as precise as possible and in line with the true outcome. The simulation model will be constructed and tested accurately on the proposed solutions identified in Section 2.3 using the following steps:

1. Analyse the dewatering components in the simulation.
2. Construct the simulation model.
3. Calibrate the simulation model.

2.4.1 Analyse the dewatering simulation

The first step in creating an accurate simulation model is to understand the simulation package and the components involved. Since the focus is on the dewatering system, only the components involving the dewatering system will be analysed.

2.4.1.1 Determine data requirements

It is vital to understand the entirety of the dewatering system throughout the course of a day. The mine works on different shifts – each with their own purpose and requirements. The resources provided to mine personnel during these shifts aid them to accomplish their tasks. It is, therefore, critical to understand the water requirements of the shaft during the various shifts in order not to hinder production.

Most water requirements are present in the drilling shift. As previously mentioned in Chapter 1, water is used during the drilling and cleaning shift for various reasons. Thus, it is vital that water is supplied without any delay or shortage to the mining personnel during the drilling shift. Energy efficiency initiatives implemented on the dewatering system of the shaft must not influence production. Furthermore, energy efficiency initiatives that reduce the flow of water must only be implemented during non-production hours or it should be ensured that they do not influence the mine's production.

Understanding how the water flows to the levels in the shaft is important. This will highlight the necessary components and data required to construct an accurate simulation model. Typically, water flows out of dams into pipes and from there into levels. These levels are normally equipped with valves and sensors that measure the various water parameters. The measurements already give an indication that dams, pipes, and valves are present in the flow network of water. Knowing the infrastructure components involved will aid in constructing an accurate simulation model.

2.4.1.2 Establish required data

To construct an accurate simulation model of the dewatering system, it is essential to understand the simulation software and its components in its entirety. PTB allows the user to model a thermohydraulic system based on the various water, air, and steam components. However, the following components will be used to create the simulation of the dewatering system:

- Water pressure boundaries.
- Water nodes.
- Water mass flow.
- Dewatering pumps.
- Pipes.
- Valves.
- Step controllers.
- Water dams.

Each of these components requires specific data in the simulation model, which ensures that the simulation is accurate. Once all the data has been inserted correctly, the simulation model is calibrated to represent a digital representation of the dewatering system for the specific shaft. A summary of the required data is given in Table 3.

Table 3: Required data for PTB components

Component	Required data
Water pressure boundary	Atmospheric pressure Atmospheric temperature Elevation
Water nodes	Water pressure Water temperature Elevation
Water mass flow	Water flow rate
Dewatering pumps	Water discharge rate Efficiency Power consumption
Pipes	Pipe size Pipe material Valve fraction
Step controllers	Start limit Stop limit
Water dams	Dam capacity Elevation Dam level Atmospheric pressure

Knowing in advance which data is required to model the existing system accurately makes the data acquisition process more efficient. The data required for the PTB components is acquired from sources described in Section 2.2. Not all data required by the PTB components is necessary to simulate the system accurately. Assumptions must be made where data is missing. The goal of the simulation is to verify whether the proposed solutions can reduce the electricity cost and consumption of the dewatering system. Potential sources for the acquisition of data for the PTB components are given in Table 4.

Table 4: Potential sources for required data

Required data	Data source
Atmospheric data	Manual measurements/calculations
Pressure in pipe	Calculations
Elevation	Layout drawing
Water flow rate	SCADA
Pump water discharge rate	SCADA/manual measurements
Pump efficiency	SCADA/calculations
Power consumption	SCADA
Pipe sizes	Layout drawing/manual measurements
Pipe material	Visual audits
Dam capacity	SCADA/layout drawing
Dam levels	SCADA
Infrastructure locations	Visual audit

2.4.2 Construct the simulation model

This section explains how once all the necessary data has been acquired, compiled and the quality verified, the simulation model will be constructed. The objective of the simulation model is to mimic real-life scenarios as closely as required to verify possible solutions. The focus is thus on determining the degree of complexity of the simulation model. Since the simulation will consist of numerous components, each component should represent the real-life aspect as closely as possible. Pump power, water flow, and dam levels will be critical aspects to consider simulating the dewatering system. The simulation parameters will be evaluated, and assumptions made to achieve an accurate model. Lastly, this section will describe how each component will be modelled.

2.4.2.1 *Determine focus and complexity*

To understand the extent of the complexity of the simulation, the purpose of the simulation should first be known. As mentioned previously, the goal of the simulation and the simulation software is to provide a platform for testing and exploring different scenarios. Since the objective of this study is to reduce the electricity expenditure and consumption of dewatering pumps, this too will be the goal of the simulation. The simulation will further be used to test the feasibility of the proposed solution and the effect on certain components. For example, while recirculating water underground and pumping to smaller dams, how many times will the dewatering pumps be stopped and started?

The complexity of the simulation varies greatly; therefore, it is vital to understand the purpose of the simulation. The boundaries of the simulation must be selected to determine the complexity of the simulation because the boundaries will influence the complexity and accuracy of the model. It is important to choose boundaries that will allow for efficient accuracy of the simulation model, but that will not needlessly complicate the model.

For example, consider that the simulation's purpose is to determine the effect of energy efficiency initiatives on the dewatering pumps. It may be needlessly complex to know the water usage of the individual components in each level. Instead, it is only necessary to know what the level consumes in total. In this instance, the specific requirements of the end users are not as important as the effect on the pumps, which is only due to the combined consumption of the level.

A simulation does not have to be complex to be accurate. For this study, the only parameters that will be focused on are those highlighted by Equation 3 and Section 2.3.1; namely, pump power and thus electricity expenditure, water mass flow, and pumping height. The reason is that simplifying the simulation will reduce the time spent on calibrating the simulation, which will in turn reduce the time spent on acquiring data that will not be beneficial to the accuracy of the model.

It is assumed that it will only be necessary to focus on the water being pumped from and to water dams because the places where the initiatives will be implemented are not in the working areas of the levels, but on the pumps and dams of the shaft. It is thus assumed that the rest of the level will be supplied with adequate water if the dams operate the same as before the intervention. However, one aspect that is required in the simulation is the control of the dam levels and the operation of the pumps. A few boundaries will be chosen to simulate the model

without accurately adding unnecessary complexity. A brief description of each boundary is given below:

Pump power

Dewatering pumps are the most important aspect for energy efficiency initiatives on the dewatering system. An accurate simulation is required to quantify the potential reduction in electricity cost and consumption on the dewatering system properly. The pumps must be modelled accurately to match the actual power consumption with the simulation's power consumption. Therefore, the pumps' discharge rate and power consumption will be important aspects to model.

Water flow

The water flow will directly influence the amount of power used by the dewatering pumps. It is further vital to understand how much water is used by the levels to avoid flooding the dams or letting the dams run dry and influencing production. It is crucial not to add too much complexity to the water flow in the simulation as this can become an intensive network.

Dam levels

Dam levels are critical parameters along with pump power and water flow. Dam levels are influenced directly by the amount of water being used by each level; therefore, managing dam levels and controlling the flow path of water will be critical to avoid flooding the shaft. PLCs are typically used to monitor dam levels to control valves and manage flow paths.

2.4.2.2 Set simulation parameters

Once the complexity of the simulation has been determined and the key boundaries identified, the time period will be established. As the dewatering system can be impermanent, it is also important that the simulation is impermanent. Therefore, the mine's operating schedule must be considered when choosing a time period for the simulation. The mine typically operates on a 24-hour cycle as previously explained in Chapter 1. The schedule can further differ on weekdays, weekends, and holidays. A typical simulation should account for normal operating weekday schedules where mining operations are present. However, dewatering pumps will always be in operation to prevent the shaft from flooding.

Simulation time frame

Sufficient time should be given to allow the full control of the control philosophy to be tested. This entails that all aspects in the control philosophy be tested. Running a simulation for an extended time period could highlight certain undetected problems in the control philosophy. Calibrating the simulation can thus be done for a single 24-hour cycle. If the calibration is done correctly and accurate data is used, the time period should not have an effect. A longer time period will, however, give a better approximation of the actual results.

Period size

PTB requires period sizes to perform calculations. A period size in PTB is a time period between calculation intervals. This can be changed in the simulation software to the desired size, which can be minute to days. However, the size of the period will influence the accuracy of the results and the time to complete the set of calculations. Although smaller period sizes deliver more accurate results, they do require more calculation time and computer processing power. Larger period sizes are less accurate but will be calculated faster. Ultimately, the period size will primarily be dictated by the resolution of the data. Along with a 24-hour time frame, previous studies used a 30-minute step size, which is small enough to achieve accurate results, yet large enough to facilitate fast simulation. Thus, this study will also use 30-minute step sizes.

Step sizes

A step size refers to the number of calculations the simulation does at one time. If, for example, the step size is stepped to 30 steps per periods size, the simulation will do 30 calculations before moving to the next time period. A combination of small and large step size can be used to simulate the solution more efficiently. Large step sizes can be used to test if the simulation works and if changes made to the simulation do not cause errors. If the simulation does not have any errors, the step size is made smaller to achieve a more accurate simulation result.

2.4.2.3 Make assumptions

Assumptions, such as values and properties that fall outside the purpose of the simulation model, are made to minimise the complexity of the simulation model. These assumptions should have a minimal effect on the outcome of the simulation as they are regarded as unnecessary data. Assumptions include thermodynamic calculations and some hydraulic values. The assumptions made in this study are the following:

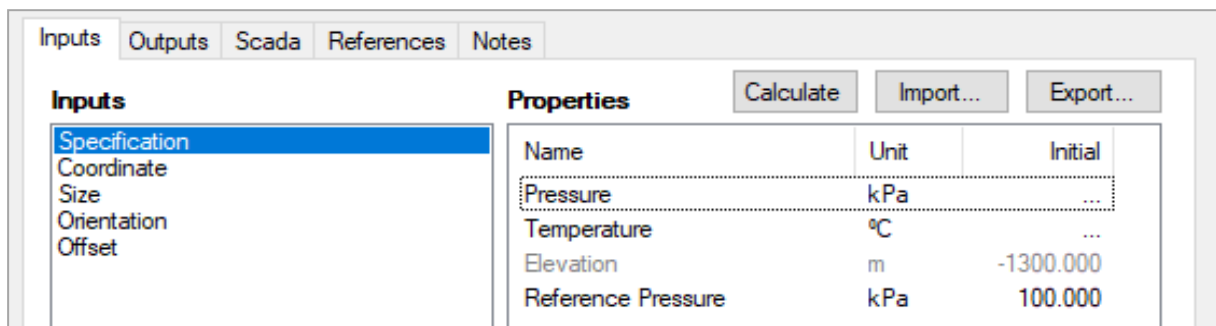
- Pressure properties do not affect the flow of water.
- Heat transfer is disregarded in pipes.
- Temperature of the water inside pipes and dams.
- Ambient air conditions (assumed constant throughout the depth of the shaft).
- The efficiency of the pumps remains constant.

2.4.2.4 Model components

PTB has several components that can be used to model the flow of water and pump power to displace the water. These components should be modelled as accurately as possible since they represent real-life components. This section discusses the method for modelling these components, including boundaries, nodes, mass flow components, pipes, step controllers, dams, and pumps. A brief description of the components follows:

Water pressure boundaries

Water pressure boundaries are fundamental components in PTB. This boundary has a constant temperature and pressure for every time period as shown in Figure 17. The water pressure boundary component will be used for outlet and inlet ambient conditions.



Inputs				
Inputs	Properties	Calculate	Import...	Export...
Specification	Name	Unit	Initial	
Coordinate	Pressure	kPa	...	
Size	Temperature	°C	...	
Orientation	Elevation	m	-1300.000	
Offset	Reference Pressure	kPa	100.000	

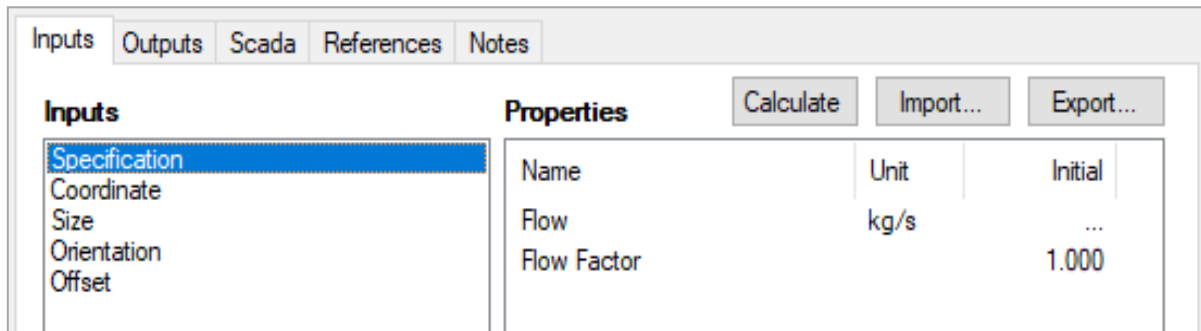
Figure 17: Water pressure boundary component input parameters

Nodes

Water nodes are essentially water property determinators. These components are points that retain certain information, such as pressure, temperature and change in network elevation. The software does the calculation using this information.

Mass flow

The water mass flow component forces a specified amount of water for each time period. It does not depend on any property and is thus ideal for simplifying water flow. Figure 18 shows that the input parameter required for the mass flow component is the flow of water in kg/s.



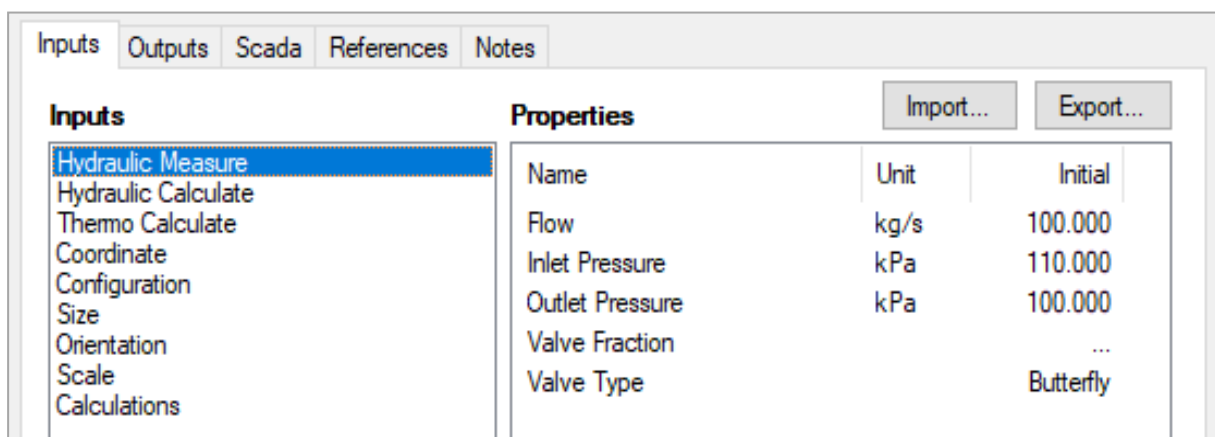
The screenshot shows a software window for the 'Mass flow' component. It has a tabbed interface with 'Inputs' selected. The 'Inputs' list on the left includes 'Specification', 'Coordinate', 'Size', 'Orientation', and 'Offset'. The 'Properties' table on the right has columns for 'Name', 'Unit', and 'Initial'. The 'Flow' property is set to 'kg/s' with an initial value of '...'. The 'Flow Factor' is set to '1.000'. Buttons for 'Calculate', 'Import...', and 'Export...' are visible at the top right.

Inputs	Properties
Specification	Name
Coordinate	Unit
Size	Initial
Orientation	Flow
Offset	Flow Factor

Figure 18: Mass flow component input parameters

Water pipe

Pipe components are important components in the simulation as they form part of the infrastructural reconfiguration requirement. The pipe component includes a variable valve fraction for flow and pressure control. This allows for modelling of a control valve when combining it with a step or proportional-integral controller component. Figure 19 shows the input parameters required to model a water pipe.



The screenshot shows a software window for the 'Water pipe' component. It has a tabbed interface with 'Inputs' selected. The 'Inputs' list on the left includes 'Hydraulic Measure', 'Hydraulic Calculate', 'Thermo Calculate', 'Coordinate', 'Configuration', 'Size', 'Orientation', 'Scale', and 'Calculations'. The 'Properties' table on the right has columns for 'Name', 'Unit', and 'Initial'. The 'Flow' property is set to 'kg/s' with an initial value of '100.000'. The 'Inlet Pressure' is set to 'kPa' with an initial value of '110.000'. The 'Outlet Pressure' is set to 'kPa' with an initial value of '100.000'. The 'Valve Fraction' is set to '...' and the 'Valve Type' is set to 'Butterfly'. Buttons for 'Import...' and 'Export...' are visible at the top right.

Inputs	Properties
Hydraulic Measure	Name
Hydraulic Calculate	Unit
Thermo Calculate	Initial
Coordinate	Flow
Configuration	Inlet Pressure
Size	Outlet Pressure
Orientation	Valve Fraction
Scale	Valve Type
Calculations	

Figure 19: Water pipe component input parameters

By recirculating water underground, the pipe network is reconfigured, which either increases or decreases the pipe length. Dynamic and static pressure drops due to pipe friction are thus altered according to the Darcy–Weisberg equation [59]. However, PTB does account for these losses. Figure 20 depicts the required input parameters for accurately simulating friction losses in a pipe.

Inputs Outputs Scada References Notes			
Inputs		Properties	
Hydraulic Measure		Name	Unit Initial
Hydraulic Calculate		Hydraulic Calculate Active	1.000
Thermo Calculate		Valve Cv Coefficient	0.000
Coordinate		Valve Kv Coefficient	0.000
Configuration		Dynamic Loss Coefficient	0.500
Size		Surface Roughness	mm 0.150
Orientation		Pipe Hydraulic Diameter	m 0.154
Scale		Pipe Flow Area	m ² 0.019
Calculations		Pipe Length	m 24.077

Figure 20: Input parameters for the Darcy–Weisberg equation use in PTB

The Darcy–Weisberg equation for calculating dynamic losses is as follows:

Equation 5: Darcy–Weisberg equation

$$h_f = f \left(\frac{L}{D} \right) \times \left(\frac{v^2}{2g} \right) \quad [5]$$

Where:

- h_f = head loss (m).
- f = friction factor.
- L = length of pipe work (m).
- d = inner diameter of pipe work (m).
- v = velocity of fluid (m/s).
- g = acceleration due to gravity (m/s²).

Equation 6 is used to calculate secondary losses, also known as minor losses, caused by physical interruptions such as valves and bends in pipes:

Equation 6: Secondary losses equation

$$h_L = k \times \frac{v^2}{2g} \quad [6]$$

Where:

- h_L = head loss due to secondary losses (m).
- k = head loss coefficient of the object.

Step controller

The step controller allows other components, such as pumps and valves (pipe components), to be controlled based on certain parameters or values. For example, if a dam is controlled between two levels, the step controller allows the pumps to only be operational between the two levels. This controls the dam between certain specified levels. The step controller allows multiple start and stop steps. Figure 21 depicts the required parameters for modelling a step controller component.

Inputs			
Inputs	Properties	Import...	Export...
Specification	Name	Unit	Initial
Coordinate	Number Of Steps		0.000
Size	Slope		0.000
Orientation	Start Limit 1		...
Offset	Start Limit 2		...
	Start Limit 3		...
	Start Limit 4		...
	Start Limit 5		...
	Stop Limit 1		...
	Stop Limit 2		...
	Stop Limit 3		...
	Stop Limit 4		...
	Stop Limit 5		...

Figure 21: Step controller input parameters

Dams

Dams function as water holding devices, which will have an important role in the simulation. Figure 22 depicts the necessary parameters to model a dam. This component has the following assumption built into the simulation software:

- 100% mixing occurs.
- Water density is 1 000 kg/m³ throughout.
- Dam cross section area is constant throughout the height of the dam.

Inputs	Properties																																	
Specification																																		
Coordinate																																		
Configuration																																		
Size																																		
Orientation																																		
Offset																																		
	<table border="1"> <thead> <tr> <th>Name</th> <th>Unit</th> <th>Initial</th> </tr> </thead> <tbody> <tr> <td>Pressure</td> <td>kPa</td> <td>100.000</td> </tr> <tr> <td>Temperature</td> <td>°C</td> <td>20.000</td> </tr> <tr> <td>Volume</td> <td>m³</td> <td>5000.000</td> </tr> <tr> <td>Level</td> <td>%</td> <td>50.000</td> </tr> <tr> <td>Heat</td> <td>kW</td> <td>...</td> </tr> <tr> <td>Top Elevation</td> <td>m</td> <td>-1299.000</td> </tr> <tr> <td>Bottom Elevation</td> <td>m</td> <td>-1300.000</td> </tr> <tr> <td>Heat Transfer Coefficient</td> <td>kW/...</td> <td>0.000</td> </tr> <tr> <td>Heat Transfer Area</td> <td>m²</td> <td>0.000</td> </tr> <tr> <td>Ambient Temperature</td> <td>°C</td> <td>0.000</td> </tr> </tbody> </table>	Name	Unit	Initial	Pressure	kPa	100.000	Temperature	°C	20.000	Volume	m³	5000.000	Level	%	50.000	Heat	kW	...	Top Elevation	m	-1299.000	Bottom Elevation	m	-1300.000	Heat Transfer Coefficient	kW/...	0.000	Heat Transfer Area	m²	0.000	Ambient Temperature	°C	0.000
Name	Unit	Initial																																
Pressure	kPa	100.000																																
Temperature	°C	20.000																																
Volume	m³	5000.000																																
Level	%	50.000																																
Heat	kW	...																																
Top Elevation	m	-1299.000																																
Bottom Elevation	m	-1300.000																																
Heat Transfer Coefficient	kW/...	0.000																																
Heat Transfer Area	m²	0.000																																
Ambient Temperature	°C	0.000																																

Figure 22: Dam component input parameters

Water pumps

Pumps generate pressure to displace water throughout the water flow network. The pump component is one of the key aspects of the simulation since this component will determine the electricity consumption of the system. The following pump assumptions are made in PTB:

- Pump motor efficiency stays constant. There are no variable speed drives on these pumps thus they can only run at full load.
- No heat transfer takes place between the water inside the pump and the ambient air.

Figure 23 shows the inputs required to model a pump accurately. Three pressure and flow values are required to draw the characteristic curve of a pump. These values can either be found on the actual pump's characteristic curve provided by the pump manufacturer or the values can be calculated. The electric power and efficiency are calculated using Equation 3.

The screenshot shows a software window with tabs: Inputs, Outputs, Scada, References, and Notes. The 'Inputs' tab is selected. On the left, under 'Inputs', there is a list: Specification (highlighted), Coordinate, Size, Orientation, and Offset. On the right, under 'Properties', there is a table with columns: Name, Unit, and Initial. The table contains the following data:

Name	Unit	Initial
Pressure 1	kPa	4145.455
Pressure 2	kPa	3116.883
Pressure 3	kPa	0.000
Flow 1	l/s	0.000
Flow 2	l/s	77.000
Flow 3	l/s	154.000
Efficiency Rating 1		1.000
Efficiency Rating 2		1.000
Efficiency Rating 3		1.000
Motor Efficiency Rating		0.600
VSD Efficiency Rating		1.000
Speed Fraction		...
Pressure Factor		1.000
Flow Factor		1.000
Efficiency Factor		1.000
Energy Tariff	R/kWh	...

Buttons at the top right include 'Calculate' (highlighted), 'Import...', and 'Export...'.

Figure 23: Pump component input parameters

If only the operating point of a pump is known, the following is done to construct the curve:

Table 5: Table used to create the characteristic curves of dewatering pumps on PTB

	Pressure (kPa)	Flow (l/s)
Point 1	$P_1 = P_2 \times 1.33$	0
Point 2	P_2	Q_2
Point 3	0	$Q_2 \times 2$

Point 2 refers to the current operating point of the pump. This data should be acquired as explained in Section 2.2.

Where:

- Q_2 = displacement rate of pump.

And:

Equation 7: Equation for calculating static water pressure

$$P_2 = H \times g \times \rho \quad [7]$$

Where:

- H = displacement height of the water (m).
- g = acceleration of gravity (9.81 m/s^2).
- ρ = density of water ($1\,000 \text{ kg/m}^3$).

2.4.3 Calibrate the simulation model

Calibration ensures that the simulation model is accurate, can be used to test the possible solution, and is relatable to the actual system. Calibrating the simulation model involves modelling the simulation model to be as representative of the actual system as possible. This ensures that the scenarios that are tested on the system are close to a real-life model.

To calibrate the model of this studies using an actual system, certain boundaries must be known. As discussed in Section 2.4.2, the boundaries to be focused on are water flow, power consumption, and dam levels. High quality data is required of these values to calibrate the simulation model for its intended purpose. After the data has been acquired as described in Section 2.2, the model will be considered calibrated. The time frame that will be chosen to calibrate the simulation is important. One average 24-hour day will be used to calibrate the simulation. Matching the water flow, power consumption of the pumps and dam levels of the simulation with the actual system will provide an accurate, calibrated system. The model will be considered calibrated if the values are within 5% of the actual results.

2.5 Development of an electricity consumption profile

An electricity consumption profile or baseline is required to compare the current electricity consumption of the dewatering system with the proposed solution's electricity consumption. This baseline will determine whether the proposed solution succeeded in reducing electricity cost and expenditure on the dewatering system. A baseline will be constructed for both the simulation model and the actual system.

The purpose of the simulation baseline is to test whether certain energy efficiency initiatives can reduce electricity consumption and expenditure on the simulation model. This model will be constructed by using a calibrated model of the current system as explained in Section 2.4.3. Different scenarios will be tested on this model and the effects will be compared with the baseline. An advantage of the simulation model's baseline is that the baseline can change depending on the input parameters. This will aid in predicting the effect of proposed solutions.

The purpose of the actual baseline is to validate the results from the proposed solutions. The power consumption of the pumps is explained by Equation 3. The only varying variable in this equation is the volume flow of water. When the shaft consumes more water, the electricity consumption of the pumps also increases. Thus, resulting in electricity consumption mainly governed by the number of end users and their water consumption. If, for example, the shaft adds more active levels, more water will be consumed, resulting in additional power consumption by the pump to remove this additional water. If there is a non-working day at the shaft, the water consumption will be reduced, resulting in less water to be pumped out by the dewatering pumps.

A dynamic baseline that scales according to the amount of water being recirculated is thus required, which will ensure that the true effect of the solution is measured. However, there must first be a correlation between Equation 3 and the actual power consumption. If a correlation exists, Equation 3 along with the correct water measurements will be used to predict the electricity consumption of the pumps based on the water consumption. An average weekday, Saturday and Sunday electricity consumption baseline will be used and scaled according to the amount of water consumed by the shaft to develop a dynamic baseline.

2.6 Implementation of solution

After a solution has been identified, verified on the simulation model, and an electricity consumption baseline developed, the solution will be implemented on the actual system. After implementation, adequate time will be taken to generate enough data. The system will be monitored closely to check for any problems that may occur. After an adequate amount of data has been generated, the performance of the solution will be compared with the baseline. This will validate the results of the simulation and determine the success of the study.

2.7 Conclusion

This chapter explained the process of how the problem will be addressed. The process is in the form of a five-step methodology, which is designed to be generic and applicable to other dewatering systems. Each step consists of individual sub-steps. The methodology has the following outline:

Step 1: Data acquisition of mine water reticulation

The process of acquiring data was explained and simplified. Sources that may contain the required data were identified as the evaluating the mine's SCADA, performing audits, and using layout drawings of the dewatering system. After data acquisition, the data quality is verified to ensure that accurate data is used.

Step 2: Analysis of dewatering network and infrastructure

This section identified the problems with the data acquired in the previous step. The problems are identified by using Equation 3 to calculate the electricity consumption of a pump. Previous studies focused primarily on water flow management and load shifting to reduce electricity consumption on dewatering pumps. Although underground recirculation can reduce the electricity consumption of the pumps, the conditions should be correct and the required infrastructure in place.

Step 3: Verification through simulation

This section explained how a simulation will be constructed and used to verify the proposed solution. This section described the necessary complexity of the model. A brief discussion followed on the components involved and their required data to be accurate. Finally, the section explained how using the data acquired, a calibrated model is constructed to test the possible solution on the dewatering system.

Step 4: Development of an electricity consumption profile

This section described how to develop a profile to evaluate the results of the proposed solution. A baseline for both the simulation and the actual system will be developed. Using the calibrated model, a simulation baseline will be developed. Using measuring devices and Equation 3, a dynamic baseline will be developed to accommodate varying flow demands. These baselines will be used to verify and validate the results.

Step 5: Implementation of solutions

This section discussed that after the solution has been verified on the simulation model and an electricity consumption baseline has been developed for the pumps, the solution will be implemented on the actual system. The results will be compared with the baseline to determine the success of the study. Further monitoring will be done to check for any problems.

CHAPTER 3: IMPLEMENTATION OF THE INFRASTRUCTURE MODIFICATION STRATEGY

3.1 Introduction

This case study is a large platinum mine located in the North West province of South Africa. The primary objective of this chapter is to apply the methodology developed in Chapter 2 to a case study shaft (see Figure 15). The purpose of this five-step methodology along with its sub-steps is to reduce the electricity expenditure and cost of the case study shaft's dewatering system. Secondary objectives include:

- Identifying potential problems in the dewatering system.
- Formulating a solution using first principles.
- Verifying the solution using a simulation model.
- Validating the solution by implementing proposed solution on an actual case study shaft.

3.2 Data acquisition of the water reticulation system

The first step in the methodology was the data acquisition phase. In this phase, an adequate amount of data was gathered, which was used to identify potential problems and constraints. Sufficient data was obtained by using the SCADA and layout drawings as well as performing visual audits. All the information needed for the familiarisation of the case study shaft's WRS is discussed in the first step below.

3.2.1 Layout drawings

To become familiar with the shaft's WRS, the first step was to understand the general layout and flow of water. Piping and instrumentation diagrams provide a general description and layout of the WRS and the infrastructural components involved. The case study shaft's WRS consisted of two main sections, namely the vertical and decline sections.

Figure 24 shows the vertical section of the WRS and the reference starting point in this system. Treated service water between 15 °C and 20 °C flows from the surface cold water holding dam (cold well) down into the shaft. Pressure builds in the pipes due to the static head of the water. To relieve this pressure, the service water falls into water breaker dams. These are large open dams that depressurise the water.

From these water breaker dams, the water cascades down to the levels and dams beneath it. Water Breaker Dam 1 supplies water to 15L and Water Breaker Dam 2. Thereafter, Water Breaker Dam 2 supplies water to the 15L dam and 16L. Next, the 15L dam fills up 16L dam and supplies 17L with service water. This pattern repeats itself until the 20L dam, which then supplies service water to 22L and 23L and supplies the 22L decline dam. When the 22L dam is full, a valve above Water Breaker Dam 1 closes to stop the supply of water to the shaft.

Figure 25 shows the decline section where the 22L dam is supplied by the 20L dam. A control valve located between 20L and the 22L dam is used to control the amount of water flowing into 22L dam. Thereafter, the 22L dam supplies service water to 24L to 28L. A PRV is located at the start of each level to reduce the water pressure that builds up at the lower level.

The dirty service water that returns from the levels flows down into dams in a section called Shaft Bottom. Two Shaft Bottom dams are located in the shaft, one on 25L and the other below 28.5L. Furthermore, 15L to 23L's return water flows to the 25L Shaft Bottom dam, from where it is pumped to 21.5L MPS's settlers. Likewise, 24L to 28L's dirty service water flows to the 28.5L Shaft Bottom dam, from where it is pumped to the 28.5L settlers.

There are two MPSs located on the shaft. These pump stations have settlers to treat and filter water, dams to contain the sludge and clear water, and pumps to displace the sludge and water. The sludge from the 28.5L MPS is first displaced to the 21.5L MPS, from where it is displaced to surface for further mineral processing. When the dam capacity reaches a maximum limit of 70% full, a control valve opens, and the clean water is pumped from the 28.5L MPS to the 21.5L MPS. From here, the water is pumped up to surface into the surface hot water holding dam (hot well).

The water in the hot well flows through a cooling tower to remove the heat picked up in the mine. However, the cooling tower at this shaft is no longer operational, meaning that the water flows directly from the hot well into the cold well. Thereafter, the water is resupplied to the shaft and the process repeats itself.

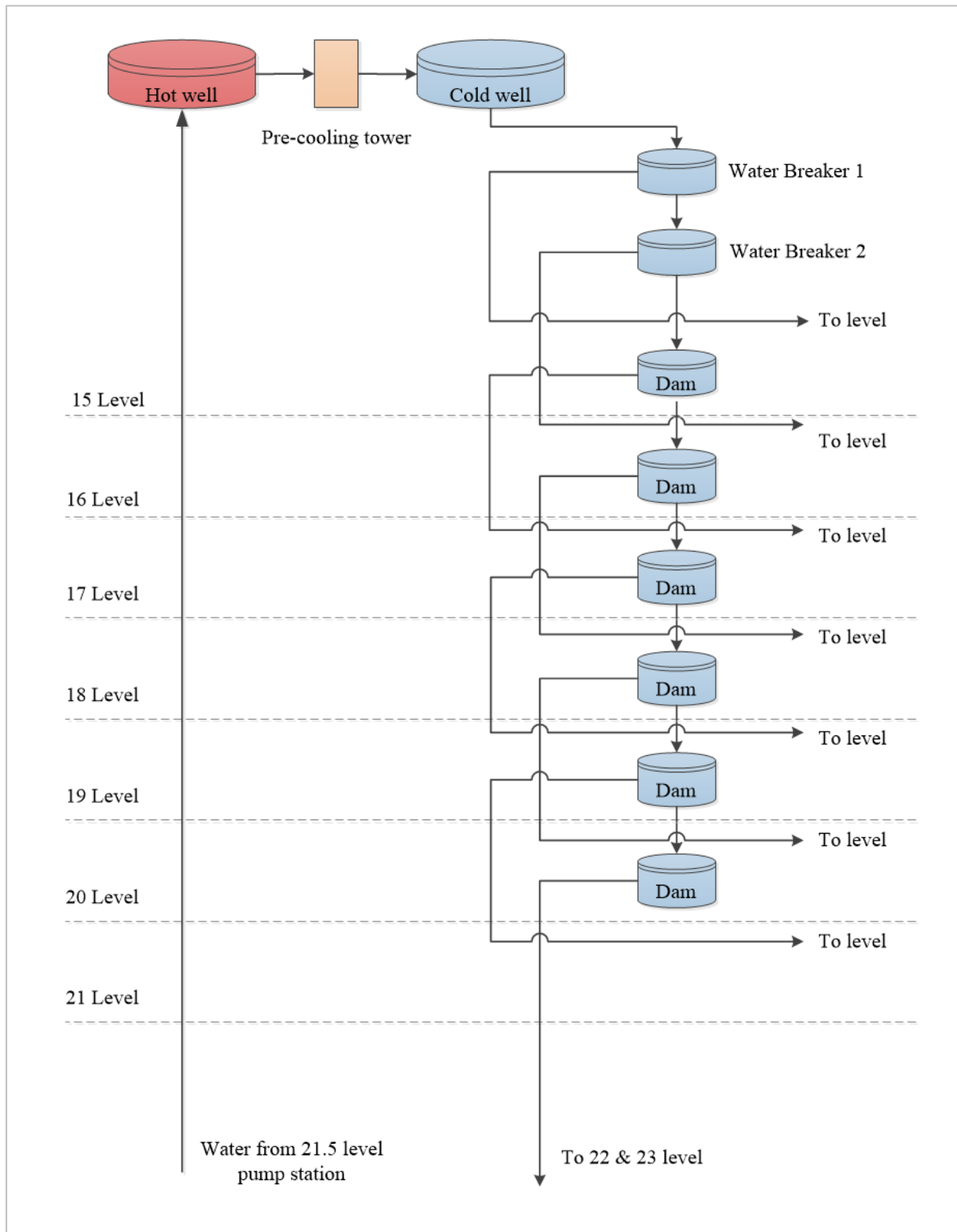


Figure 24: WRS vertical section layout.

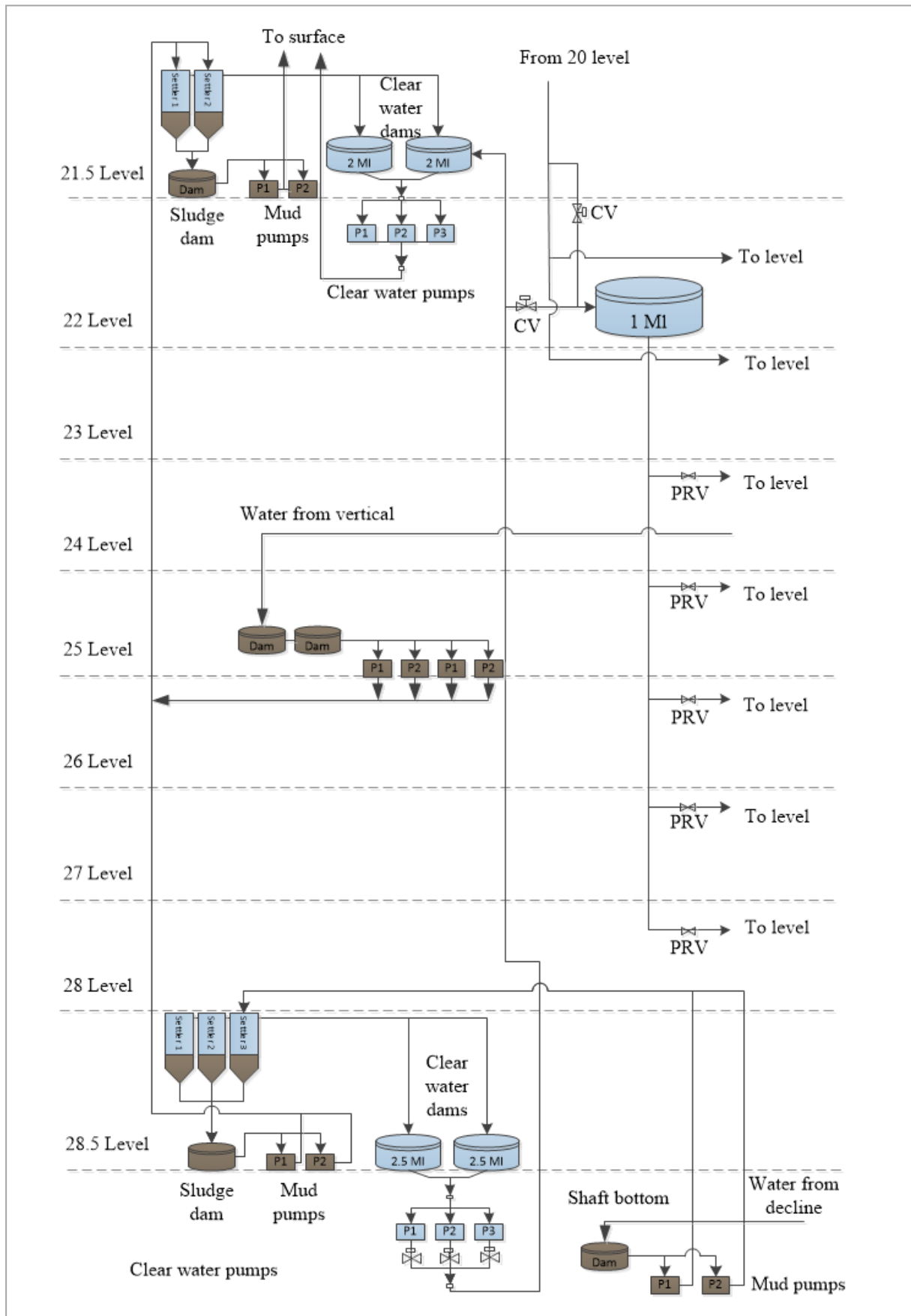


Figure 25: WRS decline section layout

Table 6 shows the depth below surface, barometric pressure, and VRT of the various levels from 21L to 28.5L.

Table 6: Depth below surface, pressure and VRT of decline levels

Level	Depth below surface (m)	Barometric pressure (kPa)	VRT (°C)
21	950.3	100.4	42.4
22	1 005.3	101.0	43.6
23	1 060.3	101.6	44.8
24	1 103.3	102.0	45.8
25	1 164.3	102.7	47.1
26	1 199.3	103.1	47.9
27	1 235.3	103.5	48.7
28	1 270.3	103.9	49.5
21.5 MPS	965.3	100.5	42.7
Shaft Bottom	1 152.6	102.6	46.9
28.5 MPS	1 300.0	104.2	50.1

3.2.2 SCADA

The mine's database, also known as the SCADA, contains various data readings. The SCADA links to a server that stores the data for future use. Important measurements to consider for the WRS of the mine are water flow, dam levels, and electricity consumption data. Figure 26 to Figure 32 show the values that are available on the mine's SCADA.

Figure 26 compares the average underground water consumption of the shaft with the average water pumped up from underground by the 21.5L pumps over a 24-hour period. The blue line indicates the water that fed the shaft, and the orange line indicates the water that the 21.5L dewatering pumps pumped out of the shaft. Thus, the water flow consumption was available for the shaft and the water displacement rate was known for the 21.5L pumps. The figure shows that most of the water was used in the drilling shift period (05:00–13:00) with a small increase in consumption in the cleaning shift period (21:00–23:00).

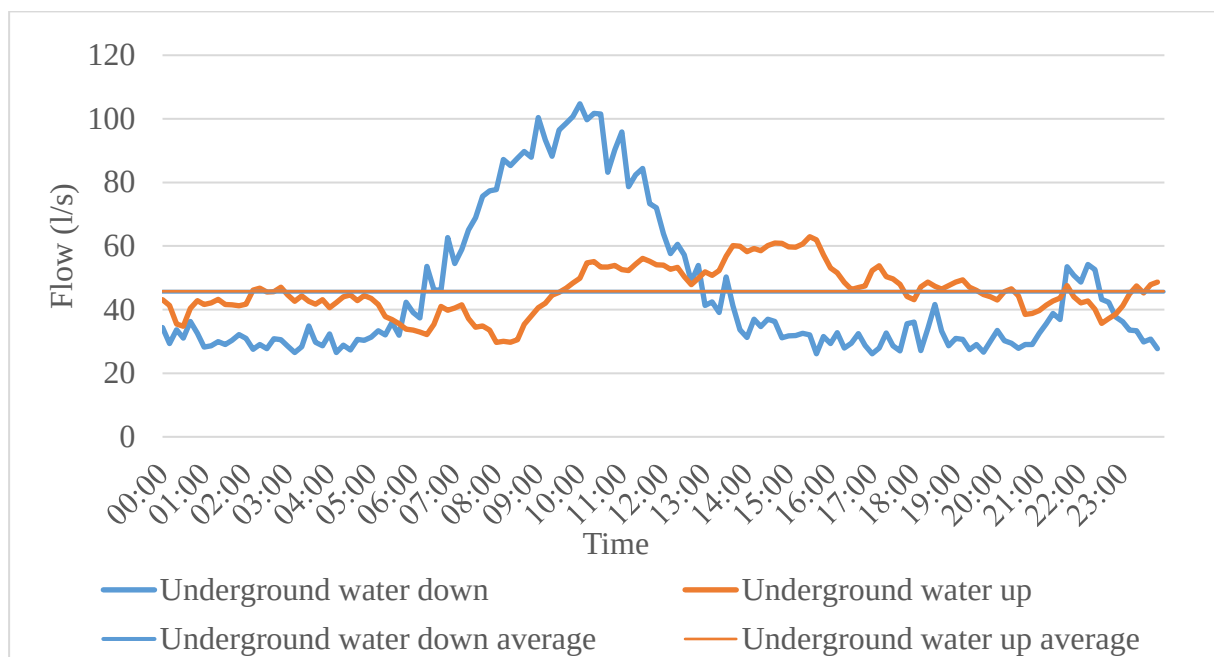


Figure 26: Underground water consumed by the shaft vs the water pumped out of the shaft by the 21.5L dewatering pumps

Most pumping from the 21.5L pumps happened between 10:00 and 16:00 as shown in Figure 26. This followed the same profile as the water consumption of the shaft, but with a three-hour delay. Thus, the water consumed in the shaft was only pumped out by the pumps after three hours. The average water consumed by the shaft was close to the average amount of water pumped out of the shaft by the 21.5L pumps. This indicates that the shaft did not experience large volumes of fissure water.

Figure 27 shows the average water consumption of the vertical and decline sections over a 24-hour weekday period. The figure shows that most of the water was used by the decline section. The decline water consumption followed a similar profile as the total water consumed by the shaft, while the vertical section had a more constant profile. The decline section's water consumption changed according to the water demand of the shaft. The demand was at its highest between 05:00 and 14:00, whereas the vertical section had a more gradual water consumption as shown in Figure 27.

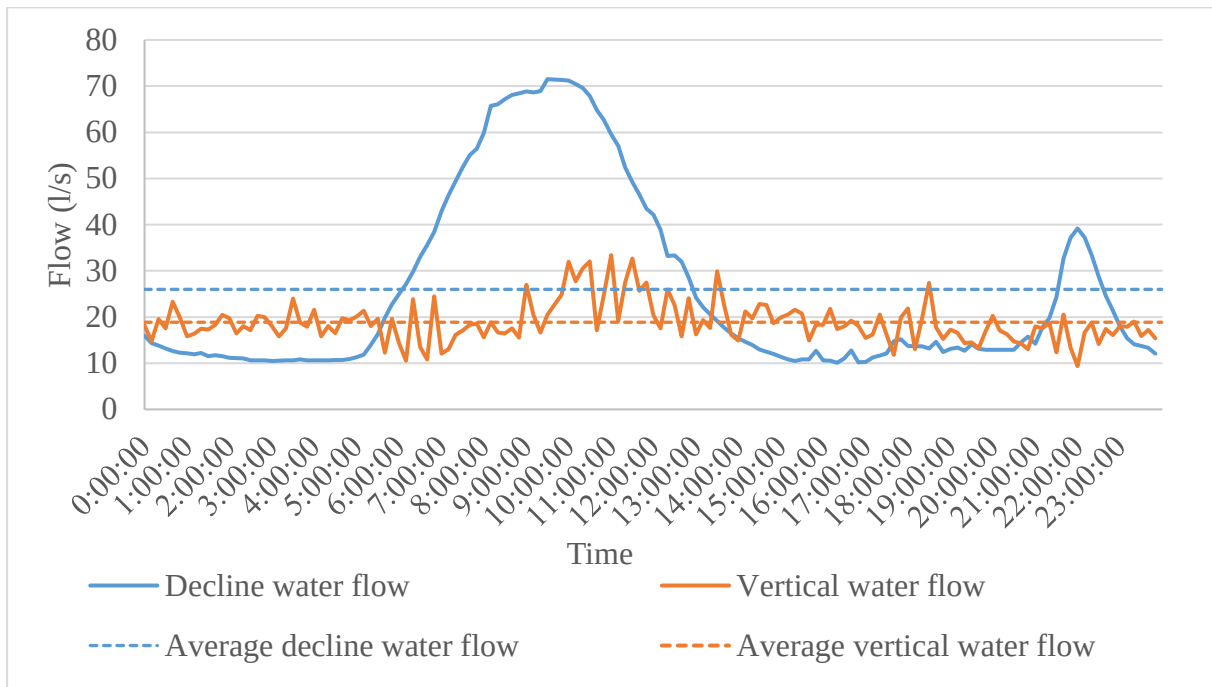


Figure 27: Decline vs vertical sections' water consumption

Figure 28 shows the average water consumption per level on the decline section. The figure demonstrates that 24L consumed the most water and 25L the least. The level's water flow consumption followed the same profile as the total underground water down and the decline water consumption. This was caused by the rising demand in the drilling shift (05:00–14:00) and the cleaning shift (20:00–05:00).

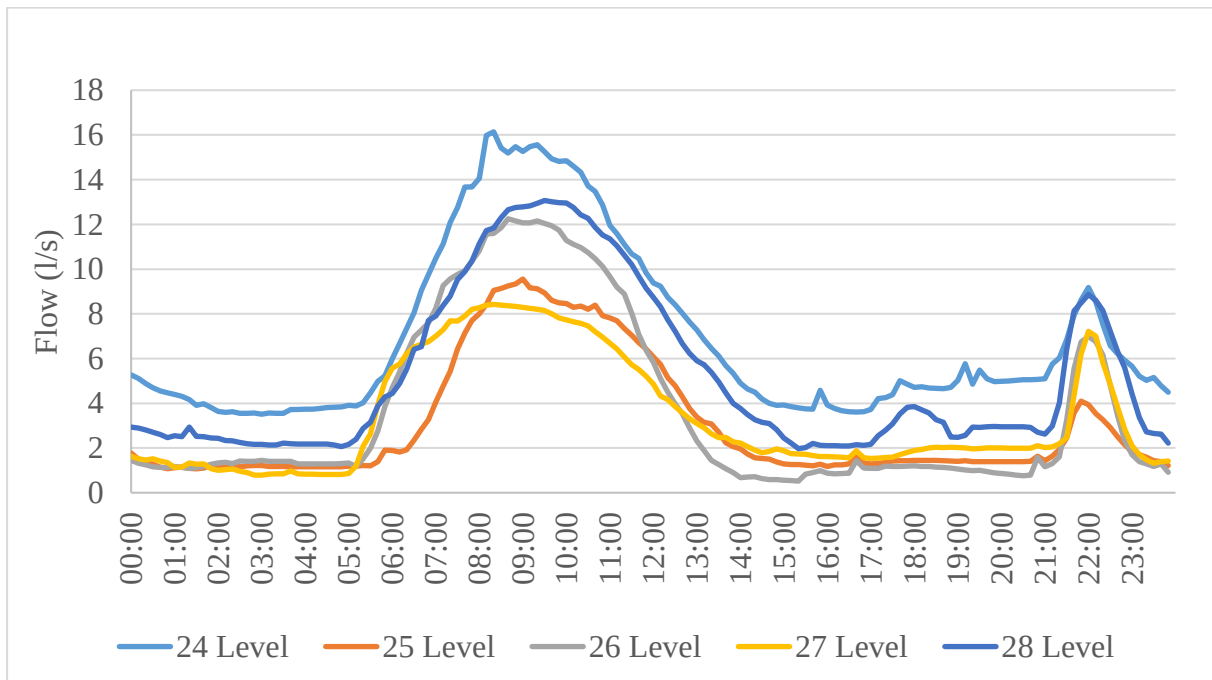


Figure 28: Decline water consumption per level

Figure 29 shows the water level in percentage for the 21.5L dam. The dam's capacity was controlled between 30% and 50%, as shown in the figure below, to ensure sufficient capacity in the case of flooding. The capacity of each dam was 2 Ml as shown in Figure 25. Figure 29 only shows the capacity of Dam 2 because Dam 1 flowed directly into Dam 2. Dam 1 was reserved as spare capacity in the event of flooding. When the dam capacity displayed 100% full on the SCADA, the actual dam capacity was at 90% full. This left 10% additional capacity to avoid water spilling out of the dam. This was true for all the dams on the shaft.

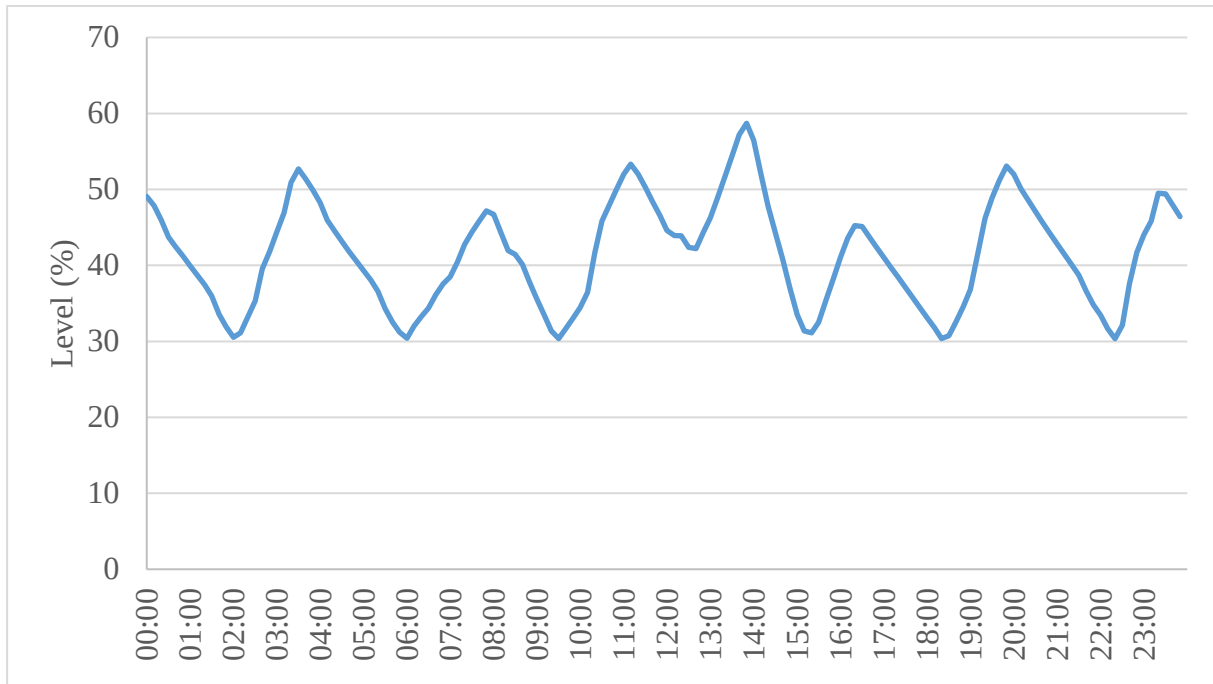


Figure 29: 21.5L dam level control

Figure 30 shows the water level in percentage for the 22L dam, which fed the decline section. The dam's capacity was controlled between 70% and 75% to ensure that service water was always available to supply the decline section. It was important that this dam always had service water so that production could proceed without interruption. The capacity of this dam was 1 Ml as shown in Figure 25.

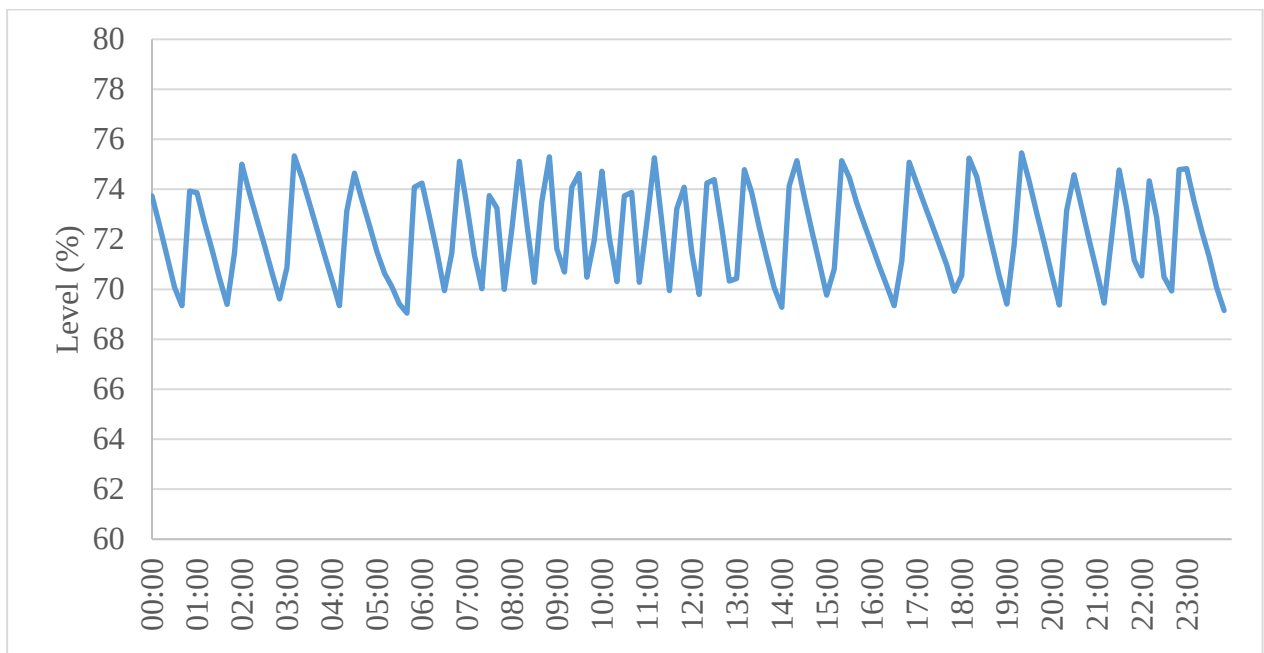


Figure 30: 22L dam level control

Figure 31 shows the water level in percentage for the 28.5L dams. Each dam had a capacity of 2.5 Ml. Dam 1 was used as a backup dam for flooding capacity. Dam 2 was controlled between a minimum of 60% and a maximum of 70%. The maximum capacity of 70% ensured that sufficient capacity would be available in case of flooding. The 10% capacity difference between the maximum and minimum limits ensured that the pumps did not start and stop too often, thereby causing additional wear on the pumps.

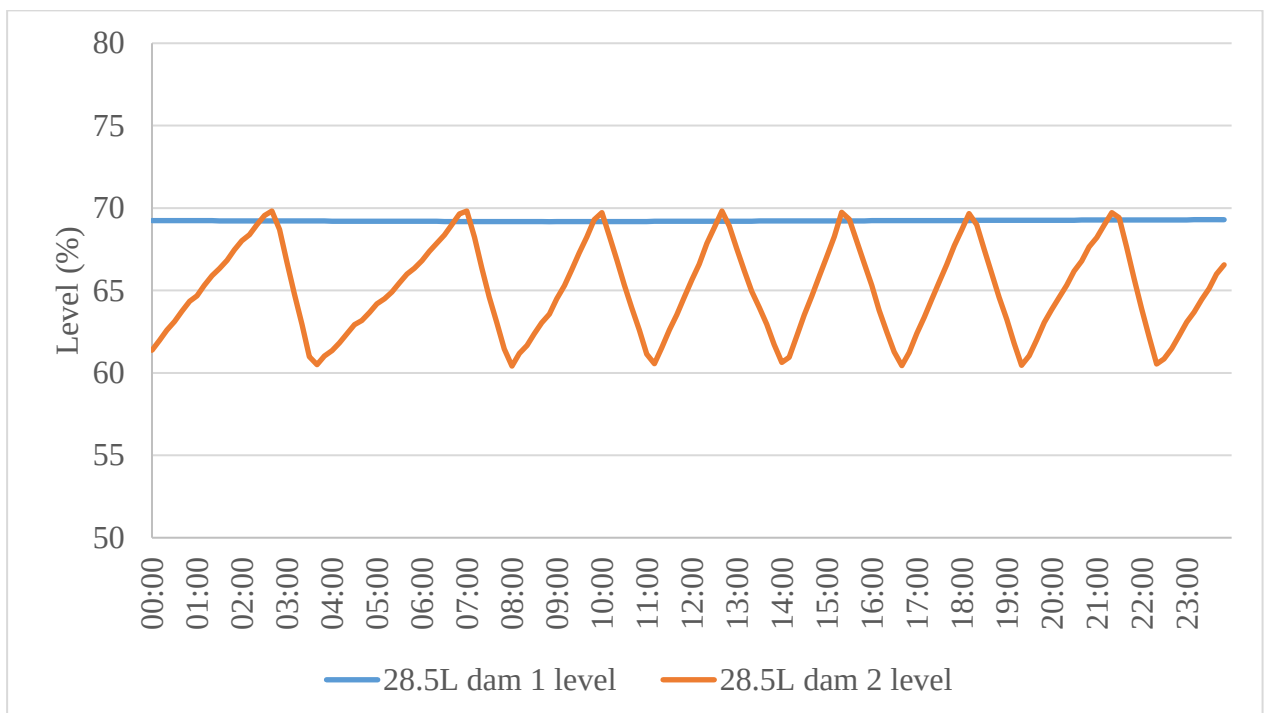


Figure 31: 28.5L dam level control

Figure 32 shows the average instantaneous electricity consumption of the 21.5L dewatering pumps. The peak consumption of these pumps was just after the mine's drilling shift period. The average overall consumption was 768 kW with a peak consumption of 1 056 kW.

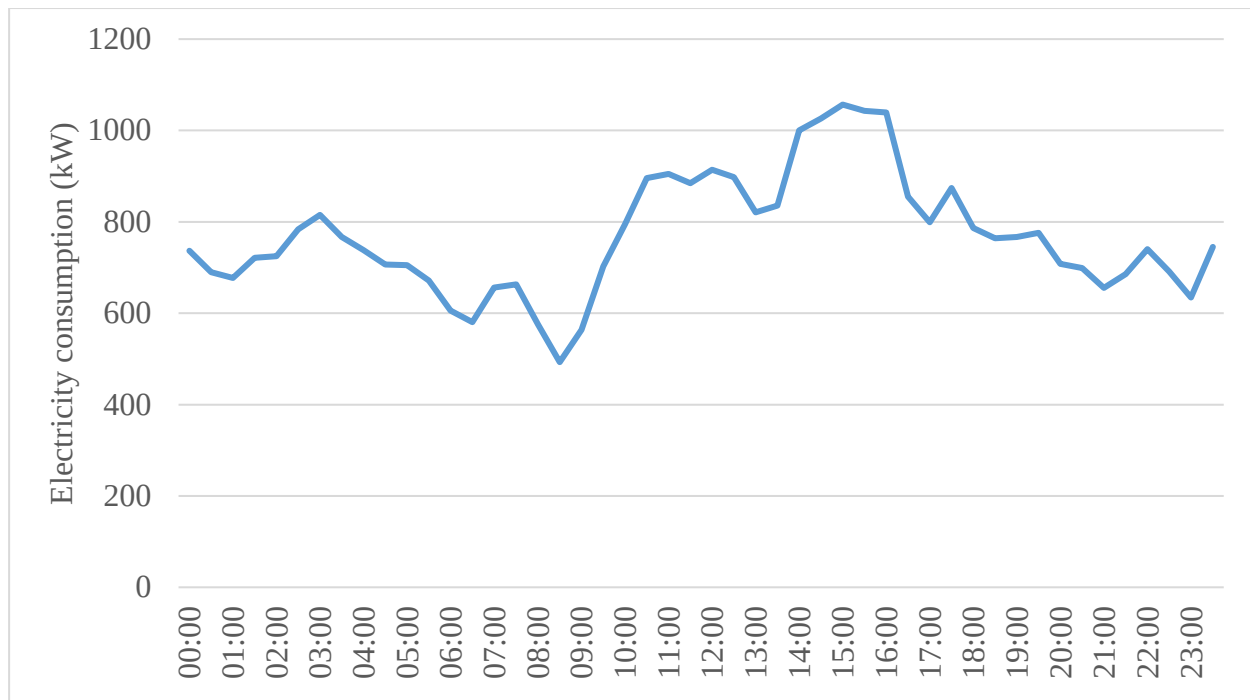


Figure 32: 21.5L average pump electricity consumption

3.2.3 Audit

An audit was performed to verify certain parameters and infrastructure components. Where certain readings were unavailable, an audit was necessary to record these values manually. One such value was the pump displacement rate of the 28.5L pumps. This was an essential parameter for gaining an understanding of the WRS of the shaft. The 28.5L dewatering pumps displaced water from the decline section to the 21.5L dam. It was important to know whether the 28.5L pumps would be capable of displacing this water to avoid flooding the shaft. Knowing the displacement rate of the pumps further ensured that the simulation model would be accurate and that initiatives that involved the 28.5L pumps were simulated accurately.

An ultrasonic water flow meter was used to measure the pump displacement rate to the 21.5L dam. Ultrasonic meters use high frequencies to penetrate the walls of pipes. Using these frequencies, the meter calculates the velocity of the fluid by using the doppler effect [60]. The measurements are provided in Table 7. The table shows that the average for Pump 2 was 76.6 ℓ/s and the average for Pump 3 was 78.1 ℓ/s . Pump 1 was not operational and could not be tested.

Table 7: Manual flow measurements for 28.5L MPS

Measurement	Pump 2 (l/s)	Pump 3 (l/s)
1	75.4	77.8
2	76.6	77.2
3	77.4	79.7
4	78.4	78.6
5	75.0	77.3
Average:	76.6	78.1

Some infrastructural components had to be verified, such as the settling and treatment station at 28.5L, the control valves on the decline, and the pipe connecting the 28.5L MPS to 22L dam.

3.3 Analysis of dewatering system

After sufficient data was acquired in the data acquisition phase, the next phase commenced. The analysis of the dewatering system phase focused on determining the problem in the WRS and finding a possible solution. This problem was identified by analysing the data in the previous phase and examining previous studies to find possible solutions for reducing the electricity consumption and expenditure on the dewatering system.

3.3.1 Power consumption

The first variable to be considered in Equation 3 was the power consumption of the dewatering pumps. Load shifting could be a possible solution for reducing the electricity expenditure of the dewatering pumps as determined by previous studies. However, for load shifting to be feasible, certain conditions had to exist:

- First, there had to be an electricity tariff structure as explained in Section 1.3.1. Load shifting works by avoiding operating electricity devices in these peak periods where electricity use is more expensive.
- Second, the dewatering pumps had to be operational in these peak periods. If not, no electricity consumption could be shifted.
- Third, abundant dam capacity had to be available as explained by Stols [46] and Venter [43]. If the pumps were not operational in the peak periods, no water would be pumped out and the dam levels would rise. Therefore, adequate storing

capacity had to be available in the dams to store the water during the duration of the peak periods and avoid flooding the dam.

As shown in Figure 32, the 21.5L dewatering pumps were operational well in the peak periods of the Eskom TOU tariff structure, which could be a possible load-shifting opportunity. However, dam capacity and automation of the dewatering pumps were infrastructural constraints that could potentially hinder load shifting on the pumps. If the dams did not have adequate capacity to store water in peak times, flooding could happen. This would ultimately mean that the dewatering pumps had to be operational, and that load shifting would not be feasible. Figure 29 shows that the 21.5L dam took approximately two hours to fill 20% in the morning peak period. Thus, if the dam was at 30% before the peak period, the dam could fill to 70% in four hours. This would result in less pumping in the peak period.

To enable load shifting on the dewatering pumps, the pumps can either be operated manually or automatically. Automatic operation is preferred because little to no human intervention is required. However, automatic load shifting requires a fully automatic pumping system. This includes PLC systems, control valves, and an integrated SCADA control system. From the data acquired, it was established that the pumps could be controlled via the SCADA system. A visual audit confirmed that the shaft had all the infrastructural components required. Thus, load shifting was considered and was tested and verified through simulation in the next phase.

3.3.2 Displacement height

Underground water recirculation can be a method for reducing the electricity consumption of dewatering pumps. From Equation 3 it was established that by reducing the amount of water that the 21.5L MPS had to displace, less power would be consumed by the pumps, which would result in electricity and cost savings. However, the correct infrastructure had to be in place to recirculate the water underground. This involved the following components:

- Multiple level supply dam – Multiple levels received their service water from a single supply dam. Thus, clean water could only be pumped to a single dam to supply multiple levels with service water.
- Pump station – The pumps had to have sufficient pumping capacity to supply enough water to the supply dams for the levels.
- Settlers – Treatment facilities had to be available to filter and treat water underground.

- Control valves – Control valves had to be present to control the flow path of the water from the SCADA.
- Correct pipe network – Rerouting the water to the correct dam would require changes to the pipe network.
- Dam capacity – Dams had to have adequate capacity to avoid flooding and immoderate stopping and starting of the pumps. Too many stops and starts would cause damage to the pumps, which would result in unnecessary maintenance costs.
- Cooling capacity – Recirculating water underground would increase the temperature of the water, in turn, which would the overall temperature of the shaft. Sufficient cooling was thus required to avoid the water from picking up too much heat and the shaft from exceeding the legal temperature limit.

The decline section of the shaft received its service water from the 22L dam. The case study shaft had two fully functioning MPSs, of which first was situated on 21.5L and the other on 28.5L. The 28.5L pump station had three operational settlers for filtering water, where dosing was done to treat the water. A brominator was installed on 22L to treat bacterial growth in service water. Existing piping connected the 28.5L MPS to the 21.5L MPS and 22L supply dam.

Dam capacities were large and sufficient. All pumps had control valves that could either be operated automatically on the SCADA or manually by mining personnel. There were also control valves on the inlet of the 22L dam and the outlet of the 20L dam. The shaft had fridge plants, BACs, and ventilation fans to supply the shaft with adequate cooling capacity.

The dirty service water was treated by the settlers on the 28.5L MPS. Afterwards, the clean water was pumped to 22L instead of the 21.5L MPS. The water was recirculated on the decline section to avoid additional water from being pumped by the 21.5L MPS and to reduce the electricity consumption of the 21.5L dewatering pumps.

Figure 33 shows the possible water flow path for the service water on the shaft. The green line indicates the water's flow path when water was recirculated underground to the 22L dam. The red line indicates the flow path where water was pumped to the 21.5L dam and ultimately to the surface dam. Underground recirculation could possibly reduce the electricity consumption

of the dewatering pumps. This possibility was tested and verified through simulation in the next phase.

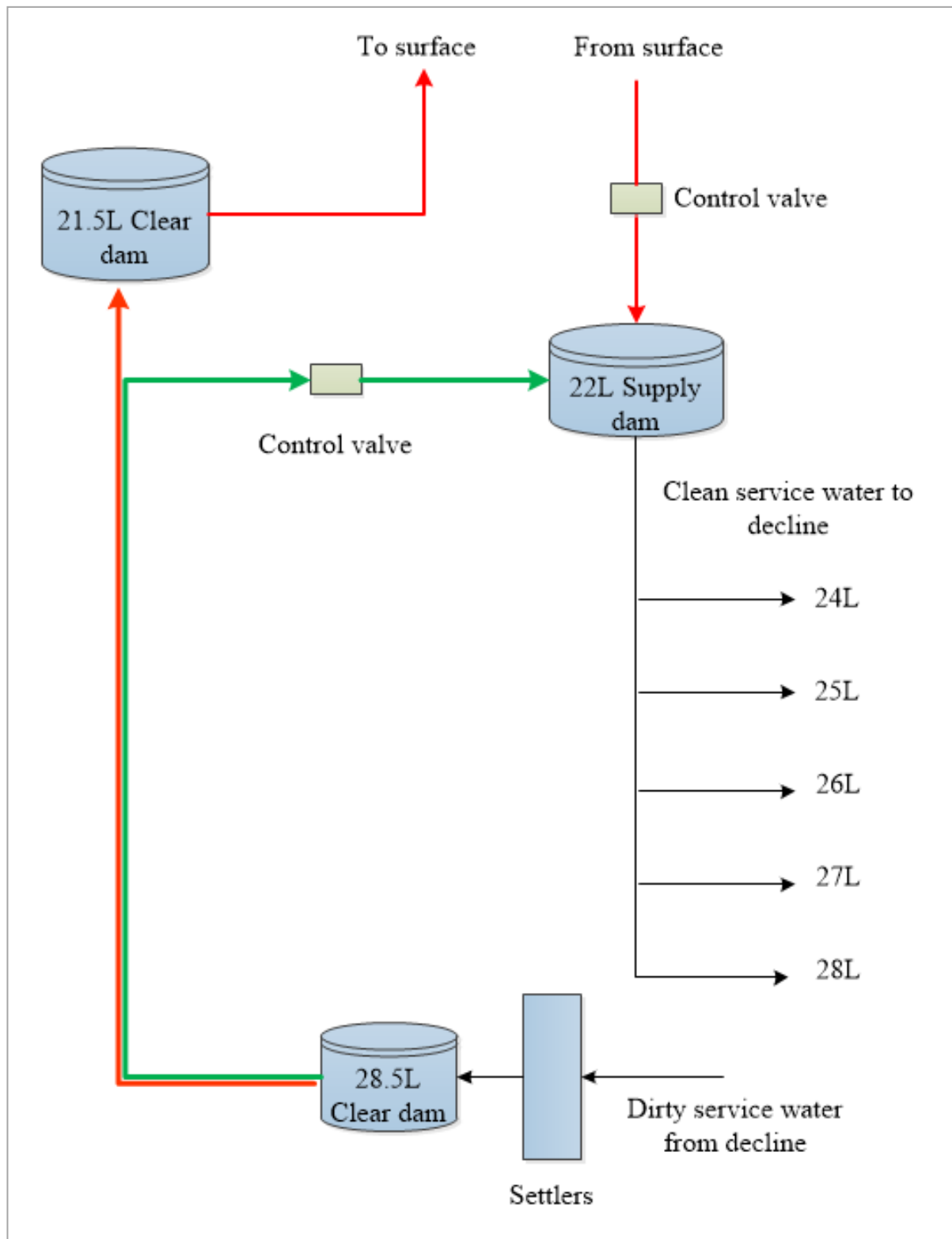


Figure 33: Service water flow path for underground recirculation and surface recirculation

3.4 Verification through simulation

A simulation model of the dewatering system was constructed using PTB. The purpose of the simulation model was to test the load-shifting and underground water-recirculation initiatives to verify if there were electricity and cost-saving benefits. This model had to represent the actual system and different scenarios had to be tested using the model. The following section describes the steps taken to construct the accurate simulation model successfully.

3.4.1 Analysing the dewatering simulation

By understanding the layout of the dewatering system of the shaft, the required data to build the simulation was determined. Important parameters for constructing the simulation model included the following:

- Level flow – To ensure that the level consumed the correct amount and that production would not be disturbed.
- Pump power – This parameter directly influenced the amount of electricity savings that would be achieved.
- Dam level – To correctly control the amount of water flowing to each dam.
- Displacement height – This parameter directly influenced the electricity consumption of the pumps.

The data gathered in the data acquisition phase was used to construct the simulation model. The data was used in the simulation software's water component to simulate the system accurately. The data requirements of the relevant components are given in Table 3. Only the decline section was simulated as all the initiatives were aimed at the decline section and did not affect the vertical section. The vertical section's effects, however, would be present on the decline section.

3.4.2 Constructing the simulation model

The simulation model was constructed using the data acquired. Figure 34 shows the levels that were constructed in the simulation using the node, water pipe, water mass flow and boundary components. The water mass flow component was used to simulate the water flow profile per level. Levels 24 to 28 were constructed in the same manner.

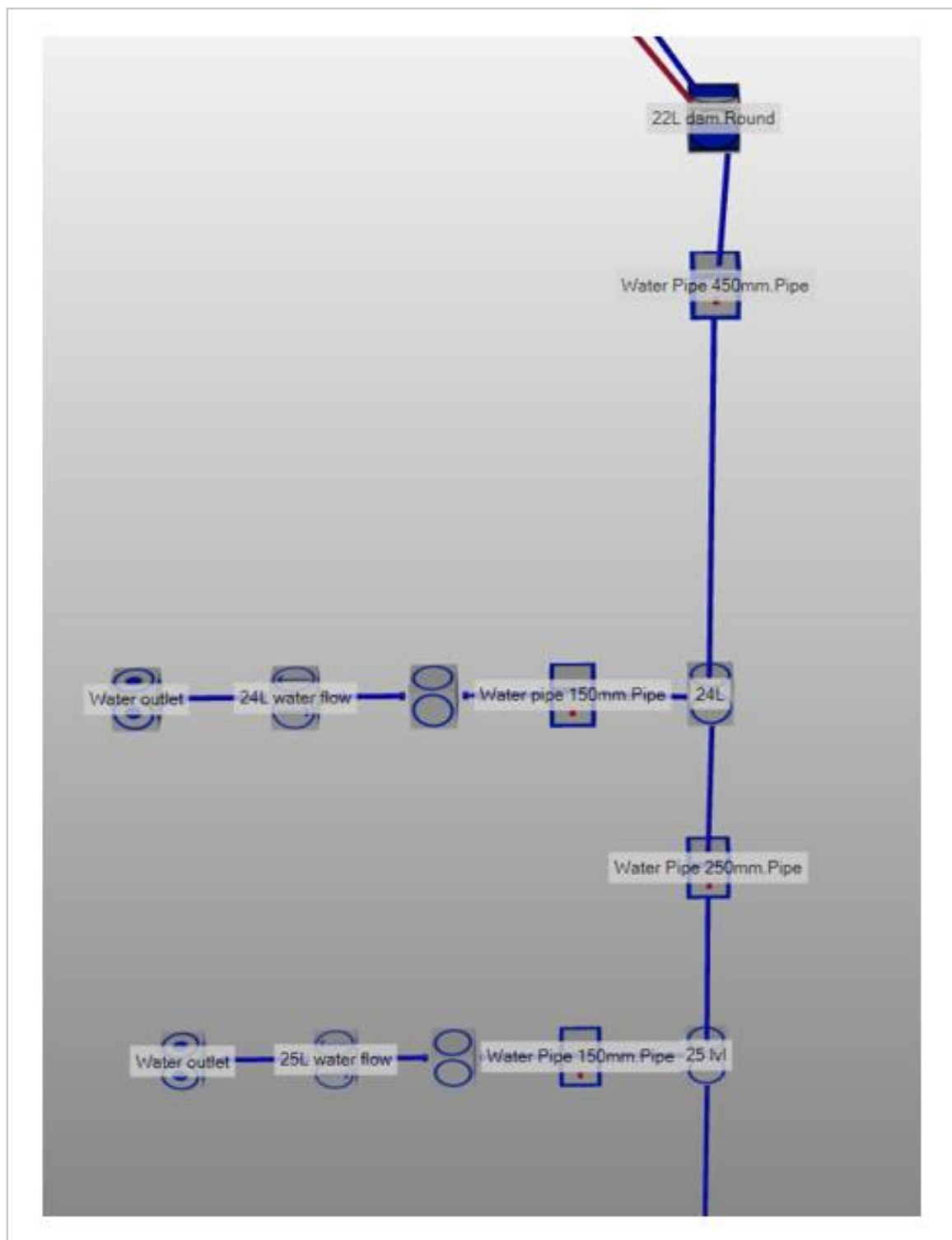


Figure 34: Simulation model construction of level water flow

Figure 35 shows the simulation model that was used to simulate the actual system. The entire decline section was simulated in this figure. Additional components included the dam, pumps, and step controllers.

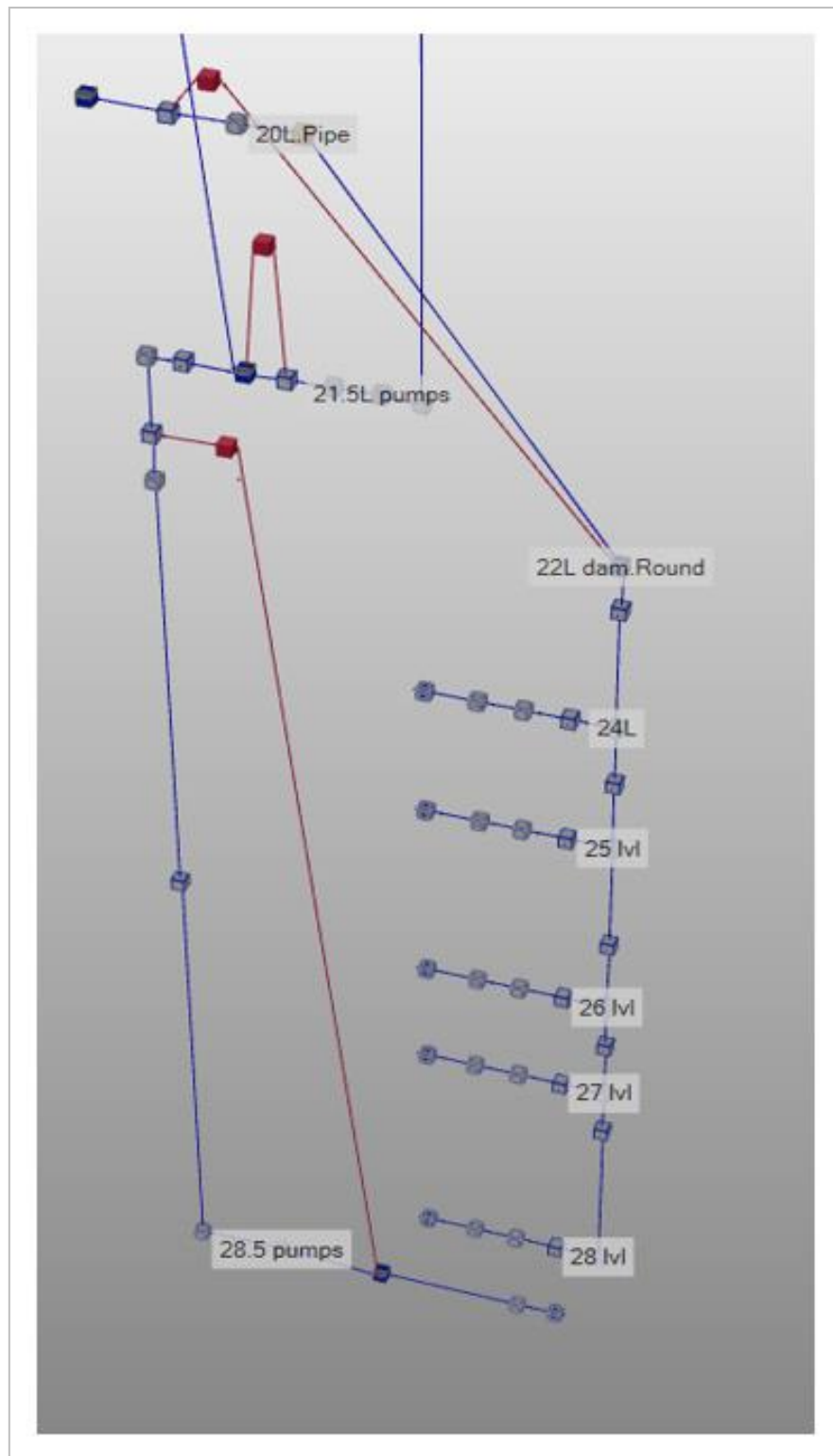


Figure 35: Decline simulation model used to verify the results

3.4.3 Calibrating the simulation model

After constructing the simulation model, it was calibrated to be an accurate representation of the actual system. The components that required calibration were the dewatering pumps, dams, and level water flows. The pumps affected the electricity consumption of the dewatering system directly, while the dams were essential for controlling the flow of water. The calibration was done by choosing a specific day and matching the simulation's output to the actual system's measured results.

The first step to calibrate the 21.5L pumps was to determine the operating pressure and flow for the pumps. This was done using Table 5. From this table it was established that the following values had to be calculated:

- $Q_2 = 60 \text{ l/s}$ (displacement rate of pump).
- $P_2 =$ operating point of the pumps.

Equation 7 was used to calculate the operating point of the pumps:

$$P_2 = H \times g \times \rho \quad [7]$$

Where:

- $H = 960.3 \text{ m}$ (distance from 21.5L MPS to the surface).
- $g = 9.81 \text{ m/s}^2$ (acceleration of gravity).
- $\rho = 1\,000 \text{ kg/m}^3$ (density of water).

Thereby:

- $P_2 = 9\,420.54 \text{ kPa}$.

Thereafter, the rest of the values from Table 5 were calculated. Table 8 shows the values that were used to calibrate the 21.5L pumps.

Table 8: Pressure and flow values used to calibrate the 21.5L pumps

	Pressure (kPa)	Flow (l/s)
Point 1	12 529	0
Point 2	9 420	60
Point 3	0	120

By using Equation 3, the efficiency of the pumps was calculated as follows:

$$P_s(kW) = \frac{\rho g(Q \times 3.6)H}{\eta \times 3.6 \times 10^6} \quad [3]$$

Where:

- $H = 960.3$ m (distance from the 21.5L MPS to the surface).
- $g = 9.81$ m/s² (acceleration of gravity).
- $\rho = 1\,000$ kg/m³ (density of water).
- $Q = 60$ l/s (displacement rate of pump).

The power consumption of the pumps was known as:

- $P_s = 1\,050$ kW.

Thereby:

- $\eta = 54\%$.

Figure 36 depicts the power consumption profile of the actual and simulated 21.5L pumps. The figure shows that the simulated results followed a similar profile as the actual measured results. There was a slight offset between the two profiles, which could have been due to the actual service water taking longer to reach the dams, thus delaying the time the pumps started. The average simulated power consumption was 940 kW, while the actual average consumption was 932 kW. This result indicated a 0.85% inaccuracy, which was assumed to be adequate for the purpose of the simulation.

Figure 37 shows the flow profile of the actual and simulated pumps. The figure indicates that the flow profiles for both the simulated and actual pumps were similar. The simulated power consumption was within 5% of the actual power consumption and followed a similar profile. The 21.5L pumps were thus considered calibrated.

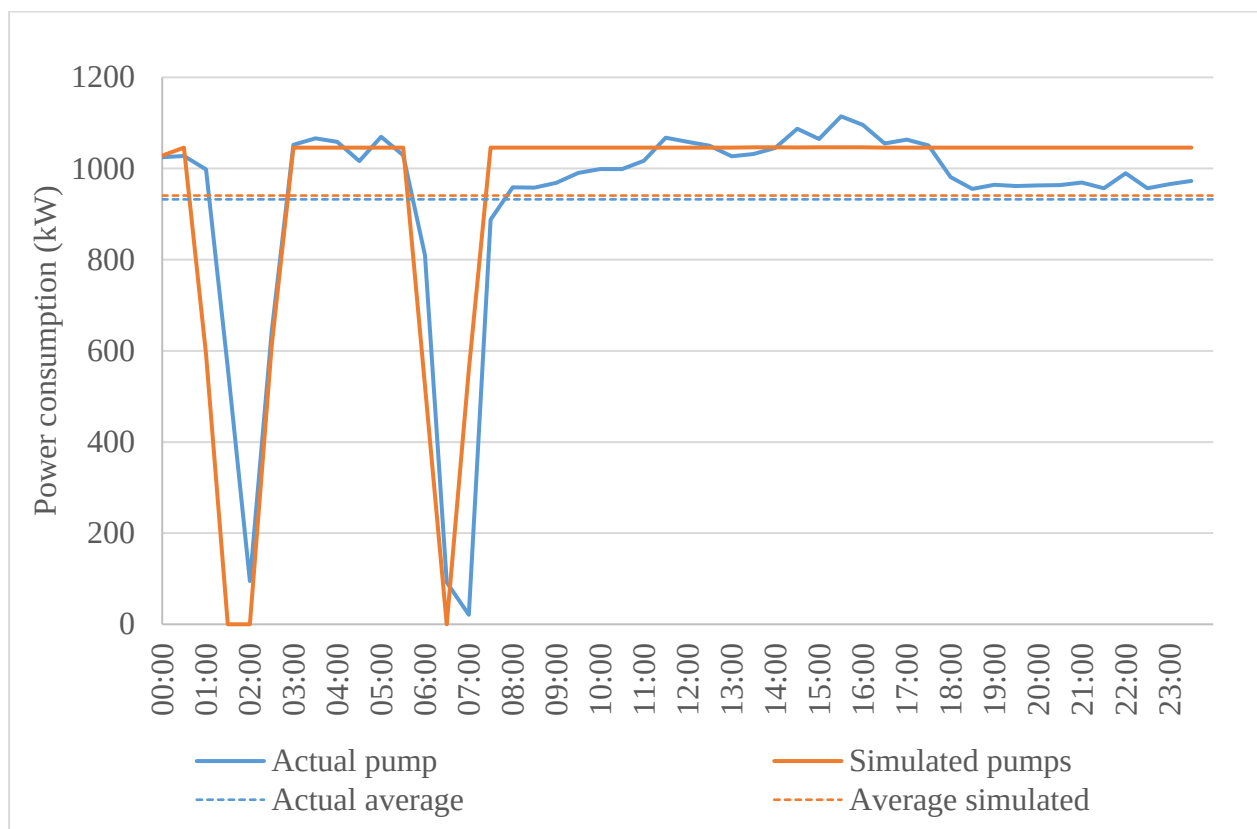


Figure 36: Power consumption comparison between the actual and simulated 21.5L pumps

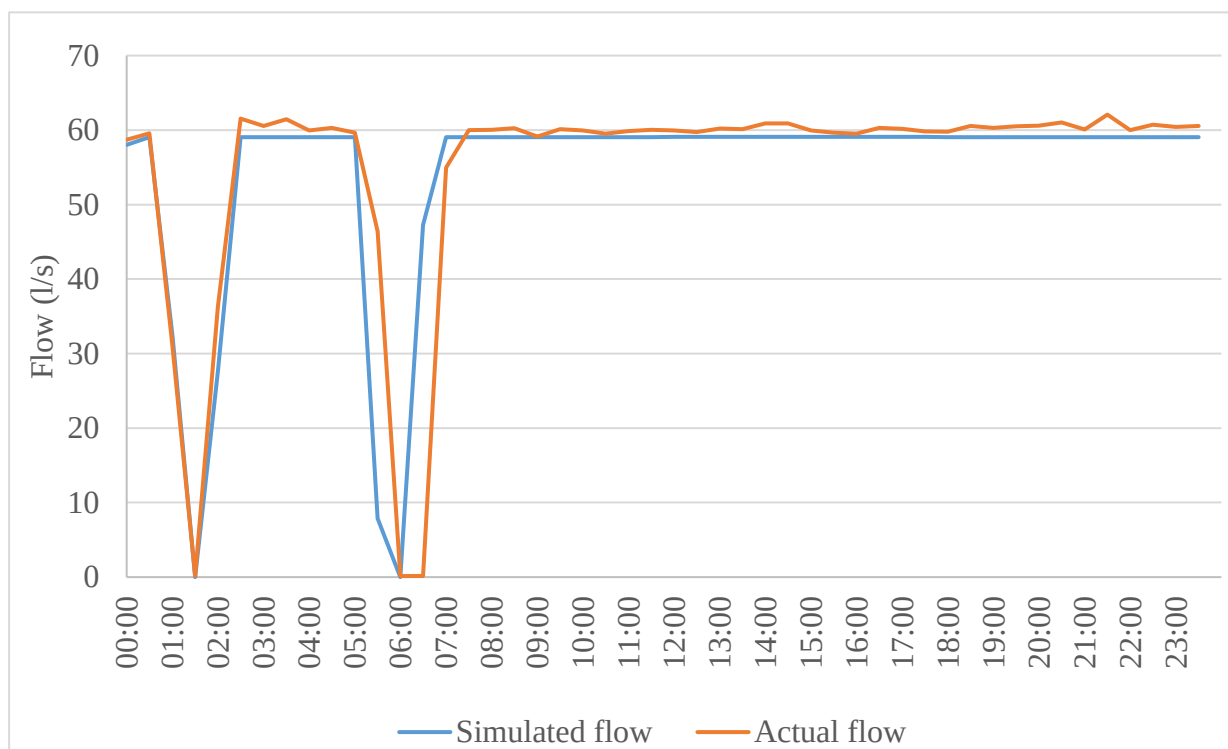


Figure 37: Water flow displacement rate comparison between the actual and simulated 21.5L pumps

The 28.5L pumps were calibrated using the same method as the 21.5L pumps. Power and water flow data for the pumps was unavailable, and thus the simulated performance could not be compared with the actual performance. The power consumption data was not considered to be important because the 28.5L MPS would not be affected by the proposed solutions. However, the water displacement rate of the pumps was important information for constructing an accurate simulation model; therefore, it was measured manually. The power consumption of the pumps was rated at 400 kW.

Figure 38 shows the dam level control between the actual and simulated 21.5L dams. The actual dam level was controlled between 30% and 50%. The figure demonstrates that both cases followed a similar profile until 10:00. Thereafter, the simulated dam level increased to just under 100%, while the actual control exceeded 60%. This could indicate that the dam capacities were not specified correctly or that the bulk of the water from the drilling shift reached the dams too soon. If flooding did not occur on the simulated model, flooding would thus not occur on the actual system. This provided flooding avoidance on the actual system and acted as a safety factor. For the purpose of the simulation, the 28.5L dams were considered calibrated. If flooding did occur, another pump in series would start to increase the discharge rate to prevent further flooding.

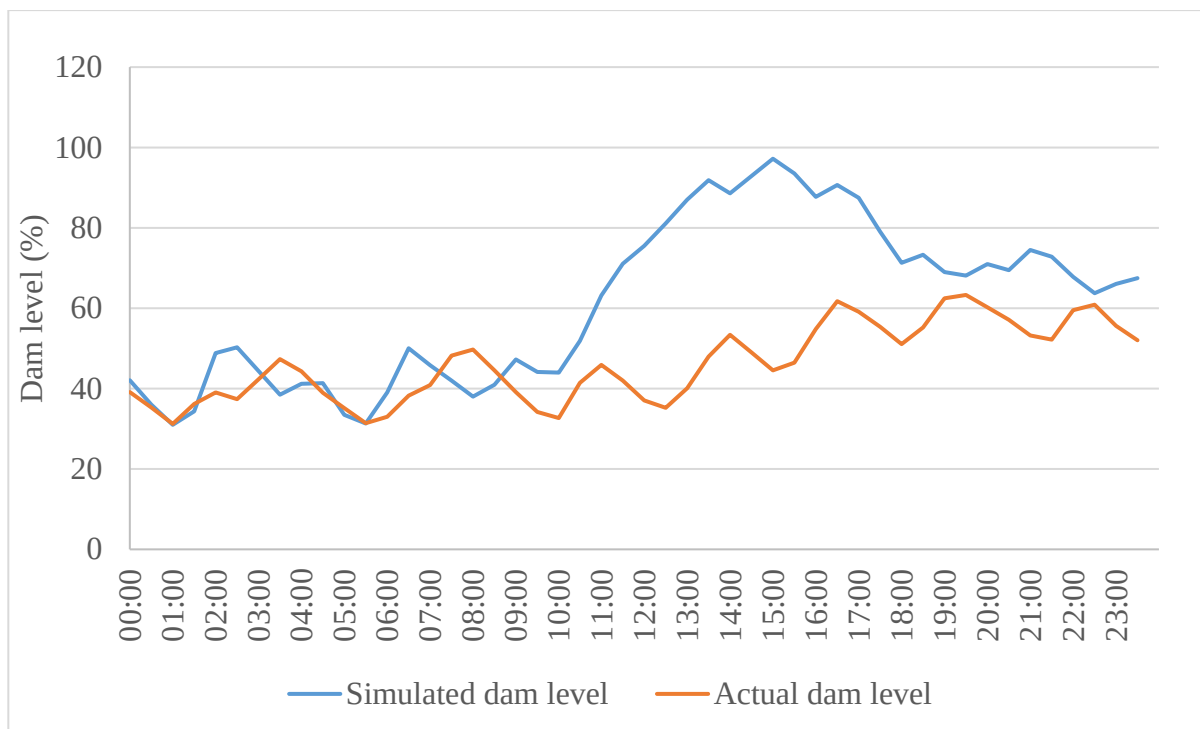


Figure 38: Dam level control between the actual and simulated 21.5L dams

Figure 39 shows the level control between the actual and simulated 22L dam. The simulated dam was controlled at 70%, which was characteristic of the actual control of the dam. The 22L dam was thus considered calibrated.

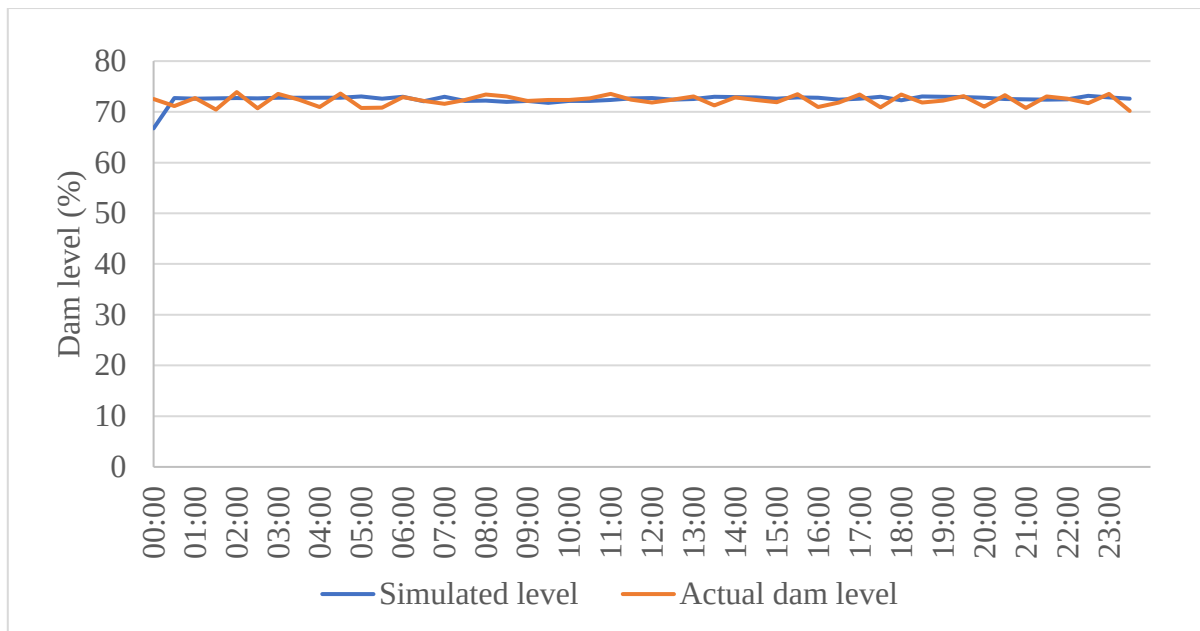


Figure 39: Dam level control between the actual and simulated 22L dam

Figure 40 shows the level control between the actual and simulated 28.5L dam. The simulated dam was controlled between 60% and 70%, which was comparable to the actual control of the dam. The 28.5L dam was thus considered calibrated.

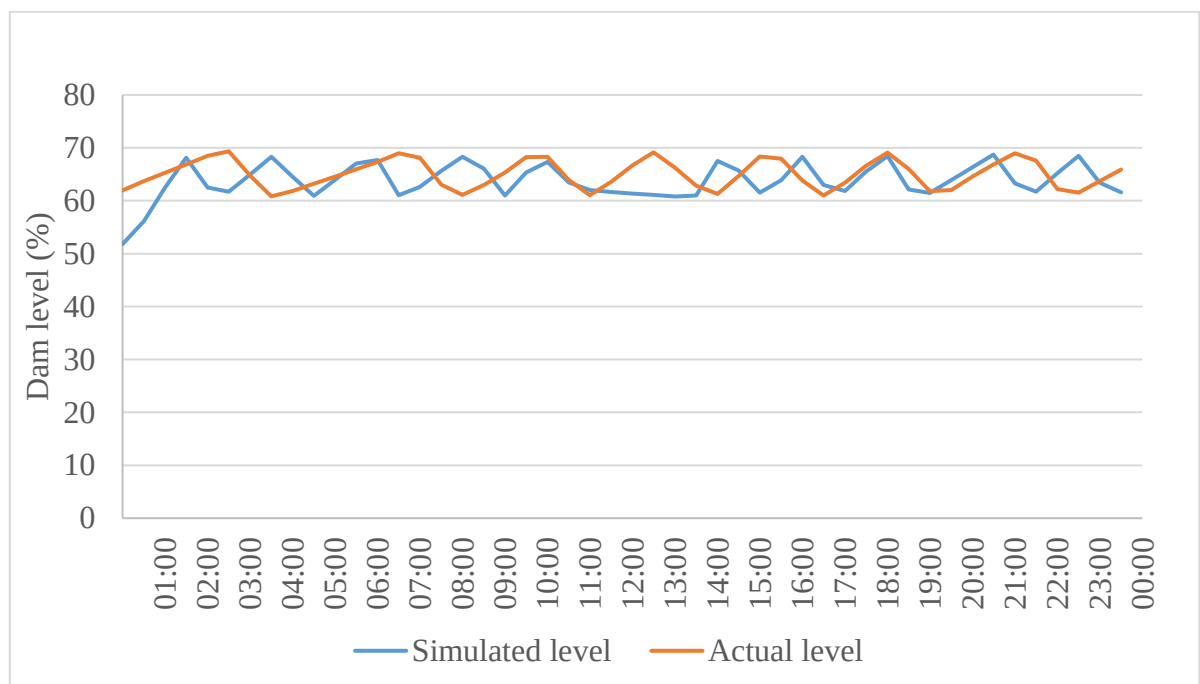


Figure 40: Dam level control between the actual and simulated 28.5L dams

Thus, the components were considered calibrated and could be used to simulate different scenarios accurately. The simulation was used to test the effects of load shifting and underground water recirculation on the electricity consumption of the 21.5L dewatering pumps.

3.4.4 Constructing the electricity consumption baseline for the simulation model

After constructing and calibrating the simulation model, an electricity consumption baseline was required for the simulation. This baseline would be used to compare the effects of the initiatives on the electricity consumption of the simulated 21.5L dewatering pumps. The baseline would ultimately be used to verify whether the proposed solution achieved the planned reduction in the electric power consumption of the dewatering system.

To construct the simulation baseline, level flow data was required and a weekday baseline had to be constructed for the simulation's purpose. This flow data was a 24-hour average, 30-minute interval over a three-month period, which ensured that the true effect was evaluated over a long-term period. The simulation ran for a period of five days with 30-minute intervals, which guaranteed that the true effect of the simulation was seen over a full working day week. Running the simulation for longer periods would generate more accurate results. However, a full working week was sufficient for ensuring that the simulation was stable and working as intended.

Figure 41 shows the simulated average electricity consumption for the 21.5L pumps. These values served as the baseline for the simulation. This baseline was used to evaluate the effect of the proposed solutions and verify the results.

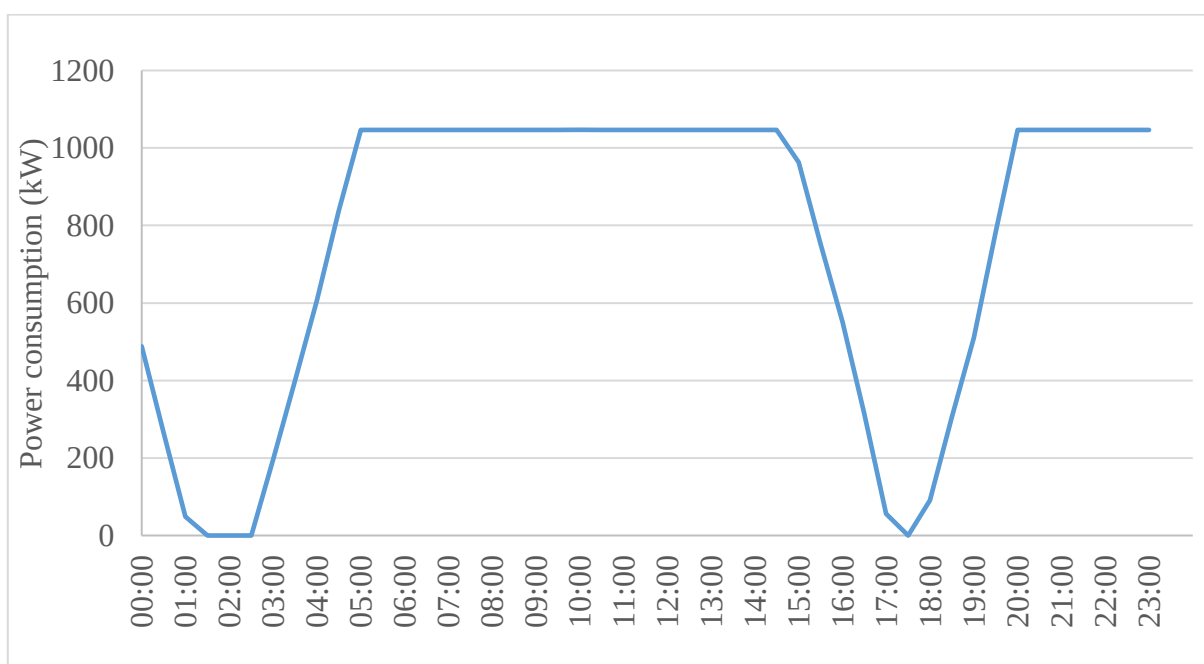


Figure 41: Simulated baseline for the 21.5L dewatering pumps

3.4.5 Testing possible solution on the simulation model

After the simulation's electricity consumption baseline was constructed, the possible solutions were tested on the simulation model. This section explains the way that the possible solutions were governed in the simulation model in the form of a control philosophy. The control philosophy followed a systemic flow diagram and a description of the system. After the control philosophy is explained, the effects of the solutions are compared with the simulation baseline. Lastly, a table summarising the electricity and cost avoidance between the simulation baseline and the possible solutions is provided.

3.4.5.1 Control philosophy

A control philosophy is needed to simulate the interaction between individual components in the system. The philosophy provides guidance to the working of a system in a virtual or real world. In this study, the control philosophy followed a systemic approach with certain conditions that had to be met to continue to the next action. In this way, the system could be controlled, and coding of the PLC would be simpler.

The control philosophy was split into two phases. Phase 1 was to refill 22L dam from the 28L pumping station when required to ensure that the dam was not refilled from the conventional section after being pumped to surface. The control philosophy used to monitor the level of the 22L dam is shown in Figure 42. If the level dropped below 40% and the 28.5L dam had sufficient water (more than 30%), the 28L pumps would be switched on. The pumps would remain on until the 22L dam reached 70%. If the 28.5L dam was below 50% at this stage, the pumps would be switched off. If the dam was above 50%, the pumps would continue running until the dam reached 50%. However, the valve in the pipeline to 22L would close, rerouting the water to the 21.5L dam. This served two purposes: First, it ensured that the water volume in the decline section remained constant to avoid flooding. Second, it ensured that the pumps were not cycled as often since it combined refilling the 22L dam and pumping to 21.5L into one pumping cycle.

The dams on 28.5L had to be above 30% when the pumps were switched on to ensure that they would not be pumped dry while filling up the 22L dam. It was recommended that an additional failsafe be included to switch off the 28.5L pumps when the 28L dam reached the minimum level of 20%, irrespective of the level of the 22L dam. In this event, the 22L dam could be topped up from the conventional section (20L) to increase the water volume in the decline section.

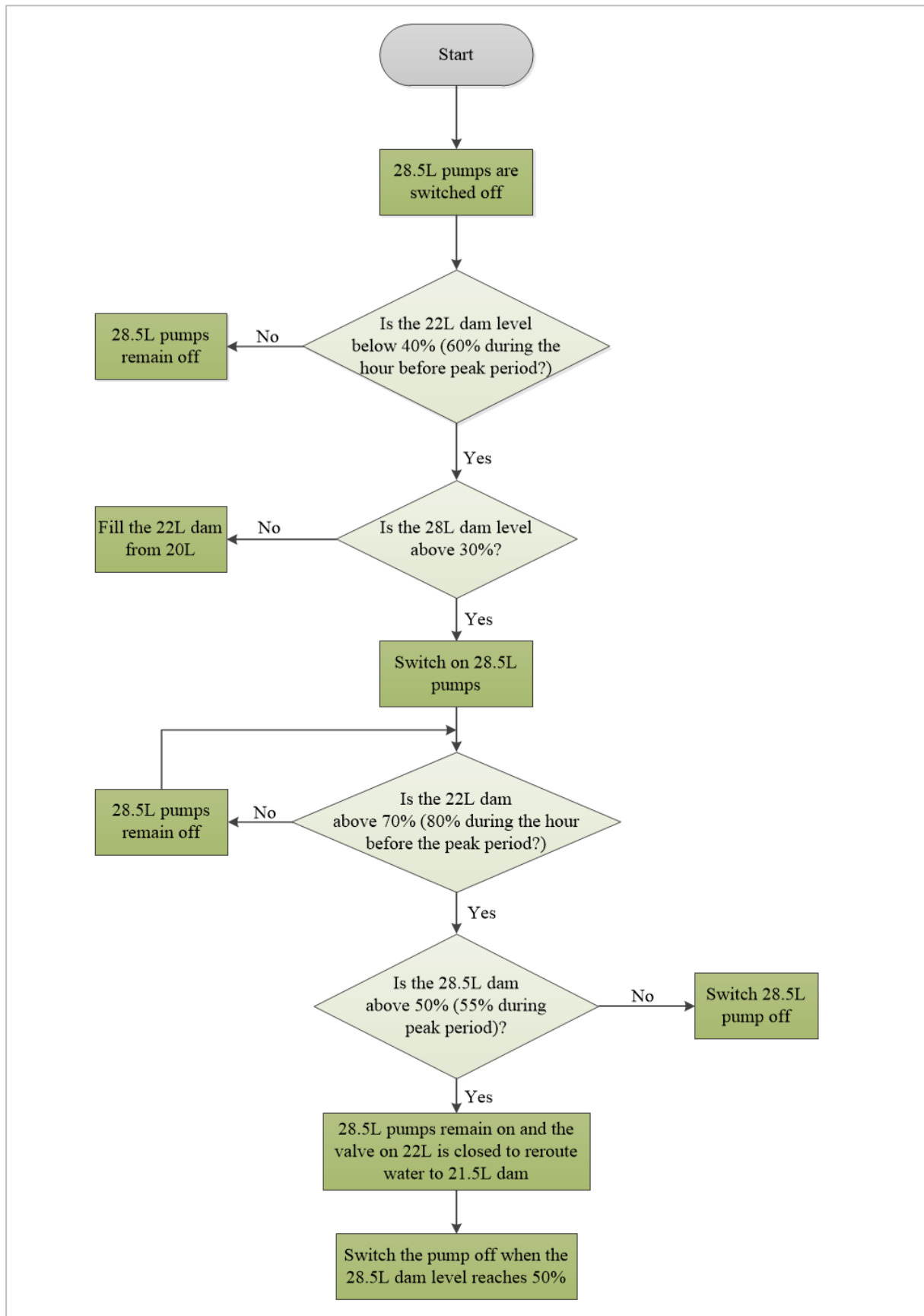


Figure 42: Control philosophy to refill the 22L dam used in the simulation

The control changed during the Eskom peak periods (07:00–10:00 and 18:00–20:00 in the summer, and 07:00–10:00 and 17:00–19:00 in the winter). First, it was necessary to prefill the 22L dam during the hour before the drilling shift started. For this reason, the control was adjusted to switch on the 28.5L pumps when the 22L dam dropped below 60% and only switch them off when the dam reached 80%. Thus, the dam level would be between 60% and 80% when the peak period started.

Lastly, the control philosophy aimed to prevent water being pumped to 21.5L during the peak period. For this reason, the dam could fill an extra 5% (to 55%) during the peak period. Since the dam was pumped down to 55% leading up to the peak period, it was unlikely that the water would be pumped to 21.5L because the large dams on 28.5L could accommodate the additional water.

The next part of the control philosophy was to ensure that the dams on 28.5L would not overflow when no water had to be pumped to 28.5L. This typically happened when the mine switched off during the weekend and no drilling took place. The control philosophy for this exception is shown below in Figure 43.

Figure 43 shows that the pumps on 28.5L started once the 28.5L dam reached 60%. If the dam level reached 60%, it implied that additional fissure water had entered the system. This water was pumped to 21L until the 28.5L dam reached 50%. During the peak period, the percentage at which the service water was pumped out was increased to 70% to ensure that the extra storage capacity was used to offset the pumping power consumption.

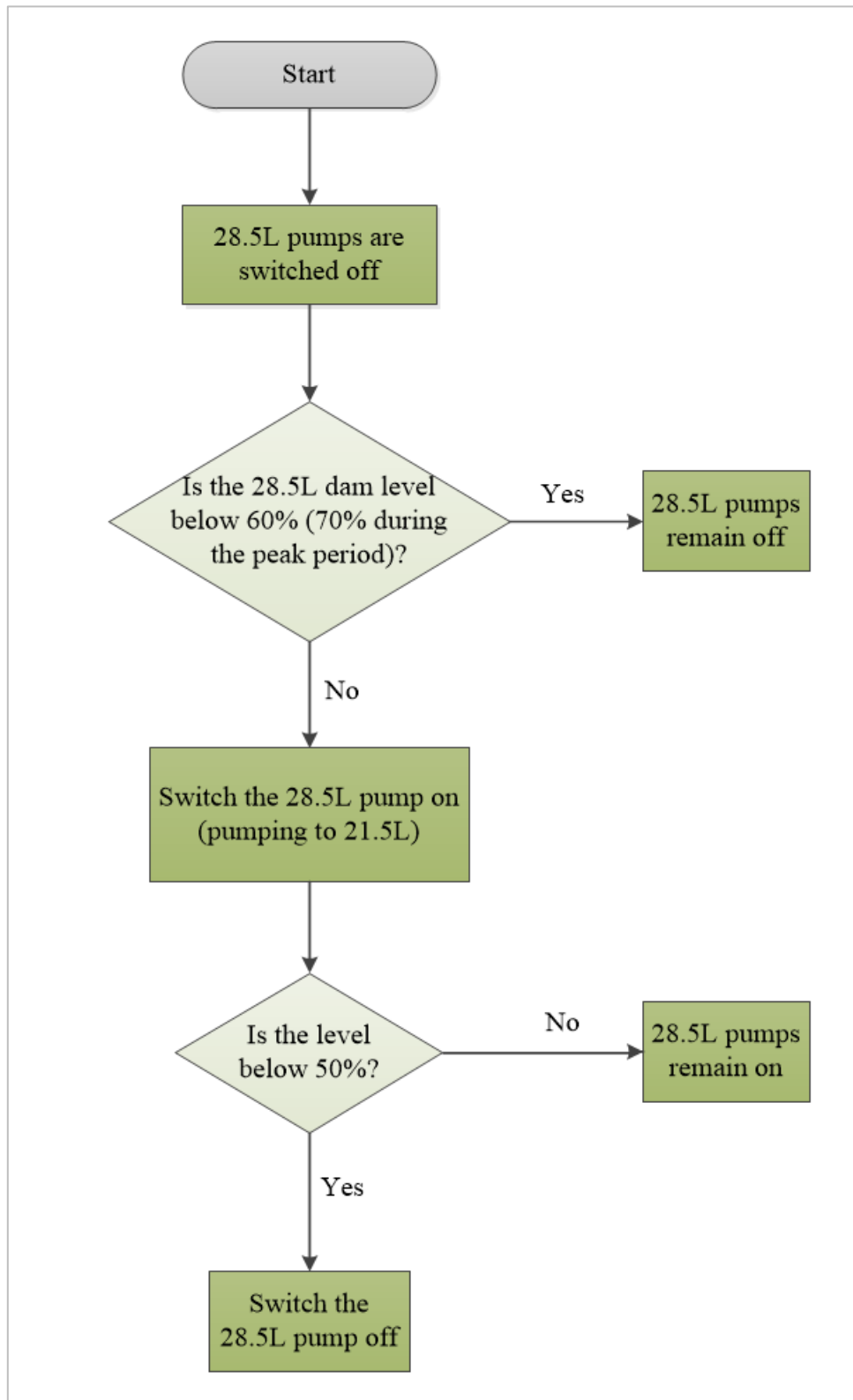


Figure 43: Control philosophy to ensure that the 28.5L dams do not overflow

The control philosophy for the 21.5L pump station had to be re-adjusted to accommodate load shifting on this pump station. This control philosophy is shown in Figure 44.

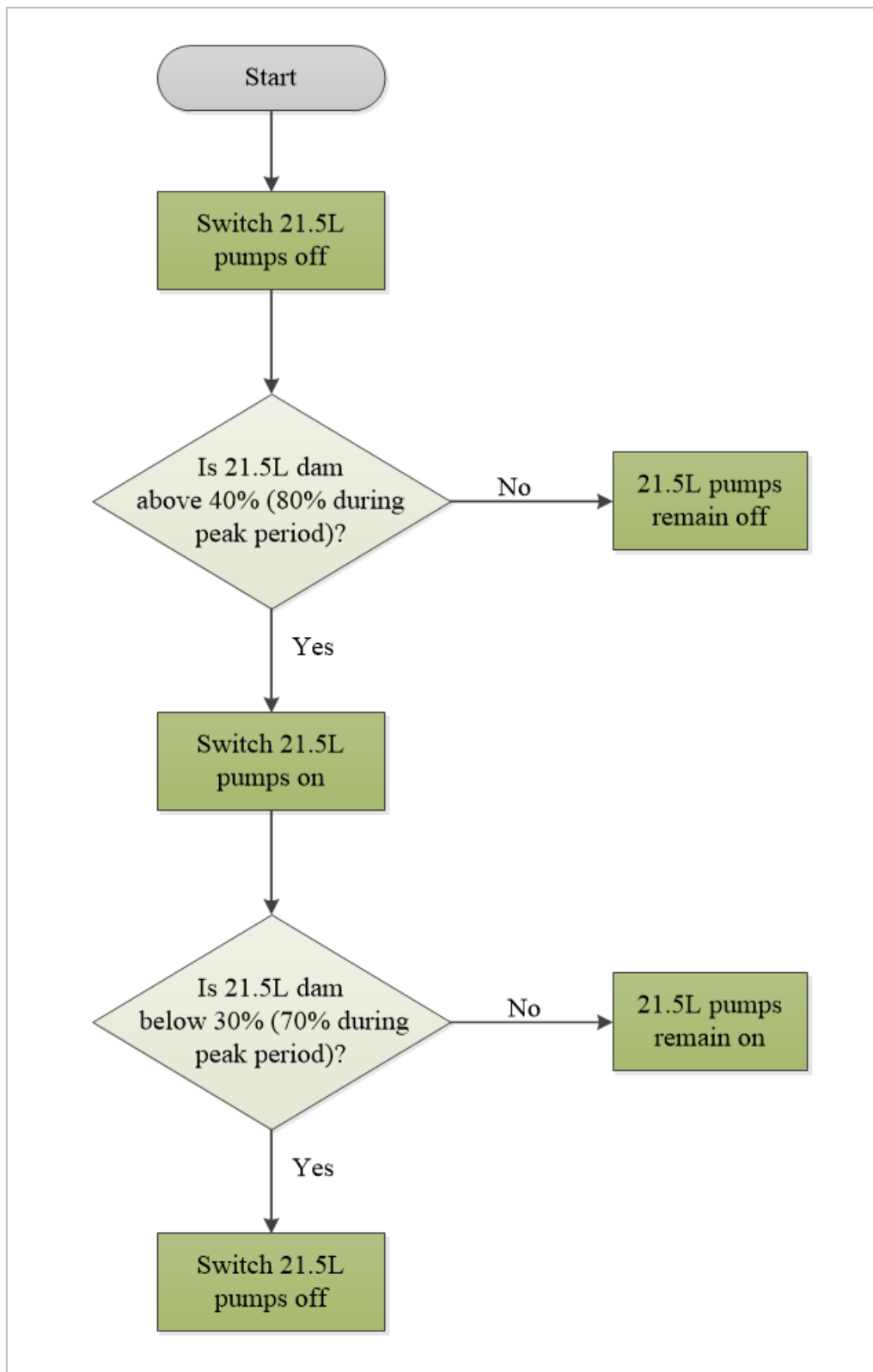


Figure 44: 21.5L load-shifting control philosophy

Figure 44 shows that the pumps on 21.5L would be started when the 21.5L dam reached 40% capacity (80% during peak periods). The pumps would only be switched off when the 21.5L dam capacity was at 30% (70% during peak periods). This control ensured that the pumps were used more efficiently by only switching them on during off-peak and standard hours and avoiding the peak hours.

3.4.5.2 Underground recirculation

Figure 45 compares the power consumption of the 21.5L pumps between the baseline and when water was being recirculated underground. The graph shows that the average instantaneous power consumption of the baseline was 756 kW, whereas it was 357 kW when the water was recirculating underground. There was an average electricity saving of 399 kW and a cost saving of R3.8 million per annum between the two scenarios.

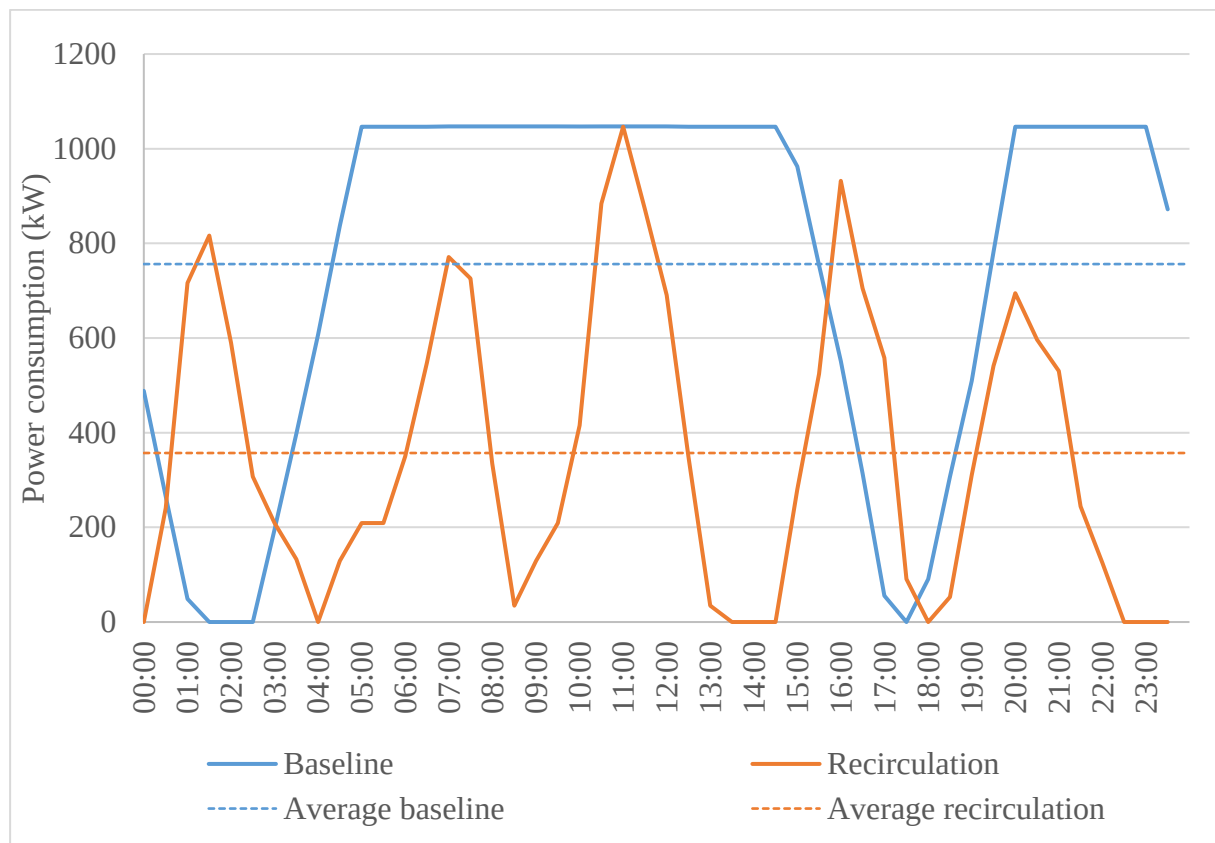


Figure 45: Comparison between the simulated baseline and underground water-recirculation electricity consumption

3.4.5.3 Load shifting

Figure 46 compares the power consumption of the 21.5L pumps between the baseline and when load shifting was implemented. The graph shows that the average instantaneous power consumption of the baseline and the simulation was similar with only a 10 kW difference. There was a cost saving of R300 000 per annum when load shifting was implemented.

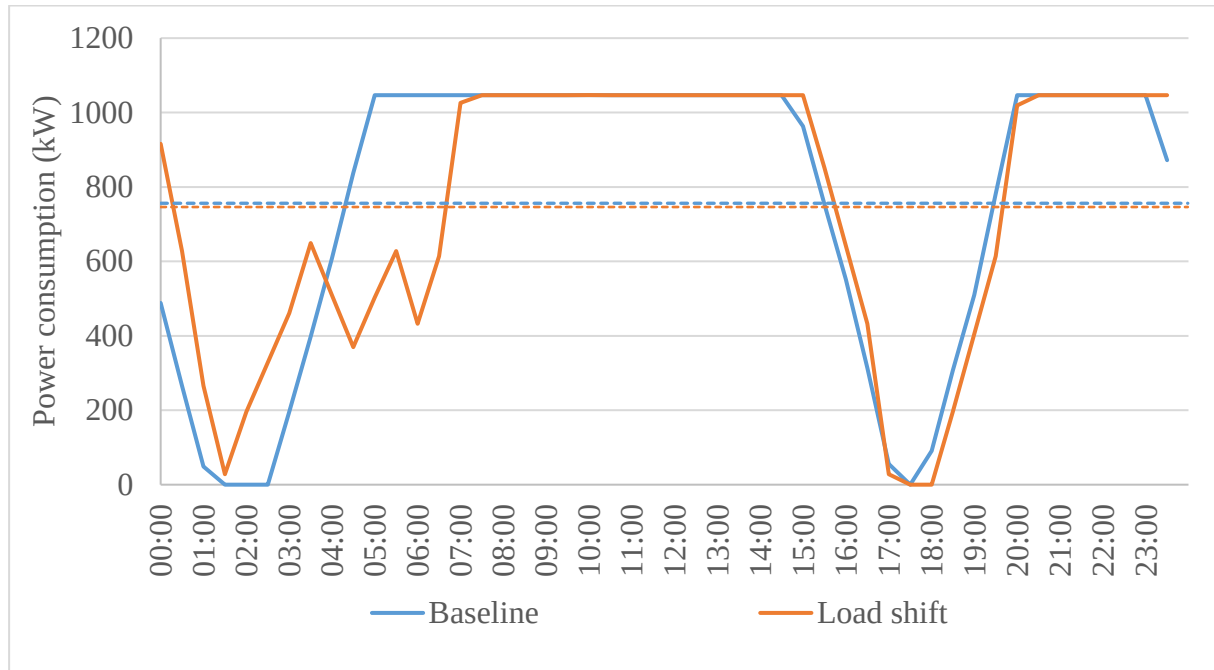


Figure 46: Comparison between simulated baseline and load shifting

3.4.5.4 Underground recirculation and load shifting

Figure 47 compares the power consumption of the 21.5L pumps between the baseline and when there was water recirculating underground and load shifting was implemented. The graph shows that the average instantaneous power consumption of the baseline was 756 kW, whereas it was 350 kW when recirculating and load shifting. There was an average 405 kW electricity saving and R4.2 million cost saving per annum between the two scenarios.

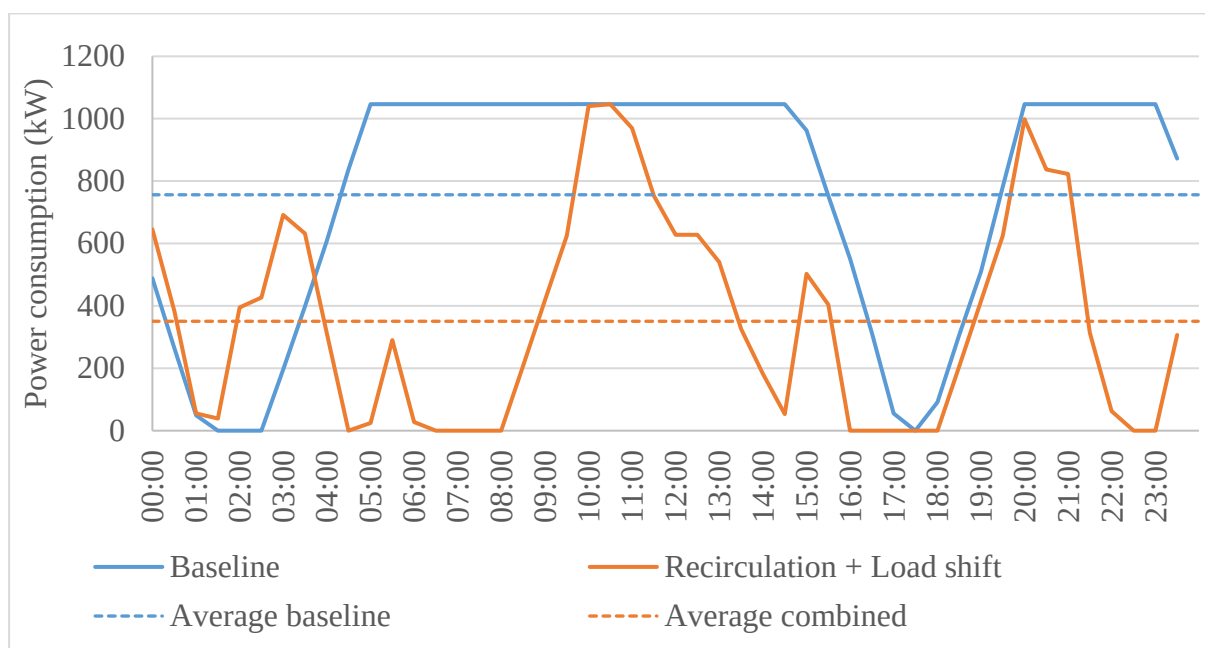


Figure 47: Comparison between the simulated baseline, underground water recirculation and load shifting

The simulation showed that underground recirculation had an electricity and cost-saving impact on the dewatering system of the shaft. The load shifting further showed a cost avoidance. The simulation results demonstrated that the proposed solutions reduced the electricity and cost expenditure of the shaft successfully. The proposed solutions were thus verified. Table 9 summarises the electricity and cost expenditure and savings for the three scenarios.

Table 9: Summary of the electricity and cost expenditure and saving per annum for the proposed solutions on the simulation model

	Baseline	Recirculation	Load shifting	Combined
Electricity cost (R million)	7.3	3.5	7.0	3.1
Cost saving (R million)	–	3.8	0.3	4.2
Electricity use (kW)	756	357	746	350
Electricity saving (kW)	–	399	10	405

3.5 Construction of the actual electricity consumption baseline

After the proposed solutions were verified, they could be implemented on the actual system, but the actual electricity consumption baselines were required first. The baselines were used to measure the effect of the proposed solutions on the electricity consumption of the shaft. The baselines would ultimately be used to quantify the electricity and cost savings and validate the proposed solutions.

The baselines for the pumping system served as the standard at which the pumps had previously been operated. The baselines were constructed using the data that was available on the SCADA from May 2021 to end of August 2021. The baselines represented the electricity consumption of the shaft's 21L pumps. The operating electricity demand of the pumps was the primary parameter required for developing the baselines.

The data obtained from the data acquisition phase was used to develop the baselines. The baseline profiles comprised the average weekday, Saturday, and Sunday profiles of the pumps. The figures below indicate the average total power consumption in kW for the weekday, Saturday, and Sunday profiles for the dewatering pumps.

Weekday profile

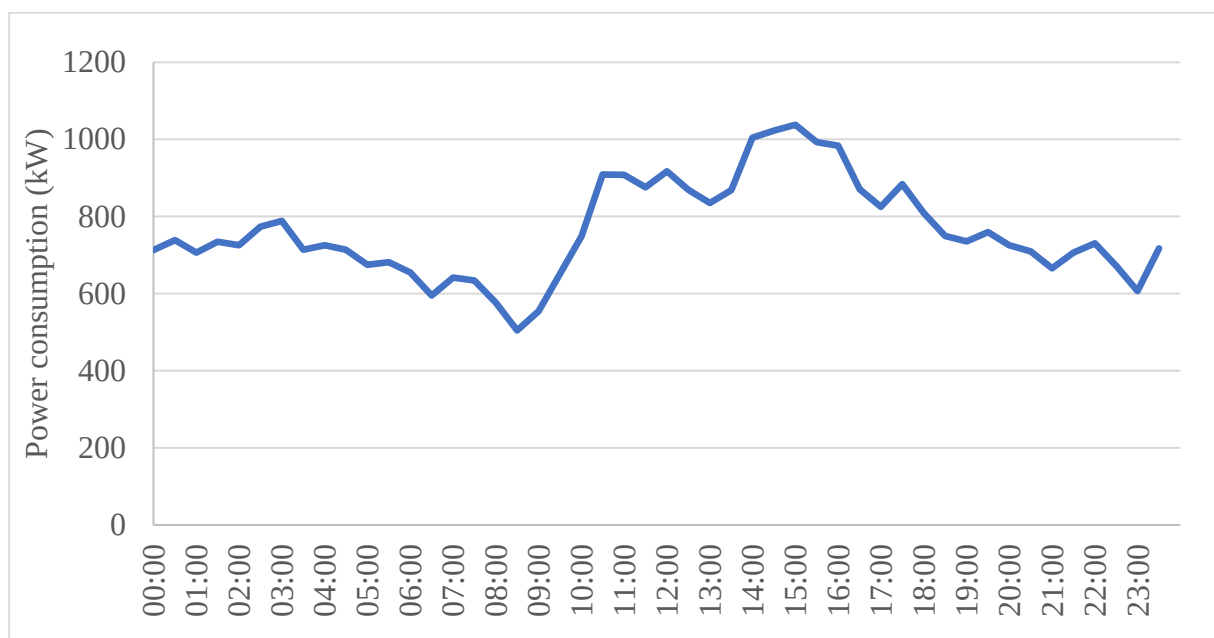


Figure 48: Actual weekday average electricity consumption profile for the 21.5L pumps

Saturday profile

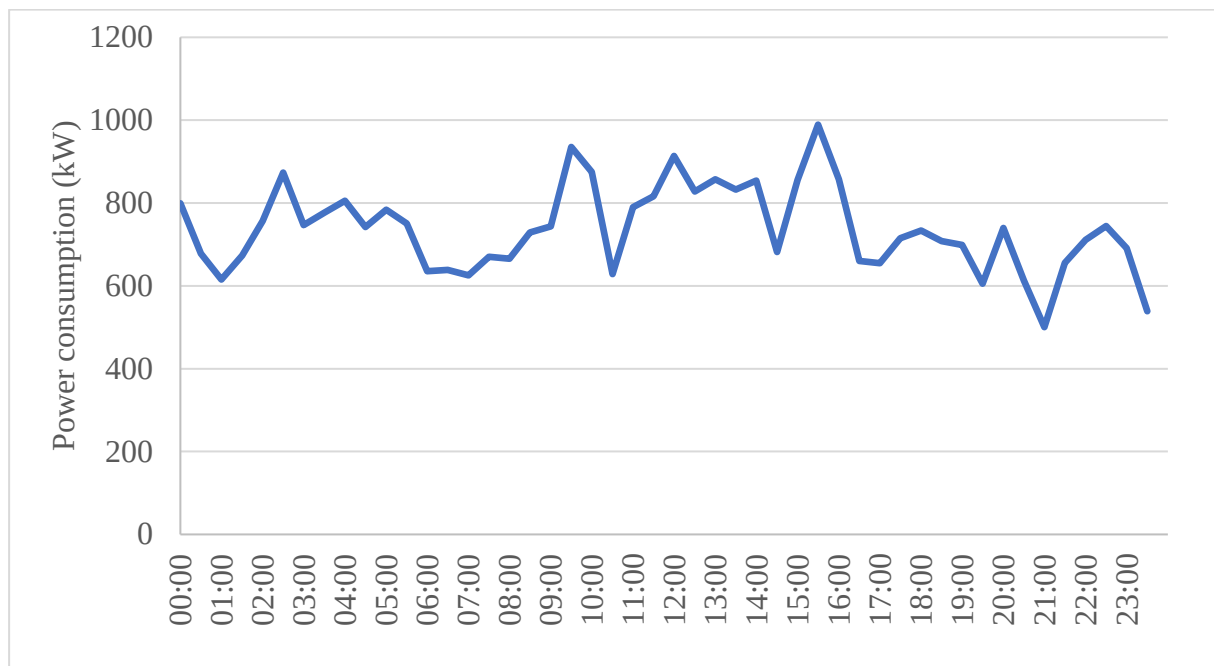


Figure 49: Actual Saturday average electricity consumption profile for the 21.5L pumps

Sunday profile

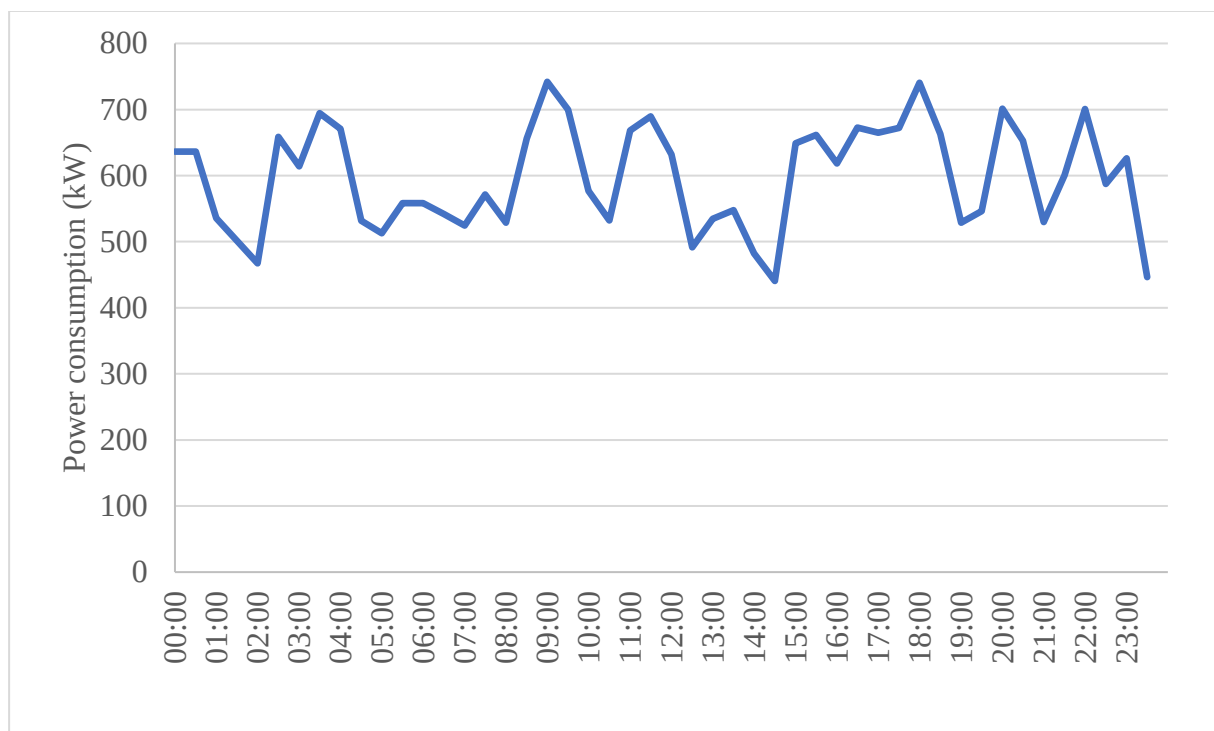


Figure 50: Actual Sunday average electricity consumption profile for the 21.5L pumps

3.6 Validation through actual implementation

After developing the electricity consumption baselines, the proposed solutions were implemented on the shaft's actual dewatering system. After careful consideration, the shaft decided that only underground water recirculation would be implemented and not load shifting. The shaft expressed concern regarding possible flooding of 21.5L dam because of its limited capacity. Although the shaft's concern regarding the possible flooding of the 21.5 MPS due to load shifting was understandable, Figure 29 demonstrated that the dam's capacity did not rise above 60%. This left 40% capacity as well as the 2.5 Ml dam as flooding capacity. However, future plans are to implement load shifting on 21.5L and 28.5L pumps once the underground recirculation is stable and working as intended.

Stols [46] did, however, determine that certain constraints, including low water storage capacity, may affect the efficiency of certain energy efficiency initiatives negatively. This study is a good example that proves that Stols's finding is correct. Thus, the control philosophy was changed to avoid potential flooding at the cost of reduced potential electricity savings.

3.6.1 Implement solution on case study shaft

Underground water recirculation was implemented on the shaft's dewatering system. The water was pumped from the 28.5L dam to the 22L dam. If the 22L dam was full, the water from 28.5L was pumped to 21.5L. If the 28.5L pumps were running and the water level of the 22L dam was rising, it meant that water was being pumped to the 22L dam. The settlers at 28.5L were successful in treating the service water to such a quality that it could be used again. Furthermore, the underground temperatures were below the legal limit. The PLC system together with the control valves enabled full automation of the system, monitoring and control changes could now be done from surface.

The recirculation control philosophy that the shaft implemented did, however, differ from the simulated control philosophy explained in Figure 42 to Figure 44. The reason is that concern was expressed that the proposed control philosophy could cause the 28.5L pumps to start and stop too often, resulting in additional wear and causing faster pump failure.

The control philosophy implemented by the shaft, as shown in Figure 51, is a simplified version of the simulated control.

The 28.5L pumps switched on when 28.5L dam reached 70% and switched off when the dam level dropped below 60%. If 28.5L pumps were on and the 22L dam was below 80%, the 28.5L pumps pumped to the 22L dam. If the 28.5L pumps were on and the 22L dam was above 80%, the pumps pumped to the 21.5L dam. The pumps on 28.5L kept the 22L dam between 80% and 79% until the 28.5L dam was below 60% and the pumps switched off. If the 22L dam's capacity fell below 60%, the 22L dam would be filled to 80% from the 20L dam. If 28.5L pumps had to pump, the 20L valve would close and 22L dam would be filled from 28.5L.

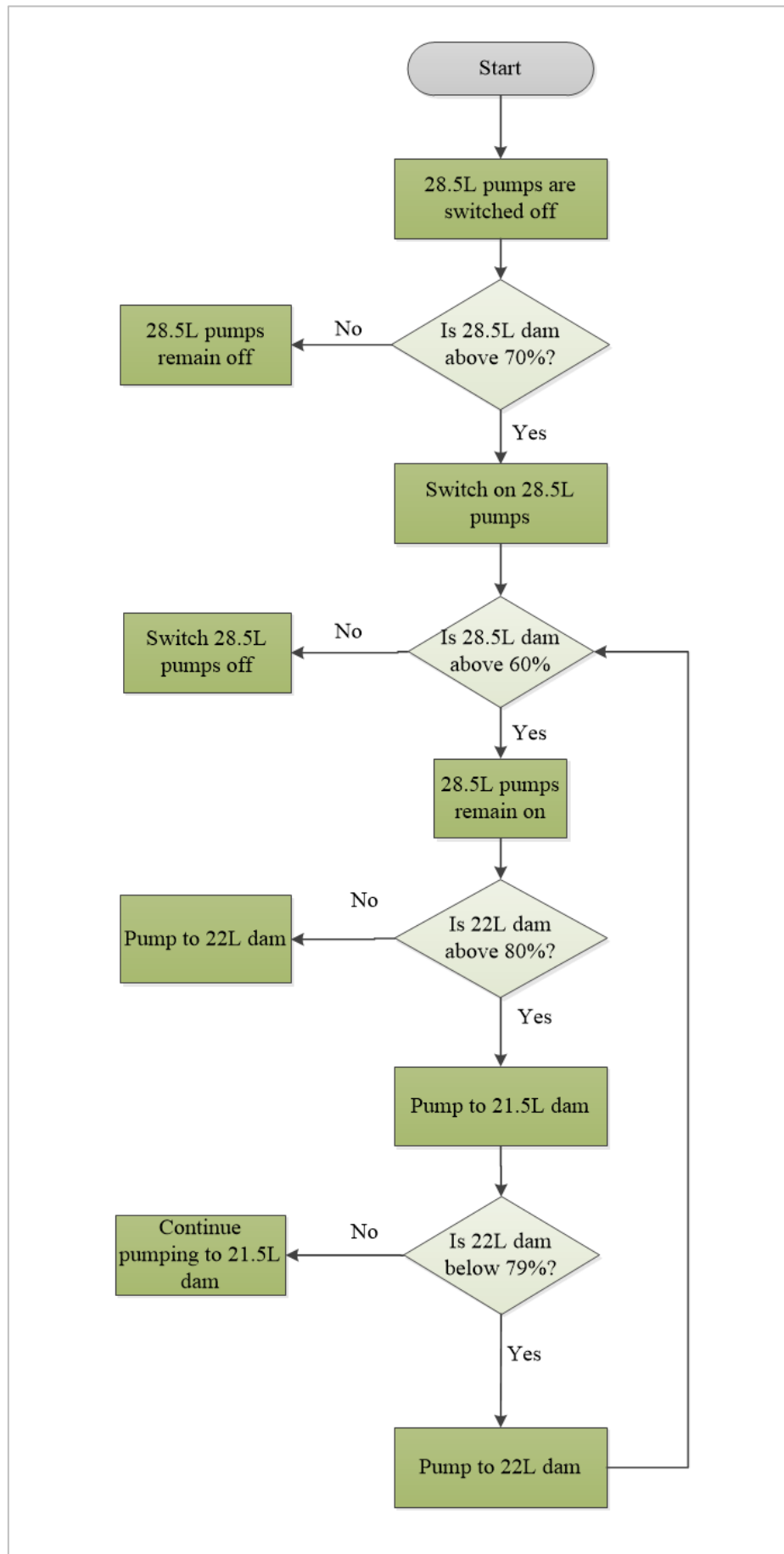


Figure 51: Underground recirculation control philosophy implemented by the shaft

Figure 52 shows the underground water recirculation at the shaft. The blue line indicates whether the 28.5L pumps were running, the orange line indicates 22L dam's capacity, while the dark grey line indicates whether underground recirculation was taking place. The figure shows that the dam level rose when the pumps were operational, which indicates that the water was being pumped to the 22L dam. The 22L dam's level also rose when 28.5L pumps were not operational. This indicates that water was being fed from 20L to the 22L dam. Therefore, the 22L dam was controlling between 60% and 80%.

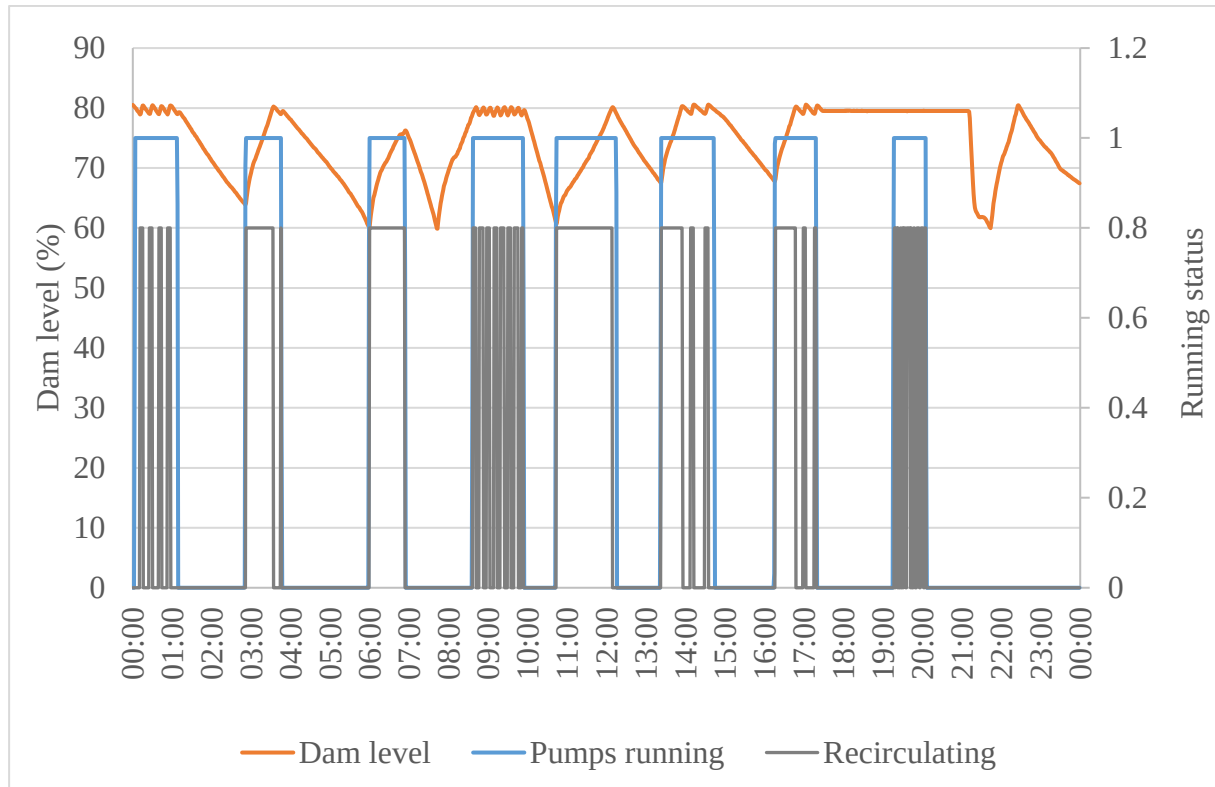


Figure 52: Recirculation of underground water on the shaft

The settlers at 28.5L were successful in filtering the service water to such a quality that it could be used again as prescribed by the Department of Water and Forestry [39]. Furthermore, the underground cooling was sufficient for cooling down the service water for reuse as determined by Mackay *et al.* [50]. The water temperature was under the legal limit of 32.5 °C as required by the Department of Mineral Resources [24]. The PLC system together with the control valves enabled full automation of the system, monitoring and control changes could now be done from surface.

3.6.2 Compare baseline and actual consumption

Figure 53 compares the actual power consumption between the baseline and the current dewatering system with the recirculation included for a weekday profile. The graph shows that

the baseline had an average consumption of 763.5 kW, whereas the current system consumed 622.1 kW. This is an electricity saving of 141.4 kW of instantaneous power or 18.5% less electricity consumed. The baseline further had an average annual weekday electricity expenditure of R5.7 million, whereas the actual system had an electricity expenditure of R4.6 million. This is a cost avoidance of R1.1 million per annum or 19.2% less electricity cost.

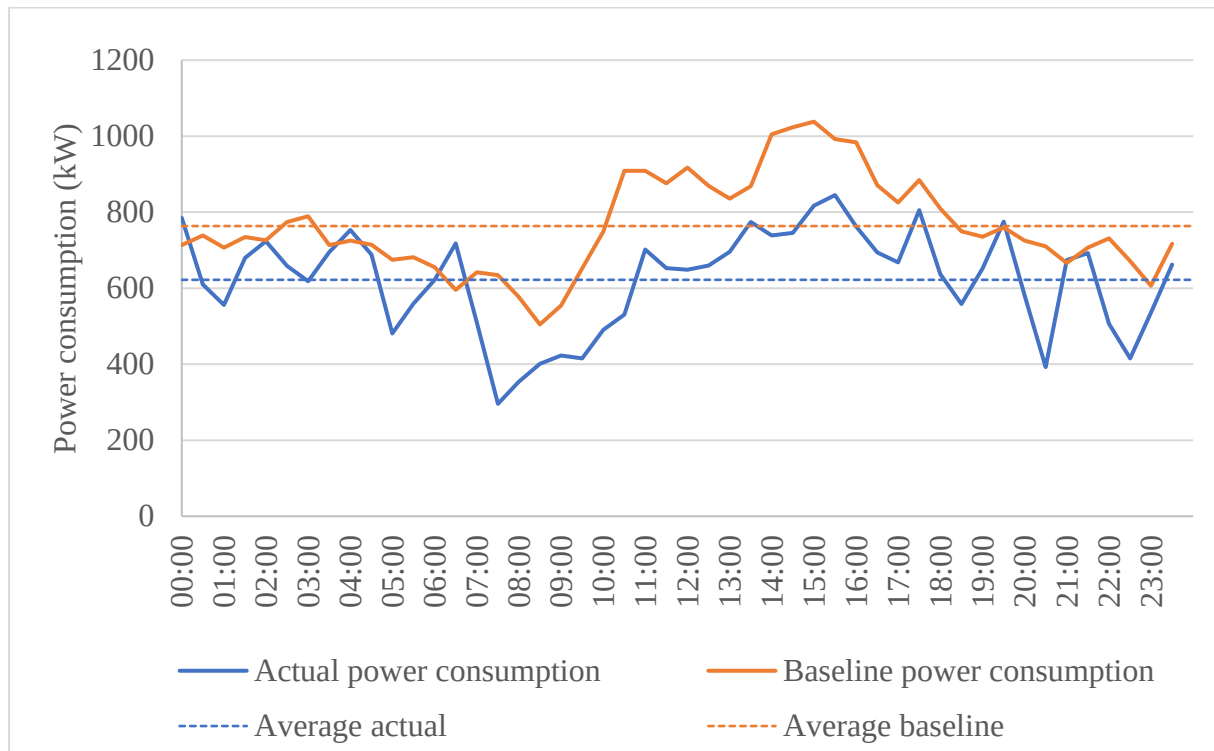


Figure 53: Power consumption comparison between the baseline weekday profile and the current system with underground recirculation implemented

The actual instantaneous power saving of 141.4 kW differed a great deal from the simulated saving of 399.0 kW. A simulation represents an ideal situation with constant values and limited parameters. However, water consumption varies daily, and water can also come from unexpected sources such as leaking drinking water supplies and other shafts. This means that the water use of the shaft was more than anticipated, resulting in an overall power increase on the dewatering pumps. Furthermore, the implemented control philosophy differed from the simulated control philosophy. The implemented control allowed more water to be topped up from 20L, which caused additional water from the vertical section, resulting in less water recirculation on the decline section.

Figure 54 compares the actual power consumption between the baseline and the current dewatering system with the recirculation included for a Saturday profile. The graph shows that the baseline had an average consumption of 737.3 kW, whereas the current system consumed

639.7 kW. This is an electricity saving of 97.7 kW of instantaneous power or 13.2% less electricity consumed. Furthermore, the baseline had an average annual Saturday electricity expenditure of R780 000, whereas the actual system had an expenditure of R670 000. This is a cost avoidance of R110 000 per annum or 14.1% less electricity cost.

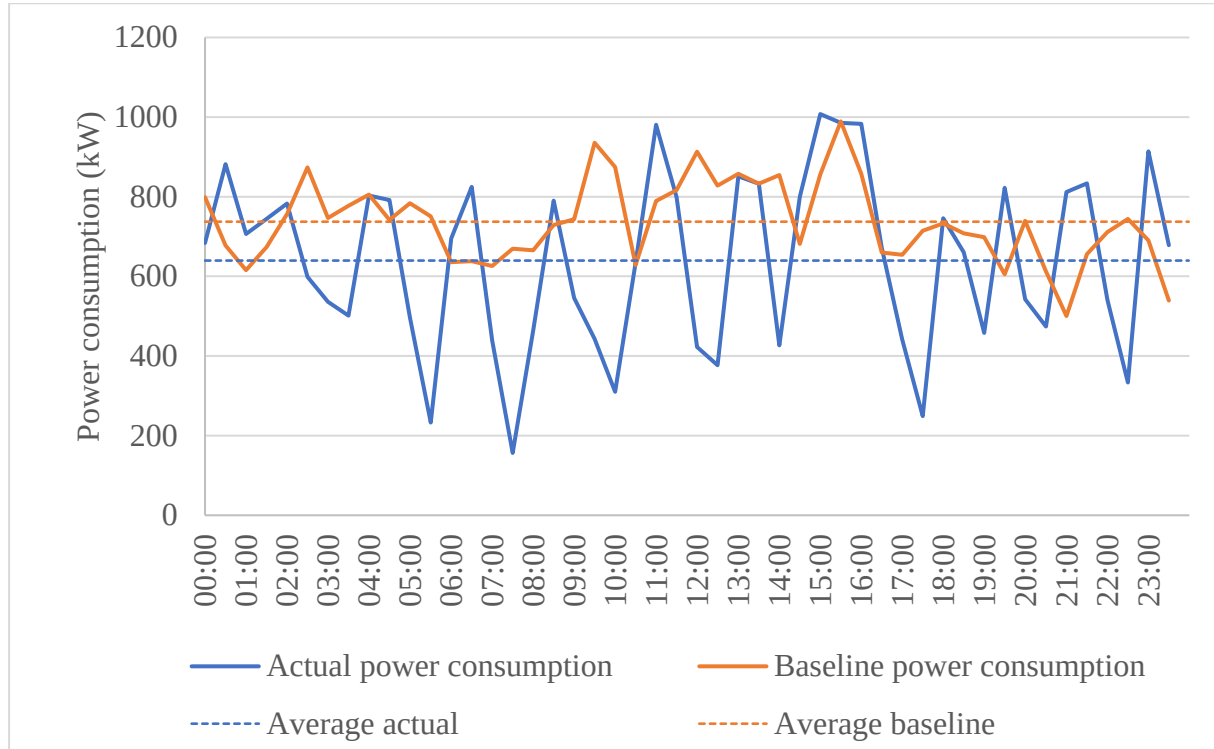


Figure 54: Power consumption comparison between the baseline Saturday profile and the current system with underground recirculation implemented

Figure 55 compares the actual power consumption between the baseline and the current dewatering system with the recirculation included for a Sunday profile. The graph shows that the baseline had an average consumption of 597.9 kW, whereas the current system consumed 576.9 kW. This is an electricity saving of 21.0 kW of instantaneous power or 3.5% less electricity consumed. Furthermore, the baseline had an average annual Sunday electricity expenditure of R550 000, whereas the actual system had a R530 000 electricity expenditure. This is a cost avoidance of R20 000 per annum or 3.6% less electricity cost.

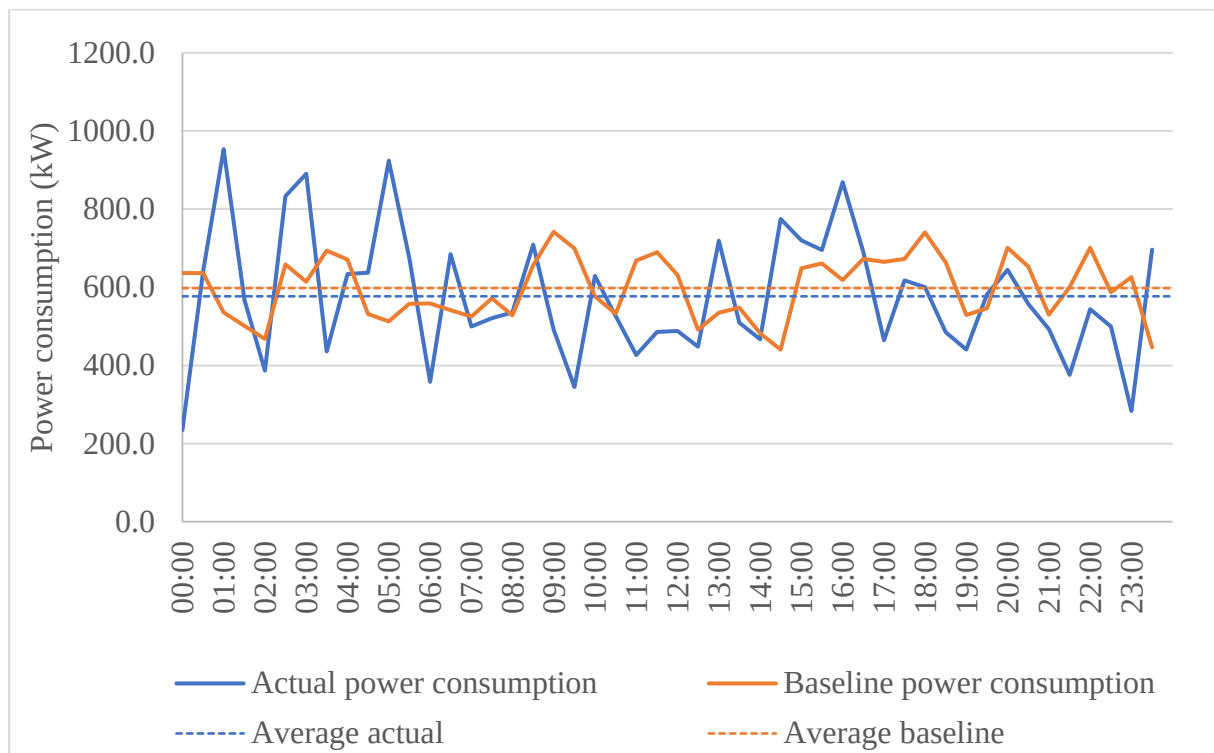


Figure 55: Power consumption comparison between the baseline Sunday profile and the current system with underground recirculation implemented

Figure 56 compares the actual power consumption between the baseline and the current dewatering system with the recirculation included for the combined power profile. The profile combined the weekday, Saturday, and Sunday electricity consumption profiles. The graph shows that the baseline had an average consumption of 736.1 kW, whereas the current system consumed 618.1 kW. This is an electricity saving of 118.0 kW of instantaneous power or 16.0% less electricity consumed. Furthermore, the baseline had an average annual electricity expenditure of R7.04 million, whereas the actual system had a R5.80 million electricity expenditure. This is a cost avoidance of R1.23 million per annum or 17.6% less electricity expenditure.

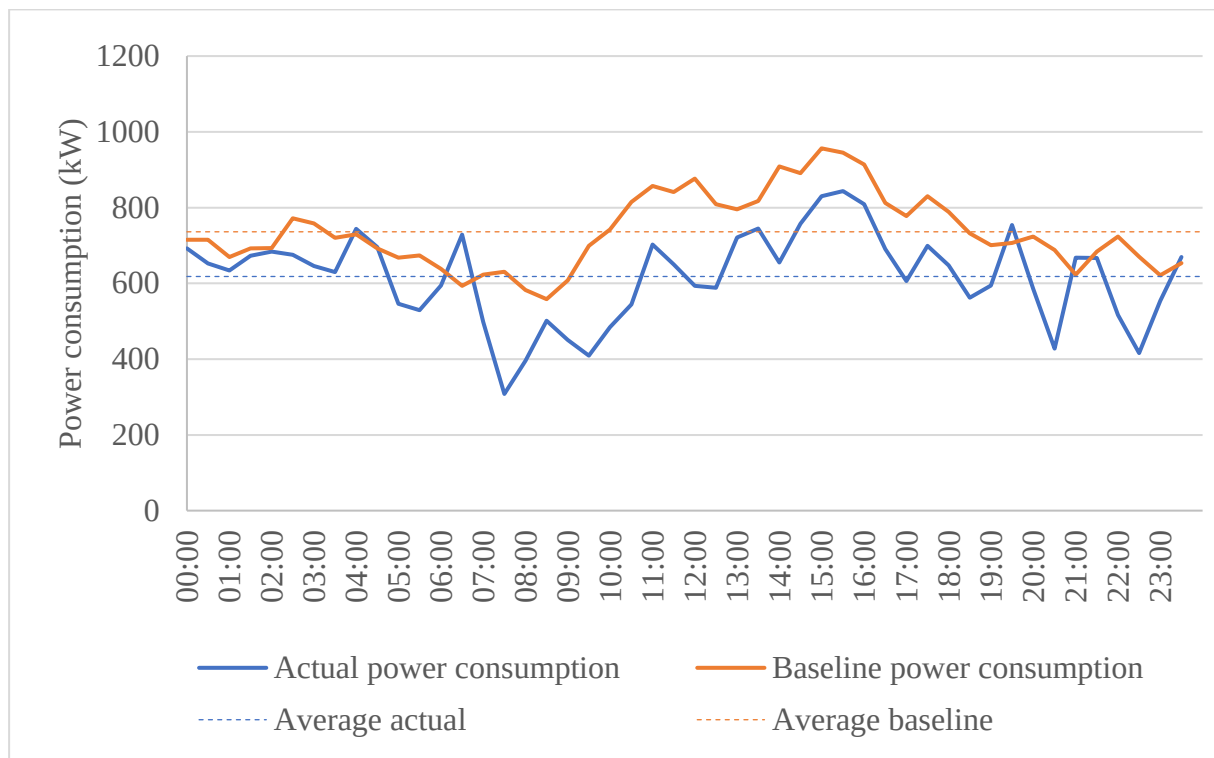


Figure 56: Everyday power consumption comparison between the baseline profile and the current system with underground recirculation implemented

3.7 Conclusion

The following section summarises the chapter.

Data acquisition water reticulation system

In this section, data was acquired to identify a potential problem in the WRS of the mine and construct a simulation model. Data was acquired by using the SCADA system of the mine alongside layout drawings and visual audits. Data such as water mass flow, pump power and dam capacity levels were essential for formulating the problem and constructing a simulation model.

Analysis of dewatering system

By using the acquired data and previous studies conducted on electricity and cost reduction initiative, potential problems, such as unnecessary services water pumping and peak time energy consumption, were identified on the WRS. Possible solutions were identified to reduce the electricity consumption and cost expenditure included recirculating underground water and load shifting the dewatering pumps. A problem was thus identified and possible solutions generated.

Verification through simulation

A simulation model was constructed to verify whether the proposed solution would reduce the electricity and cost consumption of the WRS. After constructing the model, it was calibrated using actual results and matching certain simulation output parameters with actual output parameters. A simulation baseline was constructed to compare the effects of the possible solutions on the simulation model.

Three scenarios were tested on the simulation model, namely, underground water recirculation, load shifting, and a combination of underground recirculation and load shifting. Underground recirculation showed a potential of 399 kW of instantaneous electricity saving. Load shifting showed a potential cost avoidance of R300 000 per annum. The simulation verified that the proposed solutions could reduce the electricity consumption and expenditure of the dewatering pumps.

Construction of the actual electricity consumption baseline

An electricity consumption baseline was developed to compare the effects of the proposed solution with the actual system. Average weekday, Saturday, and Sunday profiles were developed to compare the power consumption profile of the dewatering pumps with the applicable mining schedule.

Validation through actual implementation

This section discussed the results of the underground water recirculation on the actual system. The underground water recirculation showed an instantaneous electricity saving of 141.4 kW for weekdays, 97.7 kW for Saturdays, and 21.0 kW for Sundays. This is equivalent to an annual instantaneous electricity saving of 118.0 kW or 1 033 MWh per year. Therefore, an annual cost saving of R1.23 million is achievable by recirculating water underground.

The load shifting initiative was not implemented on the dewatering pumps due to concerns regarding possible flooding. However, future work does involve implementation of the load-shifting initiative on the dewatering pumps to avoid the possibility of flooding the 21.5L dams. The proposed solution was validated through the electricity and cost savings achieved by the changes to the underground water recirculation system.

CHAPTER 4: CONCLUSION

In this chapter, the study is summarised in its entirety. A brief description of the chapters is provided, and the main results are discussed. The chapter is concluded by providing recommendations for future work.

4.1 Summary

Chapter 1 commenced with providing background regarding the platinum mining industry and the electricity challenges that currently confront the industry. WRSs are large consumers of electricity with dewatering pumps being the component that consumes the most electricity. Numerous methods exist to reduce the electricity consumption and cost expenditure of mine dewatering pumps. However, it was established from literature that platinum mines are often faced with incorrect or lacking infrastructure that is keeping them from realising cost-saving opportunities. Service water is unnecessarily being pumped to surface and TOU periods are not considered in the running schedules of dewatering pumps.

For this study, one main objective and four secondary objectives were established. The main objective of this study was to reduce the electricity and other operational costs of the dewatering system of a deep-level platinum mine. The secondary objectives of this study were to:

- Identify a problem within the dewatering system.
- Formulate a possible solution.
- Verify solution using a simulation model.
- Validate solution through actual results.

In Chapter 2, a five-step methodology was developed to address these study objectives. This methodology followed a generic approach for reconfiguring WRS infrastructure to reduce electricity costs. A brief description of the five-step methodology is presented below.

Step 1: Data acquisition of mine WRS. In this step, data was acquired regarding the WRS of the mine for the purpose of identifying possible problems in the dewatering system.

Step 2: Analysis of the dewatering system. Problems in the dewatering system were identified using the data gathered in Step 1 and possible solutions were formulated.

Step 3: Verification of the solutions. Simulation software was used to construct a simulation model based on the data acquired in Step 1. The simulation model was calibrated and a

simulation baseline developed. The proposed solutions were implemented on the simulation model and verified.

Step 4: Baseline development. After the proposed solutions were verified, a baseline was developed. The baseline was used to determine the impact of the proposed solutions on the electricity consumption of the dewatering system. The achieved energy cost savings determined the success of the solutions. The baseline was developed by using the average electricity consumption of the dewatering pumps over a certain time. The baseline was divided into weekday, Saturday, and Sunday profiles to measure the true effect on the dewatering pumps.

Step 5: Implementation of the proposed solution. The proposed solution was implemented on the case study shaft and the results were compared with the baseline developed in Step 4.

In Chapter 3, the methodology was implemented on the dewatering system of a case study shaft. The underground water recirculation reduced the instantaneous electricity consumption of the dewatering pumps by 118.0 kW or 1 033 MWh per year, which is a reduction of 16% in energy consumption. An annual cost saving of R1.23 million was also achieved. The proposed solution was thus validated, addressing the main study objective. The secondary objectives of identifying a problem with the WRS, formulating a possible solution, verifying through the use of simulation, and validating through actual results were also met.

4.2 Recommendations for future work

This section discusses future work that can lead to further energy costs savings on the case study dewatering system.

Dynamic adjustment

Dynamic scaling involves developing a baseline based on the exact amount of service water that is recirculated. In this study, a static baseline was developed based on the average amount of power used on weekdays, Saturdays, and Sundays.

A dynamic baseline will use a flow meter at the entrance of the 22L dam to record and log the amount of water recirculated per day. This amount of water will be used in Equation 3 to calculate the amount of power that the 21.5L pumps would consume if no underground recirculation has been implemented. In this manner, the exact energy saving can be determined.

Further optimisation

As mentioned in Section 3.6.1, the control philosophy implemented differed from the simulation control philosophy. Thus, additional water was fed from 20L to 22L, which resulted in less water than what could be recirculated. By further improving the control philosophy, more water can be recirculated, resulting in more electricity savings for the 21.5L dewatering pumps.

Load shifting

Although load shifting was proposed in this study with positive results, it was not implemented by the shaft due to concerns about flooding the 21.5L dams. Further investigation is required to convince the case study shaft of implementing load shifting on the 21.5L pumps.

4.3 Conclusion

The above-inflation rate and increasing electricity prices are forcing the mining industry to reduce its electricity consumption. As dewatering systems are large contributors to the electricity consumption of deep-level mines, there is scope for reducing their electricity consumption.

The main objective of this study was to reduce the electricity consumption and expenditure of the dewatering system of a deep-level platinum mine through infrastructure reconfiguration. The secondary objectives were to identify a problem with the dewatering system, formulate a possible solution, verify the solution using a simulation model, and validate the solution through actual results.

The results presented in Chapter 3 indicate that the electricity consumption of the dewatering pumps was reduced, thus achieving the main objective. The secondary objectives were also achieved by implementing the methodology developed in Chapter 2.

REFERENCE LIST

- [1] Minerals Council South Africa, “Facts and figures 2020,” Johannesburg, 2020.
- [2] J. Ndlovu, “Overview of PGM processing,” Anglo American, Johannesburg, 2014. [Online]. Available: <http://www.angloamericanplatinum.com/~media/Files/A/Anglo-American-Platinum/presentations-and-speeches/standardbankconference-anglo-american-platinum-processing-111114.pdf> (accessed Mar 19, 2021).
- [3] C. O’Connor and T. Alexandrova, “The geological occurrence, mineralogy, and processing by flotation of platinum group minerals (PGMs) in South Africa and Russia,” *Minerals*, vol. 11, no. 1, pp. 1–15, 2021, doi: 10.3390/min11010054.
- [4] W. D. Maier, M. Yudovskaya, and P. Jugo, “Introduction to the special issue on the Flatreef PGE-Ni-Cu deposit, northern limb of the Bushveld Igneous Complex,” *Miner. Deposita.*, vol. 56, no. 1, pp. 1–10, 2021, doi: 10.1007/s00126-020-01027-y.
- [5] M. Q. W. Jones, “Virgin rock temperatures and geothermal gradients in the Bushveld Complex,” *J. S. Afr. Inst. Min. Metall.*, vol. 118, no. 7, pp. 671–680, 2018, doi: 10.17159/2411-9717/2018/v118n7a1.
- [6] Eskom Ltd., “Integrated report 2020,” Johannesburg, pp. 6–7, 2020.
- [7] D. Struhs, “The energy efficiency finance network,” South African Institute for Industrial Engineering. p. 13, 2010. [Online]. Available: http://www.eskom.co.za/sites/idm/Documents/121040ESKD_Mining_Brochure_paths.pdf%5Cnwww.eskom.co.za/dsm (accessed Dec 24, 2021).
- [8] ABB Mining, “Deep mining: Factors to balance when designing most productive hoist systems,” [Online]. Available: <https://new.abb.com/mining/underground-mining/mine-hoist-systems/deep-mining-most-productive-sustainable> (accessed May 30, 2021).
- [9] IMPLATS, “Audited annual financial statements 2020,” pp. 20–21, Johannesburg, 2020. [Online]. Available: <https://www.implats.co.za/pdf/afs-2020/booklet.pdf> (accessed May 20, 2021).

- [10] Implats, “Implats fact sheet 2018,” pp. 6–7, Johannesburg, 2018. [Online]. Available: <https://www.implats.co.za/pdf/fact-sheets/2019/implats-fact-sheets-dec-2018.pdf> (accessed May 20, 2021).
- [11] Eskom Ltd., “Tariffs & charges booklet 2021/22,” p. 5, Johannesburg, 2021. [Online]. Available: [http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/ESKOM TC BOOKLET 2012-13 FINAL 3.pdf](http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/ESKOM_TC_BOOKLET_2012-13_FINAL_3.pdf) (accessed May 9, 2021).
- [12] StatsSA, “Inflation remains low in January,” Pretoria, 2021. [Online]. Available: <http://www.statssa.gov.za/?p=14016> (accessed Mar 20, 2021).
- [13] H. J. Groenewald, “Developing a framework for managing compressed air in the platinum group metal mining industry in South Africa,” MBA dissertation North-West University, Potchefstroom, 2019.
- [14] D. Stephenson, “Distribution of water in deep gold mines in South Africa,” *Int. J. Mine Water*, vol. 2, no. 2, pp. 21–30, 1983, doi: 10.1007/BF02504560.
- [15] L. Zietsman, “Identification model for cost-effective electricity savings on a mine cooling system,” Masters Dissertation, North-West University, Potchefstroom, 2018.
- [16] W. W. De Graaf and W. Spiteri, “A preliminary qualitative evaluation of a hydraulic splitting cylinder for breaking rock in deep-level mining,” *J. S. Afr. Inst. Min. Metall.*, vol. 118, no. 8, pp. 891–897, 2018, doi: 10.17159/2411-9717/2018/v118n8a13.
- [17] A. Hasan, B. Twala, K. Ouahada, and T. Marwala, “Energy usage optimisation in South African mines,” *Arch. Min. Sci.*, vol. 59, no. 1, p. 61, 2014, doi: 10.2478/amsc-2014-0004.
- [18] A. Wexler, “Impala Platinum to raise cash to repair finances,” *The Wall Street Journal*, Sep. 03, 2015. [Online]. Available: <https://www.wsj.com/articles/impala-platinum-to-raise-cash-to-repair-finances-1441275689> (accessed May 30, 2021).
- [19] IOSH, “Inhalation disorders,” 2021. [Online]. Available: <https://iosh.com/resources-and-research/our-resources/occupational-health-toolkit/inhalation-disorders/> (accessed May 08, 2021).

- [20] S. Rupprecht, “Innovation in managing water usage in the stope environment,” *New Technology and Innovation in the Minerals Industry Colloquium*, Johannesburg, 9–10 June 2016.
- [21] Eurostone, “Pneumatic vs hydraulic drills: The differences and benefits,” Oct. 27, 2020. [Online]. Available: <https://www.eurostoneusa.com/blog/pneumatic-vs-hydraulic-drills-the-differences-and-benefits> (accessed May 30, 2021).
- [22] J. Migala, “7 health benefits of water backed by scientific research,” *Everyday Health*, Aug. 25, 2020. [Online]. Available: <https://www.everydayhealth.com/water-health/water-body-health.aspx> (accessed May 30, 2021).
- [23] P. N. Neingo and T. Tholana, “Trends in productivity in the South African gold mining industry,” *J. S. Afr. Inst. Min. Metall.*, vol. 116, no. 3, pp. 283–290, 2016, doi: 10.17159/2411-9717/2016/v116n3a10.
- [24] Department of Mineral Resources, “Guidelines for the compilation of a mandatory code of practice for an occupational health programme on thermal stress,” Pretoria, 2016. [Online]. Available: [http://www.dmr.gov.za/Portals/0/Resource Center/Guidelines for the Mandatory Codes of Practice/DMR 16324 Occupational Hygiene/Thermal stress_Distribute.pdf?ver=2018-03-13-013629-680](http://www.dmr.gov.za/Portals/0/Resource%20Center/Guidelines%20for%20the%20Mandatory%20Codes%20of%20Practice/DMR%2016324%20Occupational%20Hygiene/Thermal%20stress_Distribute.pdf?ver=2018-03-13-013629-680) (accessed May 28, 2021).
- [25] Mishra, Debashish & Sahay, Nageshwar. (2015). EFFECT OF AUTO COMPRESSION ON VENTILATION SYSTEM OF DEEP SHAFT COAL MINES IN JHARIA COAL FIELD – A CASE STUDY.
- [26] M. Hooman, R. C. W. Webber-Youngman, J. J. L. Du Plessis, and W. M. Marx, “A decision analysis guideline for underground bulk air heat exchanger design specifications,” *J. S. Afr. Inst. Min. Metall.* vol. 115, no. 2, pp. 125–129, 2015.
- [27] S. Van Jaarsveld, “A control system for the efficient operation of bulk air coolers on a mine,” Masters Dissertation, North-West University, Potchefstroom, 2015.
- [28] J. C. Vosloo, “A new minimum cost model for water reticulation systems on deep mines,” PhD Dissertation, North-West University, Potchefstroom, 2008.

- [29] A. Meyer, “Improved control of clear water underground pumping system for demand side management at an interconnected South African goldmine,” Masters Dissertation, North-West University, Potchefstroom, 2016.
- [30] D. Le Roux, “Energy recovery from high pressure cold water in mines,” *Energize*, no. March, pp. 1–4, 2014. [Online]. Available: <https://www.ee.co.za/wp-content/uploads/2014/03/energize-march-14-p-27-32.pdf> (accessed May 30, 2021).
- [31] F. G. Taljaard, “Analytical control valve selection for mine water reticulation systems,” Masters Dissertation, North-West University, Potchefstroom, 2012.
- [32] S. M. Abelin *et al.*, *Improving Pumping System Performance*, vol. Second edition. The Department of Energy, Lawrence Berkeley National Laboratory, 2006. Accessed: Feb. 13, 2022. [Online]. Available: <https://www.energy.gov/sites/prod/files/2014/05/f16/pump.pdf>
- [33] Z. Mighouar, L. Zahiri, H. Khatib, and K. Mansouri, “Damage accumulation model for cracked pipes subjected to water hammer,” *Adv. Sci. Technol. Eng. Syst.*, vol. 5, no. 4, pp. 523–530, 2020, doi: 10.25046/AJ050462.
- [34] Chan, J & Kolmetz, Karl & Mulyandasari, Viska & Sari, Reni. (2020). Instrumentation control valve selection, sizing and troubleshooting kolmetz handbook of process equipment design
- [35] P. De Villiers, “Reducing deep-level mine refuge bay compressed air consumption,” Masters Dissertation, North-West University, Potchefstroom, 2019.
- [36] Raghavan, Vijaya. (2021). Conveyor Control Using Programmable Logic Controller.
- [37] Capurso, Tommaso & Bergamini, Lorenzo & Camporeale, Sergio & Fortunato, Bernardo & Marco, Torresi. (2019). CFD analysis of the performance of a novel impeller for a double suction centrifugal pump working as a turbine.
- [38] Bell & Gossett, “Parallel and series pump application,” p. 18, Morton Grove, IL, 2012. [Online]. Available: <http://documentlibrary.xylemappliedwater.com/files/2012/07/TEH-1109A.pdf> (accessed May 08, 2021).

- [39] Department of Water Affairs and Forestry, “Best practice guidelines – A6: Water Management for underground mines,” pp. 97–100, Pretoria, 2008.
- [40] H. Stechemesser and B. Dobiáš, *Coagulation and Flocculation*, 2nd ed., Boca Raton, FL: Taylor & Francis, 2005.
- [41] B. Dama-Fakir *et al.*, *Mine Water Treatment Technology Selection Tool: Users’ Guide*, Pretoria: Water Research Commission, 2017.
- [42] “Brominators | Chemical Support Systems.” <https://www.chemicalsupport.co.uk/catalogue/brominators/brominators/> (accessed Feb. 13, 2022).
- [43] R. Venter, “Reconfiguring deep-level mine dewatering systems for increased water volumes,” Masters Dissertation, North-West University, Potchefstroom, 2020.
- [44] H. J. Jabir, J. Teh, D. Ishak, and H. Abunima, “Impact of demand-side management on the reliability of generation systems,” *Energies*, vol. 11, no. 8, pp. 1–20, 2018, doi: 10.3390/en11082155.
- [45] R. Dharani, M. Balasubramonian, T. S. Babu, and B. Nastasi, “Load shifting and peak clipping for reducing energy consumption in an Indian university campus,” *Energies*, vol. 14, no. 3, pp. 1–16, 2021, doi: 10.3390/en14030558.
- [46] J. A. Stols, “Quantifying the effects of system constraint improvements on the electricity cost of dewatering pumps,” Masters Dissertation, North-West University, Potchefstroom, 2016.
- [47] “Pumps - Power Calculator.” https://www.engineeringtoolbox.com/pumps-power-d_505.html (accessed Feb. 13, 2022).
- [48] E. Du Plessis, “Investigating the dewatering energy savings potential of an open pit mine,” Masters Dissertation, North-West University, Potchefstroom, 2020.
- [49] W. Van Der Wateren, “Optimising energy recovery in mine dewatering systems,” Masters Dissertation, North-West University, Potchefstroom, 2018.

- [50] L. Mackay, S. Bluhm, and J. Van Rensburg, "Refrigeration and cooling concepts for ultra-deep platinum mining," *J. S. Afr. Inst. Min. Metall.*, vol. 4, pp. 285–292, 2010. [Online]. Available: http://www.saimm.co.za/Conferences/Pt2010/285-292_MacKay.pdf (accessed Jan 01, 2021).
- [51] W. Schoeman, "The integrated effect of DSM on mine chilled water systems," Masters Dissertation, North-West University, Potchefstroom, 2014.
- [52] B. Pascoe, "Improved control processes to sustain electricity cost savings on a mine water reticulation system," Masters Dissertation, North-West University, Potchefstroom, 2018.
- [53] J. A. Deysel, "DSM strategies to reduce electricity costs on platinum mines," Masters Dissertation, North-West University, Potchefstroom, 2015.
- [54] F. Louwinger, "Case study of Ingula and Lima pumped storage schemes," *Energize*, pp. 1–13, 2012. [Online]. Available: <http://www.ee.co.za/article/case-study-of-ingula-and-lima-pumped-storage-schemes.html> (accessed Jan 06, 2021).
- [55] B. Galloway and G. P. Hancke, "Introduction to industrial control networks," *IEEE Commun. Surv. Tutorials*, vol. 15, no. 2, pp. 860–880, 2013, doi: 10.1109/SURV.2012.071812.00124.
- [56] B. M. Friedenstien, C. Cilliers, and J. Van Rensburg, "Simulating operational improvements on mine compressed air systems," *S. Afr. J. Ind. Eng.*, vol. 29, no. 3, pp. 69–81, 2018, doi: 10.7166/29-3-2049.
- [57] USGS, "Water density." [Online]. Available: https://www.usgs.gov/special-topic/water-science-school/science/water-density?qt-science_center_objects=0#qt-science_center_objects (accessed Jun. 18, 2021).
- [58] M. De Jager, "Using simulation to prioritise implementation of platinum mine compressed air efficiency solutions," Masters Dissertation, North-West University, Potchefstroom, 2020.

- [59] R. T. De Almeida Minhoni , F. F. S. Pereira, T. B. G. Da Silva, E. R. Castro, and J. C. C. Saad, “The performance of explicit formulas for determining the Darcy–Weisbach friction factor,” *Eng. Agric.*, vol. 40, no. 2, pp. 258–265, 2020, doi: 10.1590/1809-4430-ENG.AGRIC.V40N2P258-265/2020.
- [60] Universal Flow Monitors, “Ultrasonic flowmeter technology,” Hazel Park, MI. [Online]. Available: <https://www.flowmeters.com/ultrasonic-technology> (accessed Oct. 17, 2021).