

Development of a dewatering control strategy to prevent flooding within deep-level mines

A Nell

 orcid.org/0000-0003-4690-2125

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

Supervisor: Dr H.G. Brand

Co-supervisor: Dr J.H. van Laar

Graduation: May 2022

Student number: 27018644

ACKNOWLEDGEMENTS

It is a pleasure to express my sincere gratitude to the following parties for their substantial assistance and support during the duration of this study:

- I would like to thank all the mining personnel who contributed to the development of my engineering capabilities. Your accessibility and patience throughout my working experience are deeply appreciated.
- Thank you to my parents who sacrificed a lot enabling me to achieve my dreams. Without your support, completion of my studies would not have been possible.
- Thank you to my mentor, Bertus van Rooyen, for continuously providing valuable input throughout the course of this study. Your accessibility and willingness to listen are gratefully acknowledged. It was a privilege to work under your guidance.
- Thank you to ETA Operations (Pty) for assisting me in achieving my goal in completing my post-graduate studies, while developing as a mechanical engineer in practice.
- I would like to thank all my friends whom I neglected through my dedication to this study. Your understanding is sincerely appreciated.
- A special thanks to my loving soul mate, Juané Rheeders. Your continuous support and heart-warming encouragement during the most difficult times were of immeasurable value. I love you dearly.
- Finally, and most importantly, I would like to thank the heavenly Father who blessed me with the opportunity to complete this dissertation under His guidance, love and continuous grace that we all receive unconditionally.

ABSTRACT

Title: Development of a dewatering control strategy to prevent flooding within deep-level mines

Author: Mr André Nell

Supervisor: Dr Hendrik Brand

Degree: *Magister* in Mechanical Engineering

Keywords: Dewatering, control philosophy, redundancy, component failure, simulation

Deep-level mines are faced with continually increasing challenges regarding heat. New mining depths are constantly reached, and working conditions are becoming intolerable and unsafe. Underground conditions must be controlled effectively to safeguard the health of the mining personnel. Mine service water is used to control the temperature of the occupational environment. In essence, a certain portion of the overall heat is transported out of the mine via dewatering systems.

Dewatering systems play an important part in mitigating heat loads underground. Refrigeration plants integrated with dewatering systems are responsible for providing chilled water to key working areas. The hot water needs to be extracted from the working areas and removed from the mine to prevent flooding. Some hot water may also be reintroduced to the refrigeration plants to be cooled again depending on the water reticulation system design.

Unexpected failures within dewatering systems pose a major risk of flooding and mine down-time. Therefore, it is of utmost importance to maintain redundancy within dewatering systems. This can be achieved by identifying the general root cause of failures and developing an alternative dewatering control philosophy that reduces the risk of flooding within the mine.

This study focused on increasing the reliability of current mine dewatering systems using simulation software to develop and test possible solutions to identified risks. The proposed methodology was applied to a case study mine situated in South Africa. The case study mine formed part of an integrated mining complex consisting of three different shafts.

Upon case study inspection it was found that the case study mine had to stop production for a total of eight days due to dewatering column failure. The loss in production amounted to an estimated loss of R30 million for the 2019 financial year.

A calibrated digital twin model of the case study's dewatering system was constructed and used to develop alternative dewatering strategies to prevent further failure of dewatering components. All critical dewatering components and additional infrastructure were investigated and integrated into the simulation model to develop a redundant and sophisticated dewatering strategy.

Critical system control parameters were also developed to ensure all dewatering components operate within the design specifications. Two additional dewatering solutions were integrated into the current dewatering strategy to achieve redundancy, which was the main objective of this study. The developed control philosophy also introduced a buffer dam from where centralised dewatering control was possible between all neighbouring shafts.

A mass balance within the case study mine was maintained and the simulation model predicted the outcome of the system changes with an average simulation error of 4.2%. Flooding within the case study mine was prevented resulting in no loss in production due to flooding for the 2020 financial year.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	I
ABSTRACT	II
TABLE OF CONTENTS.....	IV
LIST OF FIGURES.....	VIII
LIST OF TABLES	XII
LIST OF ABBREVIATIONS	XIV
CHAPTER 1: INTRODUCTION AND LITERATURE.....	1
1.1 Outline	1
1.2 Challenges faced in the mining industry	1
1.3 Mine cooling systems	3
1.4 Dewatering systems.....	5
1.5 Literature analysis on past research.....	11
1.5.1 Overview	11
1.5.2 Study boundaries.....	11
1.5.3 Critical component failure	12
1.5.4 System reconfiguration through simulation	17
1.5.5 Control philosophy.....	21
1.5.6 Implementation.....	27

1.5.7	State of the art summary	29
1.6	Problem statement	31
1.7	Study objectives	31
1.8	Conclusion	32
CHAPTER 2: METHODOLOGY		33
2.1	Preamble	33
2.2	Breakdown of methodology	33
2.3	Process 1: Obtain system information	36
2.4	Process 2: Development of digital twin	39
2.5	Process 3: Develop alternative dewatering strategies	40
2.6	Process 4: Evaluate best solution	43
2.7	Process 5: Implementation	45
2.8	Summary	49
CHAPTER 3: RESULTS AND DISCUSSION		50
3.1	Preamble	50
3.2	Case study background	50
3.3	Process 1: Obtain system information	51
3.3.1	System layout	51
3.3.2	System design specifications	54
3.3.3	Real-time data acquisition	55
3.3.4	Critical risk assessment	57
3.4	Process 2: Development of digital twin	58

3.4.1	Develop baseline model	58
3.4.2	Simulate baseline model.....	63
3.4.3	Calibrate and verify simulation	64
3.5	Process 3: Develop alternative dewatering strategies.....	67
3.5.1	Route cause analysis.....	67
3.5.2	Additional infrastructure	68
3.5.3	Simulate possible solutions.....	69
3.6	Process 4: Evaluate best solution.....	84
3.6.1	System constraint evaluation of possible solutions	84
3.6.2	Cost implication of possible solution	85
3.7	Process 5: Implementation	86
3.7.1	Project proposal.....	86
3.7.2	Project commissioning.....	86
3.7.3	Validation of strategy	87
3.7.4	Maintenance procedures	92
3.8	Conclusion.....	93
CHAPTER 4: CONCLUSION		94
4.1	Study overview	94
4.2	Recommendations for further study	96
BIBLIOGRAPHY.....		98
APPENDIX A: REFRIGERATION PLANTS.....		104

APPENDIX B: CONTROL VALVE TYPES	107
APPENDIX C: MINE A DXF LAYOUTS.....	110
APPENDIX D: SCENARIO SCHEMATIC ILLUSTRATIONS	117
APPENDIX E: MINE A REPORTING EXAMPLE	121
APPENDIX F: PTB WATER COMPONENT BREAKDOWN	123

LIST OF FIGURES

Figure 1: Underground heat contributor breakdown.....	2
Figure 2: Mine cooling requirements at different mining depths	3
Figure 3: Schematic illustration of a typical mine dewatering system.....	5
Figure 4: Underground settlers	6
Figure 5: Underground corrosion.....	9
Figure 6: Exploded view of complete methodology	35
Figure 7: Obtain system information breakdown (Process 1).....	36
Figure 8: Development of digital twin breakdown (Process 2).....	39
Figure 9: Develop alternative solutions breakdown (Process 3).....	41
Figure 10: Root cause analysis process flowchart [43]	42
Figure 11: Evaluate best solution breakdown (Process 4)	44
Figure 12: Implementation breakdown (Process 5).....	46
Figure 13: Failing RAW pipeline	51
Figure 14: Case study water reticulation system schematic illustration.....	53
Figure 15: SCADA tag names	56
Figure 16: Dewatering mass balance	56
Figure 17: Leak identification layout	57
Figure 18: Cooling car connection	59
Figure 19: 55L ice dam connection setup	60
Figure 20: 77L settler and pump station connection setup.....	61
Figure 21: Ice dam design specifications.....	62

Figure 22: Settler design specifications	62
Figure 23: 77L pump curve.....	63
Figure 24: Baseline model.....	64
Figure 25: Ice dam level (Actual vs simulated)	66
Figure 26: Flow into ice dam (Actual vs simulated).....	67
Figure 27: Root cause analysis [43].....	68
Figure 28: Scenario 1 - Flow profile to Mine B and Mine C	71
Figure 29: Scenario 1 - PRV pressures	72
Figure 30: Scenario 1 - Ice dam levels	72
Figure 31: Scenario 1 - Flows into ice dam.....	73
Figure 32: Scenario 2 - Flows to Mine B and Mine C.....	74
Figure 33: Scenario 2 - 66L PRV pressures	74
Figure 34: Scenario 2 - Ice dam levels	75
Figure 35: Scenario 2 - Flows into the ice dam.....	75
Figure 36: Scenario 3 - Water dumped to Mine B and Mine C	77
Figure 37: Scenario 3 - 66L PRV pressures	77
Figure 38: Scenario 3 - Ice dam level	78
Figure 39: Scenario 3 - Flows into the ice dam.....	78
Figure 40: Scenario 4 - Water pumped to Mine C and Mine B through Railveyor pipeline	80
Figure 41: Scenario 4 - Buffer dam control	80
Figure 42: Scenario 4 - Flow into ice dam.....	81
Figure 43: Scenario 4 - Ice dam level	82

Figure 44: Scenario 4 - Ice dam temperatures.....	82
Figure 45: Scenario 4 - Flow from ice dam	83
Figure 46: Ice dam level validation	88
Figure 47: Ice dam temperature validation.....	88
Figure 48: Flow to ice dam validation	89
Figure 49: Flow from ice dam validation	89
Figure 50: Buffer dam level validation.....	90
Figure 51: 66L pipeline flow to Mine C validation.....	91
Figure 52: Railveyor flow to Mine B validation	92
Figure 53: Vapour-compression cycle	104
Figure 54: Typical mobile cooling unit.....	105
Figure 55: Water balance	106
Figure 56: Gate valve illustration	107
Figure 57: Ball valve illustration	108
Figure 58: Globe valve illustration	108
Figure 59: Butterfly valve illustration	109
Figure 60: 55L DXF layout.....	110
Figure 61: 66L DXF layout.....	111
Figure 62: 69L DXF layout.....	112
Figure 63: 71L DXF layout.....	113
Figure 64: 73L DXF layout.....	114
Figure 65: 75L DXF layout.....	115

Figure 66: 77L DXF layout.....	116
Figure 67: Schematic illustration - Scenario 1.....	117
Figure 68: Schematic illustration - Scenario 2.....	118
Figure 69: Schematic illustration - Scenario 3.....	119
Figure 70: Schematic illustration - Scenario 4.....	120
Figure 71: Automatic daily dewatering report example 1	121
Figure 72: Automatic daily dewatering report example 2	122

LIST OF TABLES

Table 1: Summary of control valves and their applications [24]	8
Table 2: Oosthuizen, 2013 [36] main results.....	14
Table 3: State of the art matrix	30
Table 4: Component design specifications [53]	37
Table 5: Leak identification audit example [21]	38
Table 6: Control parameter table	43
Table 7: Simulation constraint table example	45
Table 8: Case study dam design specifications	54
Table 9: Case study pump design specifications	54
Table 10: Chilled water consuming cooling units	55
Table 11: Leak identification results.....	58
Table 12: Valve to Mine B setpoints	65
Table 13: Ice dam valve setpoints	65
Table 14: 77L pump control.....	65
Table 15: Scenario summary.....	70
Table 16: Scenario 1 - 77L pump controls	70
Table 17: Scenario 1 - Valve set points	73
Table 18: Scenario 2 - Valve set points	76
Table 19: Scenario 3 - Valve set points	79
Table 20: Scenario 4 - Valve and pump setpoints.....	84
Table 21: Scenario constraint comparison.....	85

Table 22: Bill of materials (BOM)	86
---	----

Table 23: PTB water component breakdown	123
---	-----

LIST OF ABBREVIATIONS

Abbreviation	Description
<i>BAC</i>	<i>Bulk air cooler</i>
<i>BOM</i>	<i>Bill of materials</i>
<i>DB</i>	<i>Dry-bulb</i>
<i>DSM</i>	<i>Demand-side management</i>
<i>DXF</i>	<i>Drawing exchange format</i>
<i>HTX</i>	<i>Heat exchanger</i>
<i>KPIs</i>	<i>Key performance indicators</i>
<i>LOM</i>	<i>Life of mine</i>
<i>MCUs</i>	<i>Mobile cooling units</i>
<i>MPC</i>	<i>Model predictive control</i>
<i>PID</i>	<i>Proportional-Integral-Derivative</i>
<i>PLCs</i>	<i>Programmable logic controllers</i>
<i>PRVs</i>	<i>Pressure reducing valves</i>
<i>PTB</i>	<i>Process Toolbox</i>
<i>RAW</i>	<i>Return airway</i>
<i>RCA</i>	<i>Root cause analysis</i>
<i>REMS</i>	<i>Real-time energy management system</i>
<i>SCADA</i>	<i>Supervisory control and data acquisition</i>
<i>WB</i>	<i>Wet-bulb</i>
<i>WRS</i>	<i>Water reticulation system</i>
<i>X/C</i>	<i>Crosscut</i>

CHAPTER 1: INTRODUCTION AND LITERATURE

1.1 Outline

This chapter will provide an overview on the challenges faced in South African deep-level mines regarding heat loads. Refrigeration systems integrated with water reticulation systems used in the mining industry to mitigate underground heat loads, will also be discussed.

An in-depth investigation was done on current dewatering strategies mainly focusing on obtaining redundancy within dewatering systems through improved water distribution and control philosophies. The challenges faced regarding dewatering systems due to the deteriorating underground conditions were highlighted and a research problem regarding fail-safe dewatering control philosophies was substantiated by literature.

Furthermore, in the final section of this chapter, the need for the study was formulated and objectives were set based on the shortcomings that were identified from previous studies.

1.2 Challenges faced in the mining industry

Mineral consumption is continually increasing throughout the globe. Due to the rapid increase in mineral demand, deep-level mines across the world are increasing in depth and are becoming more mechanised as technology improves [1]. The mining industry is faced with many challenges due to these changes. Heat proves to be an escalating concern in the mining industry and will continue to scale in future [1].

While deep-level mining operations are experiencing these challenges, the labour workers are still present in the deteriorating conditions. Working under such extreme environmental conditions may lead to a loss in production, serious illnesses or even death [2]. Past studies have concluded that a decrease of 1°C in wet-bulb temperature leads to a 3 - 4% increase in productivity [2].

The contributing heat sources must be methodically identified and measured with the view to safeguard the health of mine workers. The biggest underground heat contributors include: the geothermal gradient, auto-compression, inefficiencies in diesel equipment, electrical equipment, broken rock and fissure water [3]-[4]. The equivalent of each heat contributor is illustrated in Figure 1 [5].

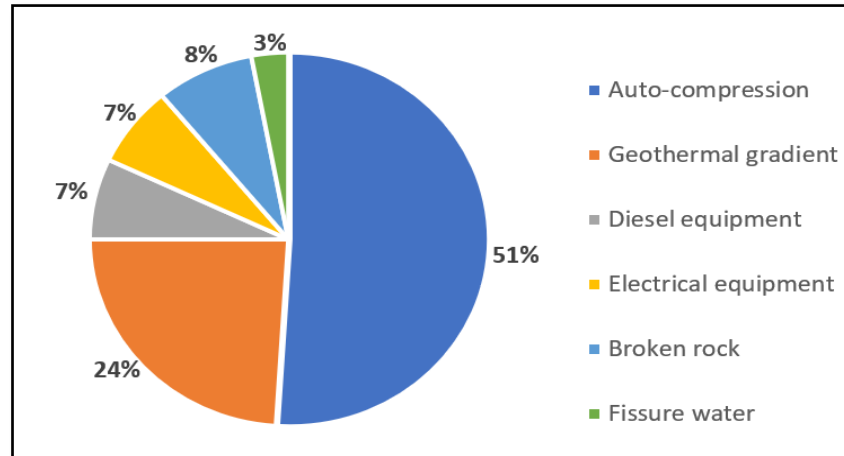


Figure 1: Underground heat contributor breakdown¹

Traditionally, the primary ventilation cooling system is responsible for removing heat from underground and supplying fresh, moving air at development- and production areas. The primary cooling system normally consists of surface fans and surface bulk air coolers (BACs), depending on the depth of the mine [6].

Ambient ventilation is adequate for mines not exceeding a depth of 700 m [7]. In some cases, the primary ventilation cooling system that utilises only ambient air is not enough to mitigate the heat load underground [8]. Mines reaching depths of 1 400 m and deeper need secondary, and tertiary cooling systems to ensure acceptable working conditions as seen from Figure 2 [7], [8].

¹ Adapted from Figure 1 in [5]

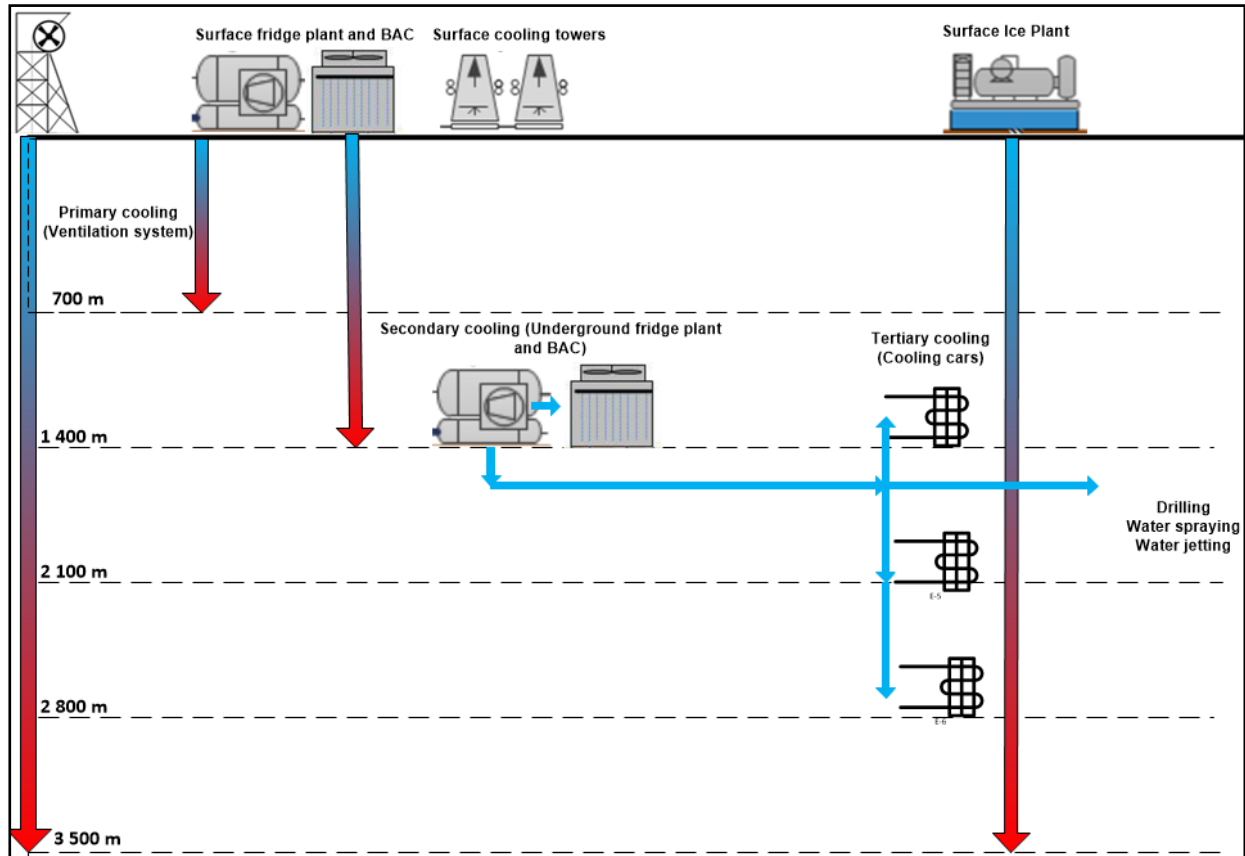


Figure 2: Mine cooling requirements at different mining depths²

Deep-level mines use large volumes of water for several mining and cooling purposes. Several cooling components combined with a network of pumps and underground storage dams are integrated to form a water reticulation system [5].

1.3 Mine cooling systems

Refrigeration plants are used to provide chilled water to cooling systems and several other chilled water-consuming activities [9]. Refrigeration plants, combined with underground chilled water supply- and dewatering strategies are integrated to form a water reticulation system [7], [10]. The refrigeration part of a water reticulation system is an integrated system containing several components. The typical components of a refrigeration system include: refrigeration plants, cooling towers, hot dams, cold dams and BACs [7], [11].

Hot water, with a temperature typically in the range of 28 °C, is pumped from underground into hot dams located on surface [12]. This hot water is pumped through pre-cooling towers into the pre-

² A. Nell, Personal illustration adapted from Figure 1 in [7], 2021.

cool dam where the water is cooled to approximately 18 °C, depending on the wet-bulb (WB) ambient temperature [12].

From the pre-cool dam, the water is pumped to the refrigeration plants to be cooled down to the desired temperature. Refrigeration plants produce chilled water in the region of 3 – 6 °C, depending on the configuration of the refrigeration plants [6]. Refrigeration plants are mostly located on surface but are present underground at mines reaching extreme depths [6]. The thermodynamic working principle of refrigeration plants is discussed in Appendix A.

Chilled water is gravity-fed from surface to underground working areas. Due to the extreme depths, the hydraulic pressure of the fluid increases to unsafe levels. There are several existing methods to reduce the hydraulic pressure of the water which include pressure-reducing valves (PRVs) and cascading dams [10].

PRVs are situated at underground pressure-reducing stations. They reduce the upstream pressure to the required downstream pressure, irrespective of the mass flow rate through the station. Several PRVs may be installed in a series configuration to form a pressure-reducing station. The high pressure is reduced through the conversion of hydraulic energy into thermal energy [13]. To obtain an in-depth analysis of the complex theory behind PRVs, refer to Vosloo [10] and Janus & Ulanicki [13].

Cascading dams or storage dams are also used as a water pressure-reducing technique. The increasing hydraulic pressure of the gravity-fed water is relieved when the water is distributed into cascading dams. From the cascading dams, chilled water is distributed to the active mining areas. Cascading dams are beneficial during high water-demand periods but are inefficient in terms of chilled water temperature increase. There may be a significant loss in water-cooling duty due to the warm environmental conditions around the stagnant water [14].

Chilled water is used in tertiary cooling components which act as heat exchangers. These heat exchangers use chilled water to extract heat from ventilation air resulting in cooler environmental temperatures. Chilled water is also often used as service water due to the cooling benefit thereof. To summarise, chilled water is used for the following applications [11], [15]:

- Mobile cooling units
- Drilling
- Water spraying
- Water jetting

Flooding of underground mining locations is constantly a great risk due to the large amounts of water used underground. A critical water balance should always be maintained for mines to operate within the designed volumes of water.

The dewatering system is responsible for the removal of water from underground to surface and is considered critical in the deep-level mining industry [16]. If the dewatering system fails, the mine is at great risk of flooding. This occurrence is regarded as a critical safety hazard and poses a threat to human life. Therefore, the refrigeration system is excluded from this investigation and focus will be shifted to dewatering systems.

The following section provides an in-depth discussion on dewatering systems to obtain a better understanding of the complexity of the system.

1.4 Dewatering systems

Figure 3 illustrates the layout of a typical dewatering system within a deep-level mine.

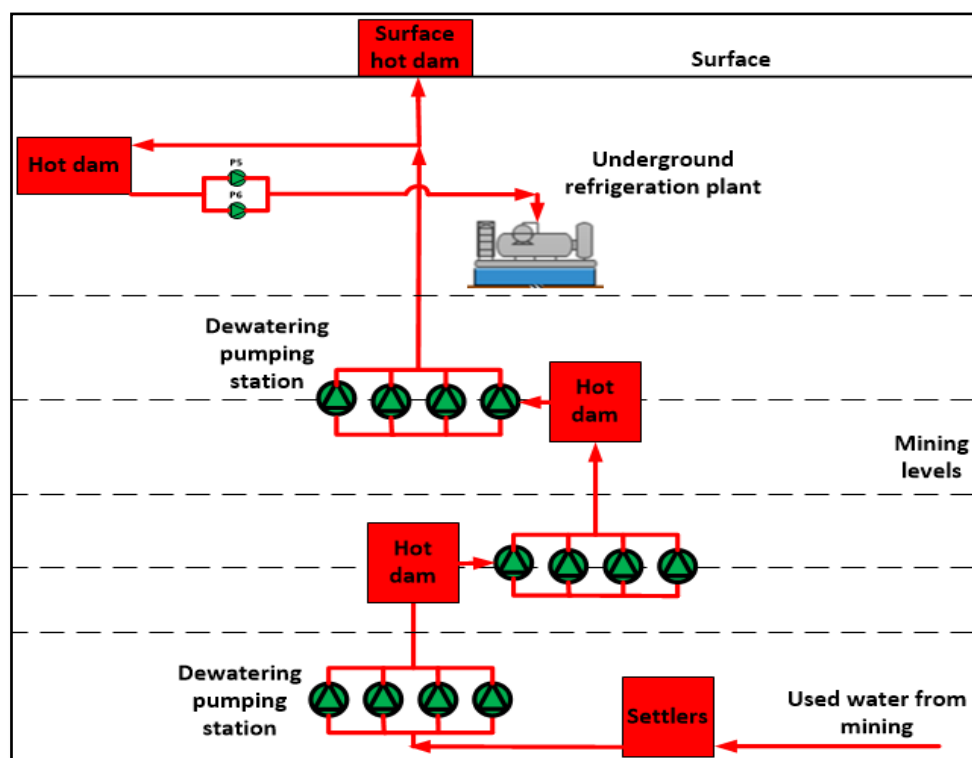


Figure 3: Schematic illustration of a typical mine dewatering system³

³ A. Nell, Personal illustration, 2021

A dewatering system may be compared to a drainage system or a water removal system. The dewatering of underground water is a constant occurrence which results in long operating hours of pumps and equipment. This may lead to a reduction in component life and an increase in maintenance cost.

After chilled water is used for the purposes discussed in Section 1.3, it is channelled or pumped to the underground settlers. Fissure water that flows through the rock surfaces also adds to the water entering the settlers. Settlers have the main purpose of separating mud particles from the used service water [17]. These mud particles may consist of rock, dust, or mining minerals. Service water accumulates in the settlers and a flocculant is used to react with the mud particles.

The flocculant increases the density of the mud particles in the water and causes the particles to sink to the underflow of the settlers [18]. Mud slurry accumulates at the underflow of the settlers. Slurry pumps are utilised to distribute the mud slurry to surface where metallurgical plants process it to extract any mining minerals still present in the slurry.

Through the repetition of the above explained process, clean water is obtained at the surface of the settler. The clear water flows over the overflow walls of the settlers and is channelled to clear hot water dams located underground. Figure 4 illustrates the above-mentioned process.

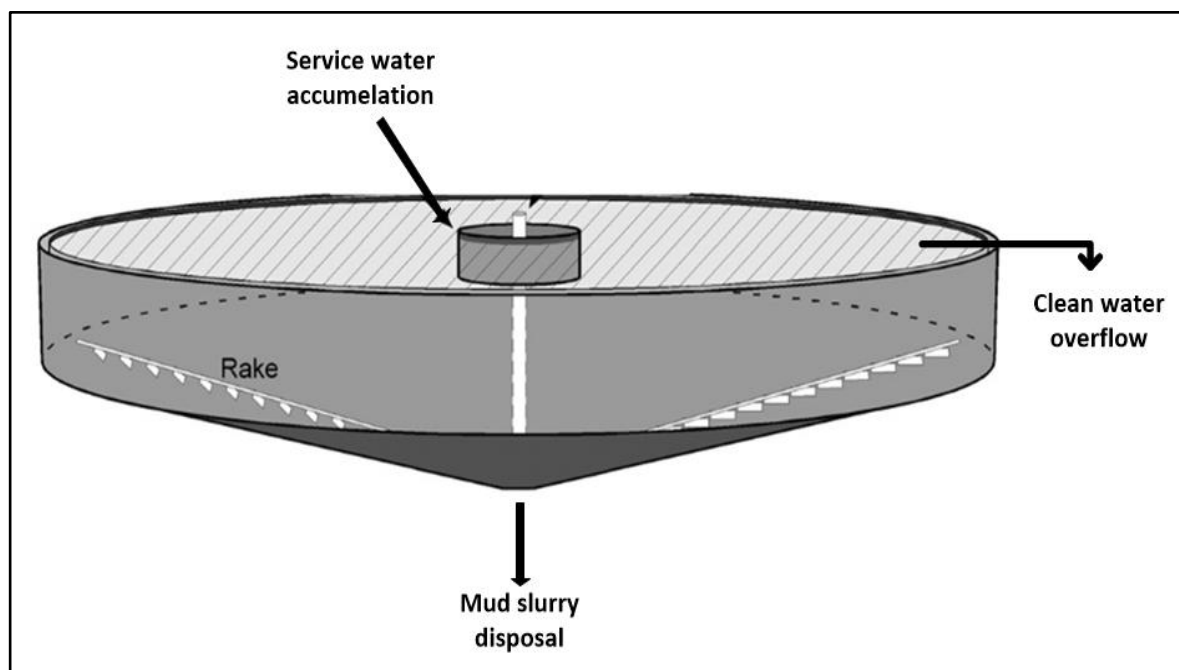


Figure 4: Underground settlers⁴

⁴ Adapted from [18]

Large multistage centrifugal pumps are used for dewatering purposes in the mining industry to overcome the large head between mining levels [19]. In most cases, multiple pumps are operated simultaneously. Dewatering pumps are typically installed in a parallel configuration to allow for larger flow volumes [19]. Dewatering pumps are large electricity consumers and several studies have been done to reduce electricity usage of dewatering pumps [16], [20]. In scenarios where dewatering pump failure occurs, electricity savings are disregarded, and focus is rather shifted to prevent flooding within the mine. Therefore, electricity savings are excluded from this investigation.

The dewatering pumps are used to pump water from the settlers to underground hot dams through underground water pipelines. Hot water dams are essential for service water to be pumped to surface due to the reduction in water pressure. There may be several hot dams per level to ensure cleaning of hot dams is possible. Mud accumulates at the bottom of the hot dams because not all mud particles are extracted in the settlers. Underground hot dam levels must be monitored and controlled to prevent flooding, and to prevent the dams from drying out. If the hot dam level falls too low, the accumulated mud at the bottom of the dam could damage the dewatering pumps [18].

The pumping head that dewatering pumps need to overcome is large in deep-level mines reaching depths of 3 000 m [8]. Hot cascading dams are located on different upper levels to allow for a smaller pumping head between pump stations. Water is pumped from the lowest level dam into the nearest upper-level dam. The pumping process between levels is repeated until the service water reaches the surface. Hot water may also be reintroduced to underground refrigeration plants, depending on the configuration of the mine cooling system. Figure 3 provides a visual illustration of the above-mentioned process.

Water consumption within a deep-level mine fluctuates throughout a 24-hour period due to inconsistent water demand, which is directly influenced by the mining activities and the amount of human intervention with water. There are normally three mining shifts where mining activities take place, namely [21]:

- Morning shift – during this time hole drilling into the face wall usually takes place for blasting purposes.
- Afternoon shift – blasting occurs during this time. The mine is evacuated for safety purposes during the blasting shift.
- Night shift – cleaning and sweeping takes place to recover and remove the ore from the stoping area.

Water planning and management are greatly influenced by the fluctuating water demand [22]. The dewatering system control is of utmost importance to ensure efficient and safe mining operation. A dewatering system consists of a complex integrated water pipeline network that needs to be controlled effectively. Control valves are used to regulate water flow to the desired locations. Control valves are described as mechanical devices that control the flow of fluid passing through the device [23].

It is important to choose the correct type of control valve for each application due to the different valve characteristics. When valves are specified, several different factors should be considered which include: operational conditions, shut-off conditions, fluid properties, flow velocity and pressure ranges [24]. Cavitation, noise and valve failure proved to be the result of incorrect valve applications [24]-[25]. The most common valves used in the industry are briefly summarised in Table 1. Refer to Appendix B for an in-depth discussion of each valve type.

Table 1: Summary of control valves and their applications [24]

Valve	Advantages	Disadvantages	Applications
Gate	Small pressure loss in fluid across valve Fluid resistance across valve is small	Removal of valve is necessary for maintenance purposes Opening and closing of valve is time consuming	Open/Close
Ball	Small pressure loss in fluid across valve Good sealing characteristics	Removal of valve is necessary for maintenance purposes High flow restriction	Open/Close and throttling
Globe	Good sealing characteristics Trim can be replaced without removal of valve	High pressure loss across valve Flow capacity is reduced	Throttling
Butterfly	Low cost Small pressure loss in fluid across valve	Poor sealing characteristics	Throttling Low pressure applications

It is self-evident that dewatering systems are vastly complex. Therefore, the design and control of dewatering systems are of utmost importance to prevent system failure. Automatic control technologies are used within the mining industry to help eliminate human error. By controlling

pumping rates, water pressure, dam levels and valve positions automatically, successful and precise operation is possible [26]-[27].

The engineering environment also developed simulation software to assist with the design of integrated systems. A direct replica of the system is imitated within simulation software where system optimisation and design are possible. The virtual representation of a real-world system is referred to as a digital twin of the system [28].

Several component control strategies can be simulated to predict the outcome of real-world system changes [29]. Controlling dewatering components automatically, can result in an increase in component service life and a reduction in both energy and maintenance costs. Automated component control also mitigates the risk of flooding within deep-level mines [30].

It is apparent that the deep-level mining environment is harsh, and several challenges arise due to severe underground conditions. A combination of high temperatures, high humidity, long operating hours of pumps and vibrations on equipment are examples of the challenges faced due to the harsh environment [31]. Figure 5 illustrates the impact of the harsh environment on underground water pipes due to corrosion.



Figure 5: Underground corrosion⁵

From the above-described background on dewatering systems, it is evident that dewatering systems play a crucial role in the mining industry in terms of safety and successful mining operation. Dewatering systems are complex and consist of several critical components. Due to

⁵ Obtained from: <https://www.dynagard.info/how-to-prevent-internal-pipe-corrosion-a-guide-for-industry/>

the harsh mining environment, component failure is unavoidable. Therefore, investigation was done into the current industry approach and new technologies in the following fields of research:

- Critical component failure
- System reconfiguration through simulation
- Control philosophies

1.5 Literature analysis on past research

1.5.1 Overview

The following section of the report elaborates on the literature analysis conducted on the industry approach regarding the operation and design of dewatering systems. Substantive investigations of various studies in the field of dewatering systems were done. Theoretical and methodological contributions are also included in this section.

1.5.2 Study boundaries

From the background conducted in Section 1.4, it was evident that a fail-safe dewatering system is very important in any water reticulation system to prevent flooding and mining downtime. An in-depth investigation was done into the current industry approach to ensure a fail-safe dewatering system.

A few critical keywords were identified through the background that was done on dewatering systems in Section 1.4. These keywords were used to scrutinise the available literature. Relevant questions were asked to determine if the studies could result in valuable insights. All studies considered were evaluated based on the following keywords and criteria questions:

- Critical component failure – Did the study analyse critical component failure?
- System reconfiguration through simulation – Did the study focus on system reconfiguration for improved water distribution throughout the dewatering system using simulation software?
- Control philosophy – Did the study develop an optimal dewatering control philosophy?
- Implementation – Did the study manage to prevent component failure by implementing the developed solution?

Many dewatering studies were identified with electricity savings as the main goal through the implementation of several demand-side management (DSM) projects [20], [32], [33], [34]. Studies that only focused on DSM projects failed to satisfy the above-mentioned criteria and were excluded from this investigation.

1.5.3 Critical component failure

From the background formulated on dewatering systems, it was concluded that the possibility of dewatering component failure arises due to the harsh mining environment. Therefore, an in-depth investigation into past literature was done regarding the industry's approach to handle dewatering component failure. How redundancy is maintained within current dewatering systems was also investigated.

The databases that were searched included ScienceDirect, Scopus, Google Scholar and African Journals. Keywords and combinations such as “dewatering strategies”, “underground flood prevention”, “dewatering component failure”, “alternative dewatering solutions” and “redundant dewatering system design” were used as the building blocks for this literature study. Only articles and journals published after the year 2010 were searched for. Nevertheless, some studies published before 2010 proved to be considerable and relevant to this study. These studies were, however, kept to a minimum.

Literature focusing primarily on alternative dewatering solutions in case of component failure is scarce. However, the literature that could be obtained is discussed below.

Study 1: Pascoe et al. (2019) [31]

Summary:

Pascoe conducted a study in 2019 that focused mainly on prediction models that prevent the loss in energy saving opportunities during critical dewatering component failure. He highlighted that the harsh mining environment often leads to critical component failure within dewatering systems. It was highlighted that common component failure includes pump failure, insufficient pumping head and dewatering column failure. Pascoe argued that attention is only given to the safety of underground workers during such scenarios. He concluded that saving opportunities are regularly neglected.

Pascoe developed a methodology to adjust the control of dewatering systems to achieve electricity savings during component failure, while still ensuring the safety of underground workers. He simulated several possible component failure scenarios and developed dewatering control strategies for each scenario. Pascoe implemented the developed methodology on a case study where several dewatering components failed.

Results/Insights:

Pascoe was able to adapt and simulate alternative dewatering control strategies to achieve savings, while maintaining a water balance within the mine. It was found through the implementation of these control strategies, an average of 25% of energy cost savings could be regained.

This study conducted by Pascoe provided valuable insight to the processes that need to be followed in case of dewatering component failure. It is evident from Pascoe's study that the use of simulation software to predict the outcome of certain scenarios is an effective engineering tool to consider.

Shortcomings:

The methodology developed by Pascoe did not provide a breakdown of the simulation development procedure.

Study 2: Rózkowski et al. (2021) [35]

Summary:

This study focused on adapting a dewatering system of an opencast mine according to the expected inflows as the mining operation expands. Rózkowski used numerical simulations to assist with the selection of the most optimal dewatering strategy. Historical data was used to determine the average ground water inflow per year.

Results/Insights:

Several water drainage concepts were developed using simulation software which resulted in enormous energy savings due to the elimination of negative drainage effects that were present in the current dewatering strategy. This study highlighted the importance of model calibration to accurately predict the system response to certain changes.

Shortcomings:

This study did not focus on dewatering component failure, but rather on unaccounted ground water inflow that leads to flooding as the mine expands. From this study it is evident that it is possible to successfully design and adapt a dewatering system through simulation software that would be capable of handling additional water as the mine expands in size.

Study 3: Schoeman et al. (2013) [36]

Summary:

Schoeman conducted a study on a mining complex consisting of five different shafts that are interconnected underground. The initiative was formulated that dewatering to neighbouring shafts could be considered in case of dewatering system failure. The main objective of this study was to optimise and integrate the entire dewatering system of the mining complex. Schoeman implemented the developed methodology on a case study where some pumping stations were out of action due to column failure in the main shaft.

Results/Insights:

Schoeman proved that automation software can be used to control the dewatering system behaviour. Several pumping options were developed to obtain an optimal pumping schedule between the neighbouring shafts. He used real-time energy management system (REMS) as automation control software. The pumping system was optimised to achieve maximum financial savings. The implemented methodology resulted in the savings displayed in Table 2.

Table 2: Oosthuizen, 2013 [36] main results

	Shaft A	Shaft B	Shaft C	Shaft D
Load shift	62 000 kWh	33 000 kWh	26 000 kWh	11 000 kWh
Annual savings	R18 700 000	R11 100 000	R7 600 000	R1 800 000

It was proven that it could be a feasible option to dewater to neighbouring shafts if an optimal control philosophy is developed. However, Schoeman emphasized the importance of investigating the capability of handling additional water at the neighbouring shafts before this is considered as a solution.

Shortcomings:

Schoeman did not predict the impact on the cooling system due to the change in dewatering system configuration. As mentioned in Section 1.3, hot water may be reintroduced into the cooling system depending on the water reticulation system configuration.

Study 4: Romero et al. (2015) [37]

Summary:

This study explored several model predictive control (MPC) strategies to ensure optimal dewatering operation during all times. MPC adapts according to the existence of physical constraints and uncertain operation conditions. Romero considered several predictive control strategies namely: centralized, distributed, and decentralized predictive control strategies. The methodology provided by Romero fills the gap between dewatering design optimisation and optimal control.

Results/Insights:

The main objective of this study was to control a dewatering system to achieve the best possible dewatering component life to prevent unexpected component failure. Savings that can be achieved through the prevention of component failure was also investigated. Romero concluded that annual cost savings of up to 50% can be achieved using these predictive control strategies.

Shortcomings:

This study did not focus on existing component failure and did not provide insight into the processes to follow when possible component failure risks are identified within a dewatering system. However, Romero proved that through efficient automatic control, component failure can be prevented to some extent.

Study 5: Witthüser et al. (2015) [38]

Summary:

This study focussed on groundwater flow modelling to enable mining to commence at current flooded parts of the mine. Another objective of this study was to predict the quantity of water that needs to be dewatered for the life of mine.

Results/Insights:

Through a flow model it was possible to determine the dewatering rate needed for a shaft that was integrated with a mining complex of shafts that were closed. Through this initiative the shaft was successfully de-risked from flooding due to unexpected ground water inflow. It is clear from this study that post-closure shafts may pose a risk of flooding operating shafts if the shafts are interconnected underground.

Shortcomings:

Dewatering component failure was neglected during this study. The method developed by Witthüser also lacked a procedure to adapt the control of the dewatering system according to the simulation results.

Study 6: Vosloo et al. (2008) [10]

Summary:

Vosloo's study mainly focused on the optimisation of a whole water reticulation system through simulation and automatic control to achieve optimal energy savings. Several energy recovery devices were incorporated into a water reticulation system using simulation software to predict the outcome of the initiative. A water balance was also proposed to ensure safe operation of the dewatering system.

Results/Insights:

Valuable and useful information was obtained through evaluating this study. It provided an effective method to set up a water balance for deep level mines. It was concluded that the amount of water entering the mine should always equal the amount of water that is dewatered. This method can be used to easily determine if the dewatering system is operating effectively. It is also evident from this study that the utilisation of simulation software is effective in predicting the outcome of real-world system changes.

Shortcomings:

Redundancy to prevent flooding and mine down-time was neglected from this study as energy saving was the main objective.

Study 7: Szczepinski (2019) [39]

Summary:

This study focused on simulations to develop dewatering strategies for Polish opencast mining operations. The simulation model was used to model groundwater flow and adapt the dewatering system accordingly to prevent flooding. The environmental impact of the dewatering was also quantified using the simulation model.

Results/Insights:

This study highlighted the importance of model calibration and verification. The provided methodology gave insight into the calibration process. It was suggested that historical data must be used to calibrate the simulation and the initial simulation should be solved in steady-state conditions. Emphasis was placed on calibration through an iterative process. Szczepinski recommended that different data sets should be used if the calibrated model fails to reflect the real system performance.

Shortcomings:

This study did not focus on addressing flooding scenarios due to dewatering component failure. The methodology, however, did successfully prevent flooding due to unaccounted groundwater flow.

From past literature conducted, it is evident that simulation software is an effective tool to consider for the development of integrated systems and predicting the outcome of real-world system changes. It was also concluded that the use of automation software results in accurate system control. Therefore, further investigation was done into current simulation practices and automation software initiatives.

1.5.4 System reconfiguration through simulation

Past literature has shown that mine dewatering systems are complex, integrated systems consisting of several components. Quantifying and predicting the effect of certain system changes proved challenging in the past. It is evident from literature that the engineering environment has developed critical tools such as simulation software that can be used to accurately predict the outcome of changes to real-world systems [40], [41].

Study 8: Luo et al. (2018) [42]

Summary

Luo did a feasibility study on simulation software tools for the development of dynamic systems. This study applied the methodology developed specifically to compressed air systems. However, it was concluded that simulation models can be validated in the fields of pneumatics and thermodynamics as well.

Results/Insights:

It was suggested that simulation packages that can use Proportional-Integral-Derivative (PID) controllers, are a necessity for accurate simulation of systems with a dynamic nature. It was also highlighted that validated simulation models can represent the actual performance of several integrated components and can thus be used for system control design, component optimisation and sensitivity analysis of applied system changes.

Shortcomings:

This study only applied the developed methodology to compressed air systems and not on water systems where flooding poses a risk.

Further investigation was done into the types of simulation packages that were validated with successful results within the field of thermodynamics. Several past studies were evaluated where a critical comprehensive literature review of the different available simulation software was done. Such literature enables researchers to make informed decisions on which simulation software to consider.

Study 9: Maré (2017) [40]

Summary:

Maré developed a method to simulate the transient response of integrated mine cooling systems. He did a comprehensive literature analysis on different simulation software packages used in the industry, namely: ENVIRON, Flownex, VUMA3D, REMS, QUICKcontrol, and Process Toolbox (PTB).

Results/Insights:

Maré concluded that PTB was the most suitable simulation software to simulate complex integrated mining systems. A complete breakdown of all PTB components as well as the thermodynamic calculations behind each component was included in this study. Maré verified the simulation within 10% of the real-world scenario.

This study also provided insight into the simulation development procedures that proved to be effective in the past. The procedure included the detailed process to calibrate, verify and validate dynamic simulations. Maré implemented the proposed method on a mine cooling system which included a dewatering system. The procedure is summarised below:

1. Select system that needs to be analysed.
2. Obtain critical system information through audits and data acquisition.
3. Select simulation application (energy savings, system control, or system improvement).
4. Select the relevant simulation properties.
5. Construct all sub-systems.
6. Repeat process for all sub-systems.
7. Calibrate sub-systems with real-time data.
8. Assemble the integrated simulation.
9. Execute simulation.
10. Investigate the simulation outputs.

The sub-systems Maré referred to included: the pumping system, the whole water reticulation system, and the water in the active mining areas. Maré recalls a simulation to be calibrated within 10% accuracy.

Shortcomings:

This study did not focus on the development of alternative dewatering strategies in case of flooding scenarios or dewatering component failure.

Study 10: Nell (2017) [43]

Summary:

Nell optimised mining production by improving the efficiency of mine compressed air networks using PTB as simulation software. Nell also did a comprehensive literature analysis on different flow simulation software packages namely: Solidworks flow simulator, KYPipe, Flownex, and PTB. Nell evaluated the advantages and disadvantages of each simulation software.

Results/Insights:

It was concluded that PTB was the most suitable simulation software due to the accessibility thereof and the capability of PTB to simulate a vast range of integrated thermodynamic systems. It was highlighted that PTB can simulate compressed air systems, ventilation systems and water reticulation systems with great accuracy. Nell verified the digital twin simulation within 5% of the real-world scenario. He also proved the effectiveness of performing the “5 whys” root cause analysis (RCA) approach to identify system inefficiencies.

An RCA is a technique that is used in the industry to pinpoint the root cause of problems that arise in systems. This technique should be performed as soon as possible after a problem or inefficiency is noted [44]. The focus is placed on the event and the system, and not the “who”. The RCA technique entails continuously asking the question “why?”. The RCA method can be broken down in the following steps [43], [44]:

1. Identify the problem.
2. Pinpoint the cause by asking: “Why did this error occur?”
3. Note down the answers in a diagram.
4. Ask the “Why did this happen?” question again for each of the causes identified.
5. Repeat process until the root cause is identified.

Shortcomings:

Nell only applied the developed methodology to compressed air network simulations.

The successful and accurate use of PTB was substantiated by further literature. Peach [16] used PTB to develop optimised control strategies for load management initiatives for deep-level mine refrigeration systems. The most optimal strategy was simulated and implemented on two case studies, resulting in energy savings of 7.28 MW and 2.00 MW respectively. The verification of the simulation resulted in an average error of less than 2%.

Developing simulations can be a challenging task due to the vast range of simulation components that need to be included. For this reason, further investigation was done into current simulation development procedures that act as a guideline for the construction of simulations like those provided by Maré in Study 9 [40].

Study 11: Bouwer (2004) [45]

Summary:

This study provided a generic methodology to develop an integrated simulation. The procedure is summarised below:

1. Develop a skeleton model of the current system including all system configurations that indicate all key measuring points.
2. Obtain actual data of critical system components (flow rates, dam levels, power usage and pumping schedules).

3. Proceed with manual measurements to compare obtained data to real-time data received from installed instrumentation.
4. Choose a typical mining operational day to perform simulations.
5. The change in ambient conditions should be considered at all times.
6. Execute simulation once relevant data is incorporated.
7. Compare simulated results to actual system performance data.
8. Calibrate simulation model through repetition of the process.

Results/Insights:

Insight was obtained into the simulation development processes that proved to be effective in the past. Bouwer also suggested that key performance indicators (KPIs) need to be identified. These KPIs are used to compare the simulation results to actual real-time data. It was also highlighted that the KPIs are crucial for the verification of the simulation.

Shortcomings:

Bouwer did not focus on the development of dewatering simulations to predict the outcome of real-world system changes.

Each simulation scenario is unique with its own system requirements. Therefore, it is of utmost importance to follow a generic approach to develop a simulation like those provided by Maré [40] and Bouwer [45]. The provided procedures are applicable to this study and may be combined to develop a successful simulation, depending on the case study.

From the past literature conducted on dewatering systems, it was clear that there are several automatic system control initiatives that proved to be effective in eliminating human error. Further investigation into the current industry approach on automatic system control is discussed below.

1.5.5 Control philosophy

Study 12: More et al. (2020) [46]

Summary:

More investigated new Industry 4.0 technologies to manage used mine water effectively. It was proven that an automated measurement system enabled mines to reach full scale production and reduce costs drastically.

Results/Insights:

This study recommended real-time data monitoring systems to constantly monitor key system parameters. This method enables mines to detect any discrepancies or component failure within the system. It was also highlighted that real-time monitoring systems should communicate to automatic control applications. From this study it was concluded that a system that is controlled efficiently, can result in enormous electricity savings.

Shortcomings:

More did not focus on the development of an alternative dewatering control strategy in case of dewatering component failure. Simulation initiatives to develop automatic control strategies were also neglected from this study.

Further investigation was done into types of real-time monitoring systems that proved efficient in the past.

Study 13: Smith et al. (2015) [47]

Summary:

Smith compared savings of manual pump control to automatic pump control. He found that manual control resulted in the highest savings. However, Smith highlighted that manual pump control is not recommended due to the possibility of system exhaustion. Major maintenance initiatives had to be developed due to pump and column failure.

Results/Insights:

Smith proved that system automation is feasible for maintenance cost savings. He highlighted that automated system control eliminates human error and prevents system exhaustion due to the safety margins that can be automatically incorporated into the system. The most optimal control strategy can be applied through the automatic system control approach. Smith concluded that automatic system control results in a reduction in maintenance cost over an extended period of time.

Shortcomings:

This study focused mainly on cost saving initiatives and failed to consider a redundant system operation at all times. A method to develop and test an automatic control strategy was absent from this study.

Study 14: Oberholzer (2014) [48]

Summary:

Oberholzer conducted a study on the current best practices for automatic dewatering system control. He conducted a root cause analysis on system failure and developed revised system control parameters accordingly. These control parameters ensured all pumps operated within the design specifications.

Results/Insights:

Oberholzer achieved an electricity cost saving of R6 million through the developed interventions. This study concluded that system reliability is drastically improved through automated system control. From this study it can be concluded that automatic dewatering system control could lead to system component failure prevention.

Similar to study 10 that was conducted by Nell [43], the RCA technique was used to determine the reason for system failure. The RCA technique results in a clear indication of the root cause of faults or problems.

Shortcomings:

The main objective of this study was to improve established best practice procedures for pump automation. Oberholzer did not consider automation practices for other components that could also be controlled automatically. Correspondingly, only pump failure was considered, and an alternative dewatering control solution was deserted from this study.

Study 15: Velleman et al. (2012) [49]

Summary:

Velleman also investigated automated control strategies on dewatering systems. This study emphasised that flooding and pump cycling are some of the most frequent concerns that mining personnel have. Velleman considered automated control strategies with the main objective to reduce pump cycling.

Results/Insights:

This study highlighted the importance of an alarming system. The alarming system should notify the user immediately when the system performance deviates outside the stated limit of the

performance criteria. Velleman also considered the dynamic nature of fissure water that needs to be pumped out of the mine.

Through automated system control and appropriate alarm interventions, Velleman was able to control dam levels within the design specifications. He proved that automatic system control eliminates human error and reduces the risk of flooding. This study highlighted that the amount of water entering the mine should equal the amount of water that is removed from the mine. The importance of maintenance procedures in the form of regular reporting on the system performance was also highlighted by this study.

Shortcomings:

Velleman did not provide a method to test and predict the outcome of the automatic system control initiatives that were implemented.

Past literature regarding automatic dewatering system control provided valuable insight in several aspects. Some important theories obtained from previous studies are now discussed:

Underground mine pump operation is generally controlled based on the following parameters [31]:

- Maximum and minimum dam levels
- Number of pumps operating
- Control ranges

The maximum level of storage dams is controlled to prevent the dam from flooding and posing a risk to underground mine workers. The minimum level of storage dams is controlled to prevent the dam from drying out. As mentioned in Section 1.4, mud particles build up at the bottom of the storage dams due to inefficiencies in the settlers. If the dam level is too low, the mud may cause severe damage to pumps [31].

The number of pumps is controlled to prevent turbulent flow characteristics. Depending on the system configuration, different pumping strategies may be used to achieve the needed output. Control ranges are important to prevent pumps from starting and stopping more often than the design specifications state. This occurrence is called pump cycling [31]. Pump cycling may cause damage to pumps over time and result in unnecessary power usage.

From past literature conducted, it is evident that automatic system control is crucial in dewatering systems. From the reviewed studies, it was concluded that a few automatic system control

methods exist. Therefore, further investigation was done on current automatic system control methods.

Study 16: Peach et al. (2019) [50]

Summary:

Peach used simulation software to determine the impact of various control strategies on the whole integrated water reticulation system. He also utilised real-time data monitoring systems to obtain historical as well as real-time data of the current system performance. This data was used to build and calibrate a digital twin model of the water reticulation system.

Results/Insights:

This study used the supervisory control and data acquisition (SCADA) system to automatically control the system performance. Peach used PTB as simulation software and validated the simulation within 4.8% error. Annual savings of R4.4 million through several load shift initiatives that were developed and simulated was achieved.

It is evident from this study that through the use of simulation, several automatic control strategies can efficiently be developed and tested.

Shortcomings:

Peach developed and tested load shift initiatives with energy savings as the main objective. Component failure and the development of solutions to prevent the mine from flooding did not fall within the scope of this study.

Study 17: Alves de Araujo et al. (2021) [51]

Summary:

Alves de Araujo investigated new concepts to optimise power generation processes in a power plant using a digital twin and a SCADA system. The optimal system control was developed and mimicked on the digital twin to obtain a prediction of the proposed changes to the system.

Results/Insights:

This study proved the robustness of a digital twin with an average percentage error of less than 5% compared to the actual system performance. From this study it was highlighted that accurate

real-time data needs to be available at all times to maintain such an accurate digital twin model. It was also concluded that automatic system control can be optimised using a digital twin to test and verify several control strategies. Insight into the development of control strategies using a digital twin was obtained.

Shortcomings:

The developed method was only tested and implemented outside the mining industry on a water-cooling system of a power station.

Study 18: Taljaard et al. (2018) [52]

Summary:

Taljaard conducted a comprehensive study on different mine dewatering control systems. This study provided a methodology to determine the most efficient dewatering control system to use in deep level mines. The following control systems were evaluated and compared:

- Control using programmable logic controllers (PLCs).
- Control using supervisory control and data acquisition (SCADA) integrated with PLC control.
- Third party control software like real-time energy management system (REMS).

Results/Insights:

This study highlights the importance of components operating within their design specifications. Taljaard recommends the use of automation control software to ensure all components are operating within the design specifications. He concluded that third-party control software like REMS, resulted in the optimal choice of control system for complex dewatering systems consisting of several dewatering components that need to be integrated into the control [52]. REMS is an integrated system between SCADA and underground PLCs.

REMS connects to the mine SCADA system to read the pumping parameters. These parameters are then managed according to the algorithm responsible for pump control. The algorithm output is sent back to the mine's SCADA from where the pumps are controlled [48], [53].

When reviewing Taljaard's study, it is clear that automatic control of dewatering systems has major advantages, such as the removal of human error, improved safety of underground workers, reduction in labour costs and cost savings through demand-side management (DSM) initiatives.

Shortcomings:

The main objective of this study was to determine the most effective automatic control method. A method to test and simulate the control initiative before implementation was not considered in this study.

From the literature evaluated, it was concluded that the decision-making process regarding different simulation packages, automatic control strategies and solution selection proved to be difficult in many instances. Decision making is an inevitable process when several different approaches to the identified problem exist. Therefore, investigation was done into decision-making strategies.

Study 19: Wei et al. (2021) [54]

Summary:

Wei [54] used a high-level analytic hierarchy process approach to make informed decisions on which wastewater treatment processes to select for the appropriate case study. The solution selection process was formulated around the goal, the system criteria, and technical indicators.

Results/Insights:

A scoring technique was used to allocate a total score for each possible scenario in close accordance with the identified criteria. The solution which resulted in the highest score proved to be the most optimal solution.

Shortcomings:

The method provided by Wei was not tested in the mining industry and a method to develop several solutions was absent from this study.

1.5.6 Implementation

Study 20: Joubert et al. (2016) [55]

Summary:

Joubert [55] covered the whole project management life cycle that was followed for many DSM projects, which included automated control projects.

Results/Insights:

Assuming that the control strategy development and evaluation phase were done, the following steps were recommended for implementing an automated control project:

1. Arrange a project kick-off meeting
2. Go through the induction process
3. Install relevant hardware
4. Chose and configure relevant software
5. Test and optimise control
6. Project commissioning
7. Project sign-off

Joubert also provided the performance assessment process after a project was implemented. This process was as follow:

1. Report on project performance
2. Review baseline
3. Compare actual performance to predicted performance (Validation)

Shortcomings:

Component failure and the development of alternative solutions to prevent flooding within a deep level mine did not fall within the scope of this study. However, Joubert highlighted the importance of project maintenance to ensure future sustainability. Therefore, further investigation was done into current maintenance practices.

Study 21: Grobbelaar (2014) [56]

Summary:

Grobbelaar [56] developed a maintenance procedure to improve the sustainability of DSM projects.

Results/Insights:

The maintenance procedure was divided into four main categories:

1. Data maintenance
2. Mechanical component maintenance

3. Control and instrumentation maintenance
4. Regular revised control parameters

It was concluded that regular reporting on the above-mentioned criteria is considered as a critical project phase to prevent future problems from arising. Through this method, alarming sections within the system can be identified immediately.

Shortcomings:

A method to develop alternative dewatering strategies including automatic control initiatives were absent from this study.

1.5.7 State of the art summary

The state of the art matrix provides a summary of the most appropriate literature that fell within the study boundaries. The shortcomings of each study are highlighted in red. From the studies evaluated, it is evident that there is enormous scope for energy savings within dewatering systems. However, little to no focus has been placed on a generic method to develop an alternative dewatering strategy that serves as redundancy in case of critical component failure. Limited literature regarding this topic clearly proved the need for this study. As seen from the state of art matrix in Table 3, limited research on critical component failure and flood prevention was found. Most shortcomings exist from past literature at these two boundaries.

Table 3: State of the art matrix

References	Date	Component failure	Automatic control	Control philosophy	Simulation	Flood prevention	Shortcomings
Vosloo et al. [10]	2008	x	✓	✓	x	x	Lack of solution redundancy
Pascoe et al. [31]	2019	✓	✓	✓	x	x	Breakdown of the simulation procedure neglected
Różkowski et al. [35]	2021	x	x	✓	✓	✓	Did not utilise automatic control strategies
Oosthuizen, [36]	2013	✓	✓	✓	x	x	Did not quantify the impact on the cooling system
Romero et al. [37]	2015	x	✓	✓	✓	x	Neglected system failure
Witthüser et al. [38]	2015	✓	x	x	✓	x	Did not integrate model into current system
Szczepinski, [39]	2019	✓	x	✓	✓	x	Failed to provide a solution development process
Maré, [40]	2017	x	x	✓	✓	x	Did not develop an alternative dewatering solution
Nell, [43]	2017	✓	x	x	✓	x	Focused only on compressed air simulations
Luo et al. [42]	2018	x	✓	✓	✓	x	Only implemented on compressed air systems
Bouwer, [45]	2004	x	✓	x	✓	x	Concentrated on simulation development only
More et al. [46]	2020	x	✓	✓	x	x	Failed to develop alternative solutions
Smith et al. [47]	2015	x	✓	✓	x	x	Failed to consider component failure solutions
Oberholzer, [48]	2014	x	✓	✓	x	x	Focused only on optimal system control
Velleman et al. [49]	2012	x	✓	✓	✓	x	Did not study component failure
Peach et al. [50]	2019	x	x	✓	✓	x	No alternative solutions developed
de Araujo et al. [51]	2021	x	✓	✓	✓	x	Method was tested only on a power station
Taljaard et al. [52]	2018	x	✓	x	✓	x	Did not develop several solutions
Wei et al. [54]	2021	✓	x	x	x	✓	Most optimal solution selection was the main focus
Joubert et al. [55]	2016	x	x	x	✓	x	Project management life cycle was the main focus
Grobbelaar, [56]	2014	x	x	x	✓	✓	Alternative dewatering strategies were absent

1.6 Problem statement

From the background formulated on dewatering systems, it was concluded that several risks arise due to deteriorating underground conditions. As explained previously, due to the continuous increase in depths of mines, several cooling systems are utilised to mitigate the heat load that is directly proportional to the increase in depth.

Several additional risks occur using these complex integrated cooling systems. These risks include component failure, flooding, and mine down time. The dewatering system is responsible for the removal of underground water to surface. When critical dewatering components fail, the whole integrated water reticulation system fails. It is therefore of utmost importance that an alternative dewatering solution is always available.

From the state of the art matrix in Table 3, it is clear that there is a need for the development of alternative dewatering strategies in case of dewatering component failure and flooding scenarios in deep-level mines.

1.7 Study objectives

Deep-level mines are continuously faced with several challenges that pose a safety threat to mine workers. Due to the large volumes of water that is used for underground purposes, the risk of flooding and mining down time escalates. Therefore, it is of utmost importance to maintain a water balance within a dewatering system.

Previous studies failed to provide a methodology that primarily focused on the development of an alternative dewatering strategy to prevent critical component failure within current dewatering systems. The deterioration of underground conditions will continue to scale in future. Inevitably the need exists to maintain redundancy within dewatering systems in case of unexpected component failure.

This study will therefore focus on the development of alternative dewatering strategies using simulation software with the main objective to prevent flooding in deep-level mines.

A breakdown of the study objective provides the following sub-objectives listed below:

1. Identify possible risks for component failure.
2. Develop and verify a simulation of the system.
3. Develop alternative dewatering strategies using simulation software.
4. Implement flood prevention strategy to maintain redundancy.

The findings from this study will provide a significant decrease in the possibility of flooding in case of unexpected component failures within mine dewatering systems.

1.8 Conclusion

This chapter provided background on mine water reticulation systems with all the challenges faced. The harsh mining environment was highlighted, and a clear problem statement was formulated. From the research done on water reticulation systems, it was clear that the dewatering part of a water reticulation system is of utmost importance in terms of underground safety.

Critical component failure within dewatering systems can lead to flooding, loss in production and dangerous working conditions. An in-depth investigation was done into the current dewatering strategy development processes with the main objective to prevent flooding within mines. Safety is considered a high priority in the mining industry and therefore it is important to maintain redundancy at all times.

The latter part of this chapter provided the findings of past studies regarding the control and development of current dewatering strategies. It was found that there is a gap in past literature regarding the process to follow to develop an alternative dewatering strategy in case of possible component failure. Most studies optimised dewatering systems to achieve energy savings but failed to provide a solution in cases where possible critical dewatering component failure was identified. A lack in redundant dewatering system development was identified. Therefore, the following chapter will utilise the relevant literature to develop a methodology that addresses the identified shortcomings.

CHAPTER 2: METHODOLOGY

2.1 Preamble

The literature analysis conducted in Chapter 1 forms the basis of this methodology. Chapter 1 evaluated past research that was done on optimal mine dewatering system design. Research was done in the following fields:

- Current practices to handle dewatering component failure scenarios
- Simulation practices used in the industry
- Automatic control of mine dewatering systems

To develop an alternative dewatering control philosophy that serves as redundancy is challenging due to the vast range of components that may typically fail within a dewatering system. Therefore, this is a generic approach on how to deal with possible component failure and adapt accordingly. Where past research failed to provide relevant information, new processes were developed by combining near-relevant approaches.

2.2 Breakdown of methodology

The first step in solving any problem, is to acknowledge that there is one. It is thus important to fully understand and evaluate current dewatering systems to identify possible risks. Therefore, Process 1 in Figure 6 entails obtaining the system information. The mining industry is known for its dynamic nature. Each dewatering system is unique and therefore it is important to obtain a critical understanding of the function of all the system components. This process also includes a critical component risk assessment.

Process 2 in Figure 6 entails the development of a digital twin with the system information obtained in Process 1. A digital twin is a direct simulation replica of the integrated system. From past literature, the use of a digital twin proved to be an efficient way to predict the outcome of system changes in the real world [40], [57]. Consequently, it is important to develop an accurate simulation of the current system to be able to accurately simulate the possible outcome of certain system changes.

The next sub-process of Process 2 is to verify the digital twin. This step is of utmost importance to ensure accurate and trustworthy simulation results. Verification is done by comparing the simulation results to actual system data. Past literature concluded that simulations need to be verified within 10% accuracy when compared to the current system [40]. The simulation error can

be obtained by comparison between the average value of the real-time data, and the average value of the simulated data over a 24-hour time period. Visual comparisons by means of plotting the data profiles must also be used to highlight deviations during the 24-hour time period as suggested by Maré [40] in Section 1.5.4. If the simulation results in an error greater than 10%, calibration should be done.

Process 3 in Figure 6 entails the development of possible alternative dewatering strategies. A root cause analysis followed by the identification of the system constraints are included in this phase of the methodology. The digital twin developed in Process 2 is used to test several possible solutions to the identified risks in Process 1.

Process 4 in Figure 6 entails evaluating the best solution. This process includes the system constraint evaluation of the possible identified solutions in Process 3. During this process, the simulation results of all possible solutions are evaluated and compared. A detailed cost analysis approach is also provided to determine the feasibility of the solution.

Process 5 in Figure 6 entails implementing the best solution identified in Process 4. This process covers the entire project lifecycle. After the implementation phase has proceeded, the simulation results obtained from Process 4 need to be validated. This is done by comparing the actual implemented results to the predicted results obtained from the digital twin.

Figure 6 provides an exploded view of the developed methodology:

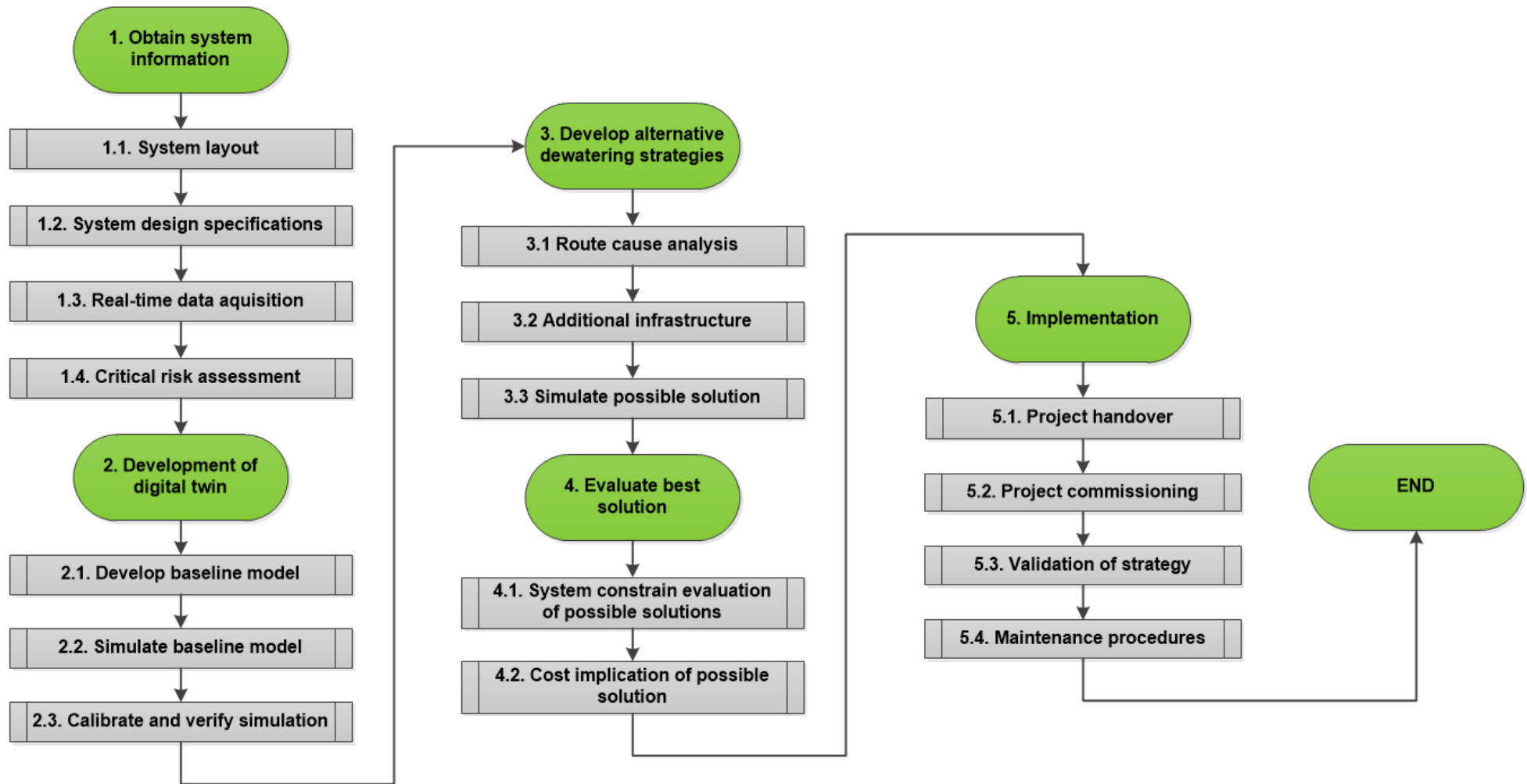


Figure 6: Exploded view of complete methodology

2.3 Process 1: Obtain system information

This step of this methodology aims to address the first sub-objective of this study namely: Identify possible risks for component failure.

As proposed in Section 1.5.4 of the report, Maré [40] recommended that the first step in understanding a system is to obtain the system layout (Process 1.1). The goal of this step is to understand the interaction between the integrated water reticulation system and dewatering components, as well as the collection of all the necessary and critical information of the system.

Figure 7 presents a visual breakdown of Process 1:

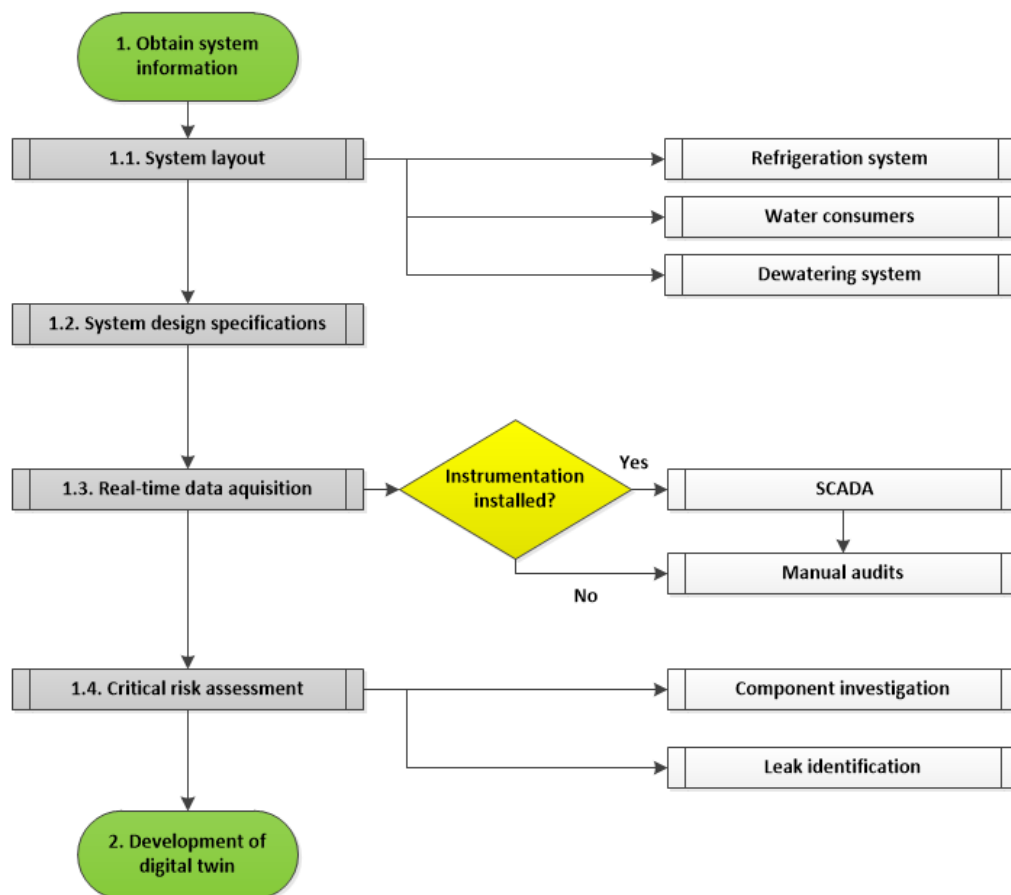


Figure 7: Obtain system information breakdown (Process 1)

Process 1.1 will generally entail:

- a site walkthrough,
- becoming familiarised with the current system, and
- obtaining access to site data.

The system layout includes the layout of the water reticulation system in drawing exchange format (DXF) and the locations of all main components. Section 1.5.3 proved that an efficient way of obtaining an understanding of an integrated system.

The location of the following components within a water reticulation system should be taken note off:

- Refrigeration plants and BACs
- Chilled water consumers
- The dewatering components which include settlers, pumps, dams, pipes, and valves.

Recalling from Section 1.5.3, it is crucial that the main dewatering components operate within the design specifications. Therefore, Process 1.2 entails gathering critical component design specifications, pumping criteria, valve limitations and the quantity of water that needs to be dewatered.

The main components within dewatering systems have unique design specifications. This information can be gathered from manual mine audits and data acquisition packages installed on the mine. It is important to note, due to the uniqueness of each mine, the design specification will most likely differ between case studies. Table 4 provides the general design specifications required in Process 1.2:

Table 4: Component design specifications [53]

Components	Parameter	Unit
Settlers	Capacity	<i>l</i>
Pumps	Power Head Flow Efficiency	<i>kW</i> <i>m</i> <i>l/s</i> <i>%</i>
Pipes	Diameter Length	<i>mm</i> <i>m</i>
Dams	Volume Maximum level Minimum level Elevation	<i>Ml</i> <i>%</i> <i>%</i> <i>m</i>
Valves	Type Pressure	— <i>kPa</i>

After gathering the system layout and component design specifications, historical performance data as well as real-time data of all main components need to be obtained (Process 1.3). Previous studies proved that there are a few effective data acquisition strategies in practice which were discussed in Section 1.5.5.

Most of the mines have digital real-time data available from SCADA systems [52]. It is important to obtain access to these data systems because this data will form the baseline of the simulation that will be developed in Process 2 of this methodology. Each component has a given address by which it can be identified on the SCADA system. This address is known as a tag name. The tag name of each component should also be identified.

It is of utmost importance to validate the real-time data. This can be done by comparing the manual underground data to the real-time data. All instrumentation should be verified within 10% accuracy. Calibration should be arranged for instrumentation that proves to be inaccurate. In cases where data acquisition packages like SCADA are not present on the mine, manual data audits should proceed. Measuring equipment like ultrasonic flow meters, pressure logging devices and temperature sensors with data logging capabilities, must be installed at the desired locations to record measurements [21].

With the knowledge obtained up to this point, focus can be shifted to problem identification. Process 1.4 includes familiarisation with the current problems that the mine experiences within the dewatering system. Recalling from Section 1.5.3 the most common challenges within dewatering systems include pump failure, insufficient pumping head and column failure due to the harsh mining environment.

As mentioned previously, manual mine audits must be done to understand the system better. Any individual working on a mine will testify that one only understands a system if one has manually inspected it. Section 1.5.3 suggested that regular water leaks are a good indication of possible column failure and enable one to pinpoint problem areas within the dewatering system. A typical leak identification audit table is displayed in Table 5.

Table 5: Leak identification audit example [21]

Leak	Location	Description	Leak flow [l/s]
1	69L, North 8 X/C	Flange leak	2
2	69L, South 3A X/C	Hole in pipe	4
3	71L, South Split	T-Piece leak	3

2.4 Process 2: Development of digital twin

The second step of this methodology aims to address the second objective set for this study namely: To develop and verify a digital twin of the current system.

Section 1.5.4 highlighted critical tools such as simulation software that can be used to accurately predict the outcome of changes to real-world systems. After reviewing the comprehensive studies that were discussed in Section 1.5.4, Process toolbox (PTB) was selected as the simulation software for this study due to the accessibility thereof. PTB proved to be an efficient simulation program to use in numerous studies that were reviewed in Section 1.5.4.

There are several approaches for the development of accurate integrated simulations, also discussed in Section 1.5.4. These approaches are combined to satisfy the objectives set for this study. Figure 8 provides an exploded view of Process 2.

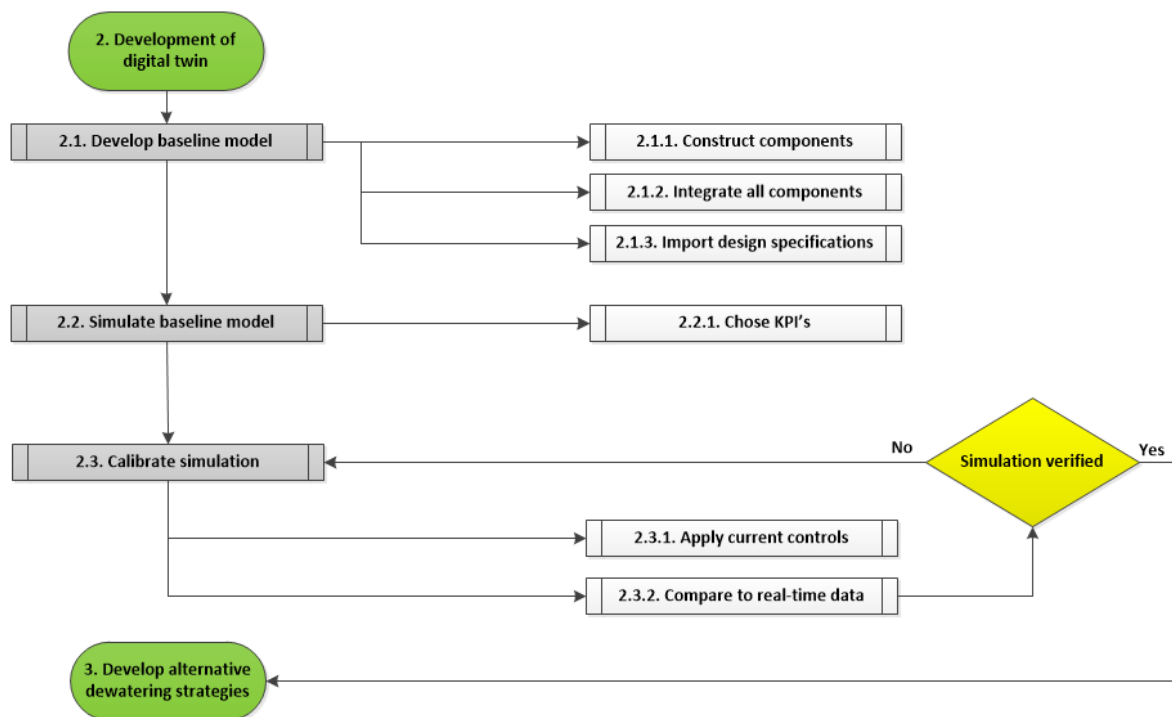


Figure 8: Development of digital twin breakdown (Process 2)

Recalling from Section 1.5.4, the first step to develop a digital twin is to develop the baseline model (Process 2.1). The baseline model is a simulation-based replica of the current system.

Process 2.1.1 entails the construction of all components. These components include pumps, dams, pipelines, settlers and valves. Each component needs to be inserted at the correct location as indicated on the DXF layouts obtained in Process 1.1.

After all components have been constructed in the simulation, Process 2.1.2 may commence. This involves the integration of all components. Integration is achieved by connecting all component nodes in the correct flow direction. After the integration process, the baseline simulation model should represent the actual dewatering system.

The following step, Process 2.1.3, entails importing all the component design specifications into the simulation. This step is of utmost importance to ensure the simulation is truly a direct replica of the actual system.

The next step is to simulate the initial simulation model to ensure all components are connected and to verify that the simulation procedure runs without any errors (Process 2.2). It is important to simulate the model on a regular basis to prevent errors from appearing within the simulation.

Before the simulation results can be compared to actual data, key performance indicators (KPIs) should be identified (Process 2.2.1). Literature highlighted that flow profiles, temperature profiles and dam volume profiles proved to be good KPIs to consider [40]. These KPIs will be used to verify if the simulation accurately reflects the operation of the actual system.

The next step of this methodology, the verification step, is crucial to prove that the simulation developed is accurate and trustworthy.

Process 2.3.1 is to apply the current controls of the system to the simulation. These controls include pump schedules, valve statuses, and dam levels. Section 1.5.4 highlighted that the simulation may be regarded as accurate if the simulation results deviate with a maximum of 10% from the actual system performance results. If Process 2.1 and Process 2.2 were performed with high accuracy, the simulation output should match the real-time data with small deviations.

Process 2.3.2 entails evaluating each KPI in the simulation and comparing the simulation data to real-time data obtained from the Mine's SCADA system or manual audits. When the simulation results correspond within the 10% error range, the simulation is verified and is deemed as a digital twin of the current system.

2.5 Process 3: Develop alternative dewatering strategies

The third step of this methodology aims to address the third objective set for this study, namely: To develop an alternative dewatering strategy using simulation software.

At this point in time, the case study system should be fully understood and a crucial engineering tool, namely, a digital twin of the actual system, has been developed. During the “obtain system

information” phase of this methodology (Process 1), a critical risk assessment (Process 1.4) was done. If Process 1.4 resulted in no possible risks identified, the rest of this methodology would be irrelevant.

In cases where Process 1.4 resulted in possible risks identified, Process 3 must commence. Process 3 aims to address the shortcomings identified in literature, namely, the development of alternative failsafe dewatering strategies using simulation software.

Figure 9 illustrates the exploded view of the “develop alternative dewatering strategies” part of this methodology:

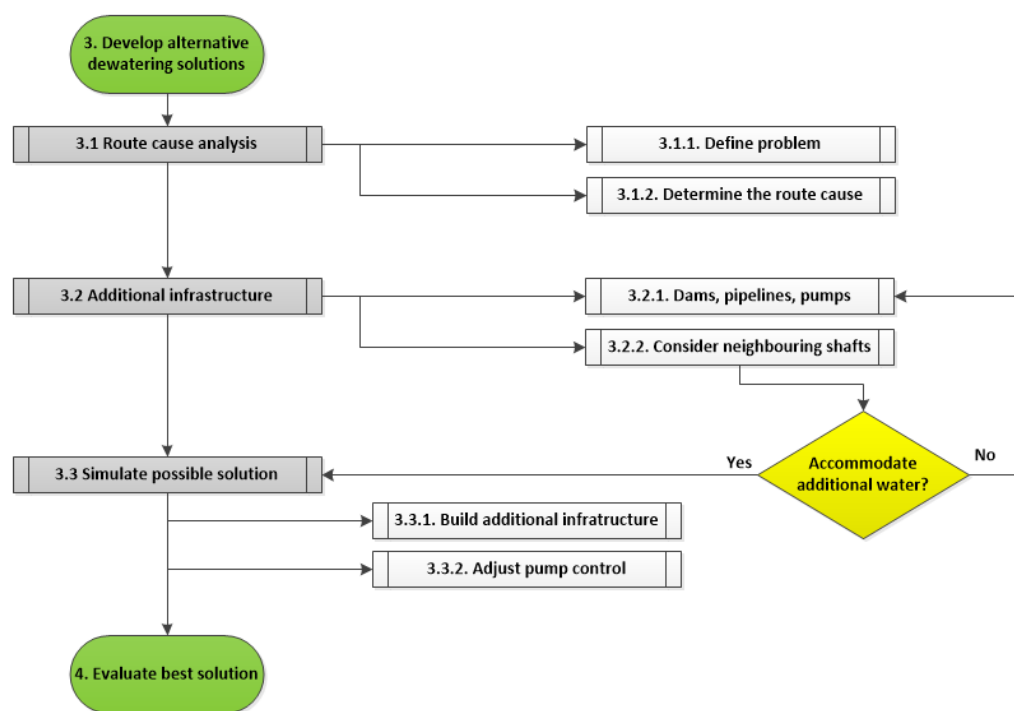


Figure 9: Develop alternative solutions breakdown (Process 3)

Past literature discussed in Section 1.5.4 highlighted the effectiveness of the root cause analysis method to determine the origin of inefficiencies and component failure within integrated systems. Therefore, Process 3.1 entails performing a root cause analysis by continuously asking the question “why” to determine the root cause of the problem.

Firstly, the identified problem needs to be fully defined (Process 3.1.1). To define a problem efficiently, an in-depth inspection needs to be performed. After the problem has been defined, and fully understood, the root cause needs to be determined (Process 3.1.2).

Nell [43] and Oberholzer [48] in Section 1.5.4 suggested the RCA approach to identify the root cause of problems. The “5 whys” approach is used with the aim to eliminate the reappearance of the problem. This will ensure that the focus will remain on the root cause of the problem. Figure 10 provides a simplified breakdown of the root cause analysis process:

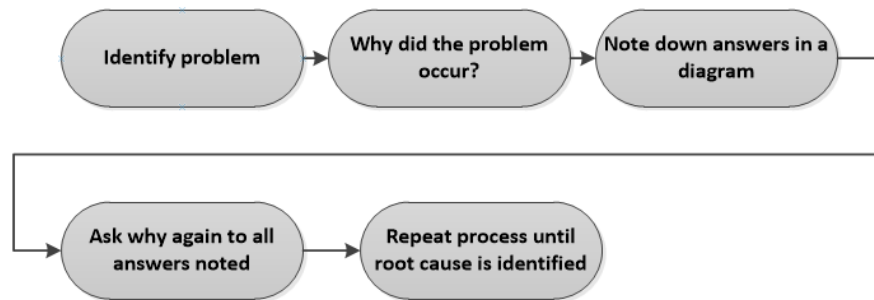


Figure 10: Root cause analysis process flowchart [43]

Once the root cause of the problem is identified, different possible solutions can be developed accordingly. The first step is to inspect additional infrastructure (Process 3.2).

The most common types of infrastructure to inspect are alternative storage dams, pipelines, and pumps (Process 3.2.1). The condition of such infrastructure should also be inspected to prevent future problems from arising.

Previous studies discussed in Section 1.5.3 proved that water distribution between neighbouring shafts could also be a temporary feasible option in case of dewatering component failure. Therefore, Process 3.2.2 includes the investigation process that needs to be done to determine if dumping water to neighbouring shafts could be feasible. The following investigation procedure should be followed to make an informed decision:

1. Determine if there are available pipelines to the nearest neighbouring shaft.
2. Investigate the physical condition of the existing pipelines if there are any.
3. Determine what quantity of water the neighbouring shaft is capable of handling.

In cases where no pipelines are available to the neighbouring shaft, a cost analysis should be done to determine the feasibility of implementing new pipelines. If the neighbouring shaft is limited to accommodate additional water, Process 3.2.1 should be reiterated.

The next step is to simulate the possible identified solutions, to predict the outcome of the system changes (Process 3.3). All additional infrastructure should be built into the digital twin model that was developed in Process 2. This includes dams, pipelines, and pumps at the exact location

underground. All components must be linked, and the simulation should execute without any errors (Process 3.3.1).

Once the digital twin simulates without any error, the pump controls can be adjusted. The pump controls can be determined by implementing the current control limits, system parameters, dam levels and equipment limitations (Process 3.3.2). When simulating each scenario, the control parameters used in the simulation should be stated clearly. This can be done by setting up a control parameter table as illustrated in Table 6:

Table 6: Control parameter table

Valve	Valve position	KPI parameter
A	Open	= x %
	Closed	= x %
B	Open	= x %
	Closed	= x %
C	Open	= x %
	Closed	= x %
Pump	Pump status	KPI parameter
1	Start	= x %
	Stop	= x %
2	Start	= x %
	Stop	= x %
3	Start	= x %
	Stop	= x %

The pump controls and set points will differ from each identified possible solution. Each scenario must be simulated through an iterative process, until a satisfactory output is achieved.

2.6 Process 4: Evaluate best solution

It is important to recall the last and most important objective set for this study, namely: Choose and implement revised dewatering strategy to maintain redundancy. Process 4 involves an evaluation process to determine which developed solution satisfies this objective.

Figure 11 illustrates the evaluation of the best solution process:

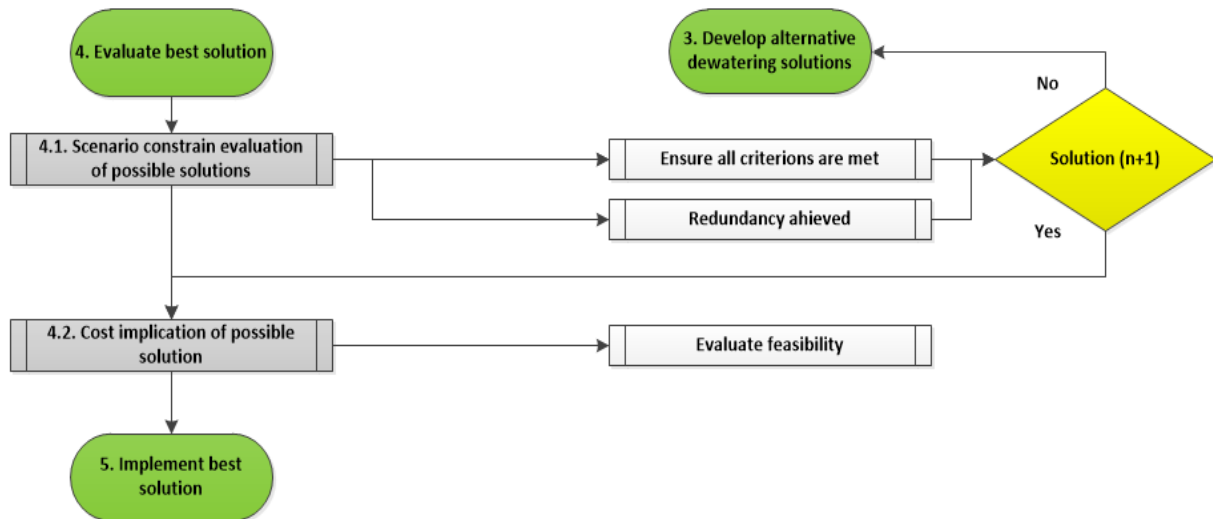


Figure 11: Evaluate best solution breakdown (Process 4)

After each possible solution has been simulated, the simulation outputs need to be compared to the system criteria that were obtained in Process 1.2. It is of utmost importance that all criteria are met to ensure safe operation of equipment and infrastructure (Process 4.1).

If the simulation output of the possible solution is unsatisfactory, the control strategy should be adjusted and re-simulated until all system criteria are met. Scenarios that fall short in satisfying all system criteria should be discarded and alternative options must be developed.

It is important to compare the chosen baseline KPIs in Process 2.2.2 to the new simulation profiles of each possible solution. This includes dam level profiles and flow profiles to ensure the new solution won't deviate from the safety limits set for all components. It is also important to always maintain the water balance as discussed in Section 1.5.3.

The above-mentioned processes should be performed for each possible solution simulated in Process 3.3. A simulation constraint table can be used to directly compare the simulation outputs of all scenarios to each other. Recalling from Process 1.2, certain system design specifications, or system criteria have been identified. These system criteria should be listed as follows:

- Criteria 1 – Storage dam A level should not exceed 85%
- Criteria 2 – Storage dam A level should not descend below 50%
- Criteria 3 – “X” amount of water should be dewatered

A scoring technique can be used to determine the best suitable solution as stated in Section 1.5.5. The simplified scoring technique entails allocating a score of one when a certain stated

requirement is met and allocating a score of zero when the scenario fails to meet the requirement. Table 7 illustrates an example of a simulation constraint table.

Table 7: Simulation constraint table example

Requirement	Scenario A	Scenario B
Criteria 1	0	1
Criteria 2	1	1
Criteria 3	0	1
Total	1	3

From Table 7 it is clear that Scenario B satisfied all the system criteria and received the highest score. It is therefore obvious that Scenario B resulted in the best possible solution in this example. Once the possible solution is identified, Process 4.2 must commence.

Process 4.2.1 includes the cost analysis of the possible solution. All additional infrastructure should be listed, and a complete bill of materials (BOM) should be obtained and supplied to the mine. If more than one possible solution satisfied all the criteria, the cost analysis should be used to determine the feasibility of each solution. The decision should be made based on the feasibility findings.

2.7 Process 5: Implementation

The final step of this methodology is the project implementation step. During this step, the developed solutions are proposed to the management department of the mine. It is of utmost importance to clearly explain all limitations and constraints to the mine before the project is implemented and signed off to prevent unforeseen errors from occurring.

When the proposed solution is approved by all relevant parties at the mine, the physical implementation must commence. The following implementation procedure illustrated in Figure 12 was developed through manipulating the project implementation procedure that was discussed in Section 1.5.6 to suit this specific study.

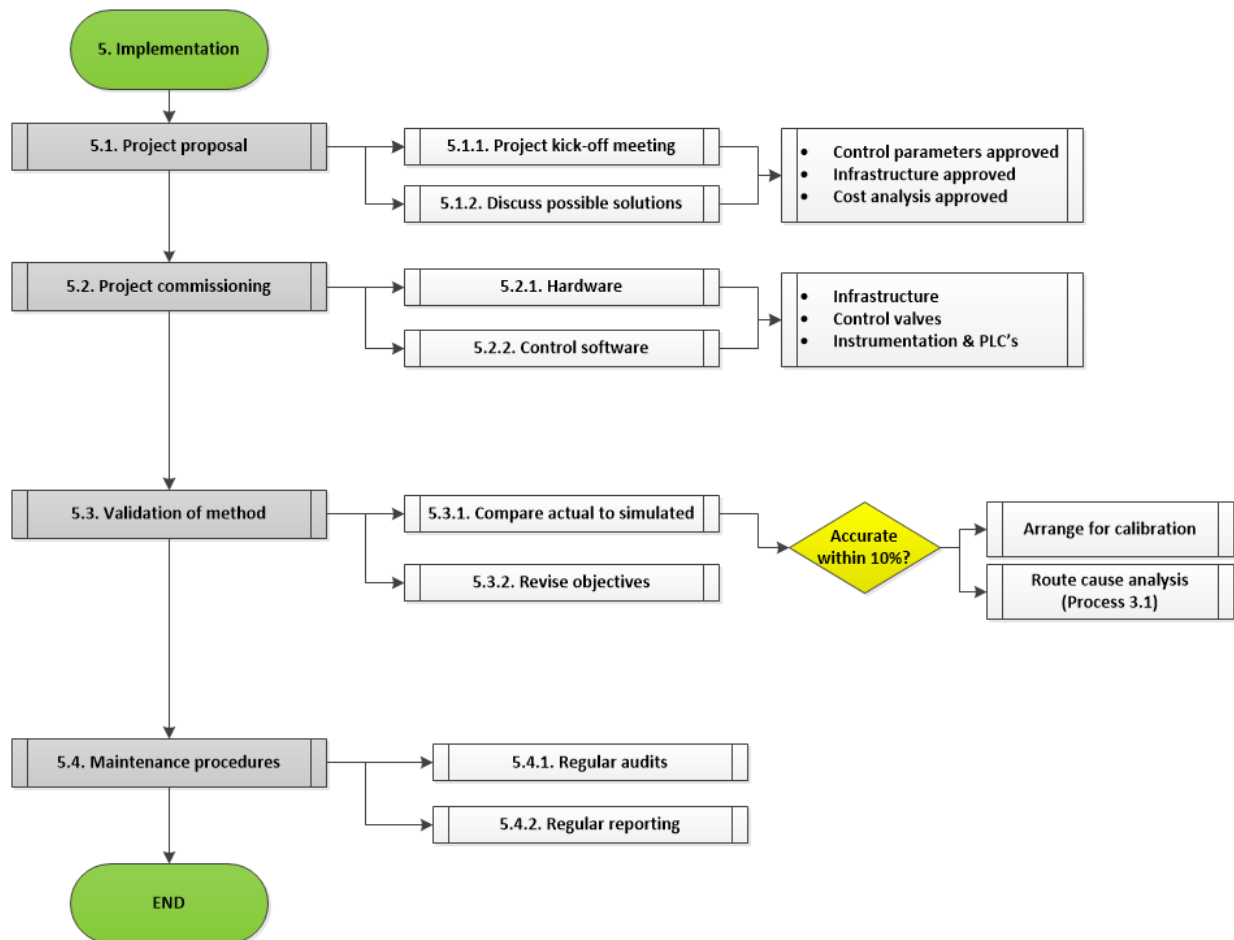


Figure 12: Implementation breakdown (Process 5)

Process 5.1 entails presenting the proposed solution developed in Process 3 to the mine. The first sub procedure in this phase is to arrange a project kick-off meeting with all relevant mining personnel (Process 5.1.1). These personnel include engineers, mine managers, general managers, and mining foremen. During the kick-off meeting, it is important to clearly illustrate that the problem was well understood before the solutions were developed.

All possible solutions need to be presented in fine detail to the meeting audience, highlighting all limitations and constraints (Process 5.1.2). A detailed breakdown of all additional infrastructure, which includes a bill of materials, must be provided to the mine. The proposed control philosophy should also be explained in detail, emphasising the main KPIs and control parameters identified in Process 2.2. The final important factor to discuss with the meeting audience is the expected cost analysis of the proposed solution.

The above-mentioned documentation should be approved by all upper management of the mine before the next step may commence. The development of alternative dewatering solutions

process (Process 3) must be reiterated in scenarios where some members prove to be doubtful in the proposed solution.

Project commissioning is the next step (Process 5.2). The applicable mine is fully responsible for the implementation of the approved equipment and components. However, it is important to investigate and report on the progress regarding the implementation of all additional equipment.

Process 5.2.1 considers the implementation of all hardware. This includes pipelines, dams, valves, and pumps. Regular inspection should be done to ensure all hardware specifications comply with the proposed hardware specifications. Pipe and pump sizes, locations and valve types are examples of these hardware specifications.

Process 5.2.2 requires reviewing the automatic control strategies discussed in Section 1.5.5. Most modern mines already make use of data acquisition packages like SCADA due to the enormous benefit thereof. Recalling from Section 1.5.5, most data acquisition packages used in the industry can also be used to automatically control several system components.

The importance of automatic control of dewatering systems was noted from numerous studies discussed in Section 1.5.5. It is important to note that mines that still utilise manual control methods only, are not applicable to this study. During this sub procedure, inspection should be done to ensure the control software and PLCs are in good operational condition.

As concluded from the study conducted by Taljaard [52] in Section 1.5.5, REMS proved to be the most optimal control system package used for complex dewatering systems. Therefore, REMS was considered as the automatic control strategy for this study. REMS has also already been implemented on numerous mines in South Africa. There are many benefits of using REMS that was substantiated by literature [21], [52]:

- Full automation of system components.
- Condition monitoring of components (for example pump running statuses, valve positions, dam levels and vibration of equipment).
- Alarms can be set to monitor the KPIs of the system.
- Human error is eliminated from the control equation.

Process 5.2.2 includes the physical programming of the simulated control parameters into the applicable REMS controllers. These parameters include pump control, pressure setpoints, dam levels, and valve positions.

Process 5.3.1 includes comparing the actual data received from the verified instrumentation (Process 1.3) to the predicted simulated data from the developed simulation in Process 4. Recalling from Section 1.5.4 a simulation is deemed accurate when verified within 10% of the actual system. In scenarios where the simulation proves to be inaccurate, the RCA method (Process 3.1) should be performed to determine the reason for the deviation.

The final crucial step in validating this method, entails revising the sub-objectives or outcomes set in Section 1.7 (Process 5.3.2). These sub-objectives include:

1. Identifying possible risks for component failure.
2. Develop and verify a simulation of the current system.
3. Develop alternative dewatering strategies through the use of simulation software.
4. Implement flood prevention strategy to maintain redundancy.

The main outcome of this study is to lower the risk of flooding within the mine by maintaining redundancy. This objective was formulated in Section 1.5 by identifying the shortcomings in past literature conducted. The first three objectives need to be achieved before the final and most important objective can be reached. The first three objectives serve as “tools” that can be used to achieve the final objective.

Redundancy is referred to as an alternative option in case of critical component failure. A revised definition of redundancy can be expressed as a plan B when plan A fails. Therefore, Process 5.3.3 entails ensuring a fail-safe plan B is in place in case of critical component failure within the current dewatering strategy.

The last step must be performed on a constant basis throughout the life of mine (LOM). Past literature concluded that maintenance procedures should be in place to prevent future system failure (Process 5.4). From the background formulated in Section 1.2, it is evident that gold mines are constantly expanding due to the increase in mineral consumption throughout the globe. In addition to this, system changes are unpreventable.

Process 5.4.1 entails conducting manual audits when the real-time monitoring instrumentation provides data that seems suspicious. Through this method, the real-time data can be verified on a regular basis.

The final critical step (Process 5.4.2) in the maintenance phase, entails reporting on the dewatering system to create awareness. Regular reporting on the system status will ensure fast

response when sudden system changes occur. Fast response to possible problems identified will also lead to the decrease in probability of critical system failure.

2.8 Summary

A methodology was developed to prevent flooding within deep-level mines by maintaining redundancy within the dewatering system. The developed methodology consists of a combination of the best current approaches that proved to be effective in past literature presented in Section 1.5, to achieve the study objectives formulated in Section 1.7. This method also aims to address the shortcomings identified from previous studies. The five-process methodology is applicable to any deep-level mine with an automated dewatering system.

The presented method covers the entire process to follow, from baselining a dewatering system to implementing and maintaining the solution. The method entails developing a thermohydraulic simulation which serves as a direct replica of the current system (digital twin). General guidelines were given on how to use the digital twin to develop alternative dewatering solutions to de-risk the mine.

The latter part of this method describes the solution evaluation process as well as implementation and maintenance procedures that need to be followed to ensure successful operation. The next chapter applies the method to a relevant case study where an integrated dewatering system was present. The results are discussed, and the method is verified and validated.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Preamble

A methodology to develop alternative dewatering strategies to reduce flooding in case of component failure was proposed in Chapter 2. The methodology included an in-depth discussion on the processes to follow to identify possible component failure and to develop a solution accordingly using simulation software. These processes included developing a baseline simulation of the current system. From the baseline model, different strategies were developed and simulated to predict the outcome of real-world system changes.

This chapter will apply the 5-process method developed in Chapter 2 to a real-world case study. The case study was selected in close accordance with the study objectives to ensure it provided enough scope to verify and validate the developed methodology.

Recalling from Section 1.7 the developed methodology aims to address the following objectives formulated from the shortcomings identified in past literature evaluated in Section 1.5.

1. Identifying possible risks for component failure.
2. Develop and verify a simulation of the current system.
3. Develop alternative dewatering strategies through the use of simulation software.
4. Implement flood prevention strategy to maintain redundancy.

3.2 Case study background

The methodology developed in Chapter 2 was applied on a deep-level gold mine's dewatering system situated in South Africa. The case study mine formed part of an integrated mining complex consisting of two neighbouring shafts. The water used for mining purposes at the case study mine was pumped to one of the neighbouring shafts where the water was removed from underground.

During case study inspection, it was found that the case study mine had to stop production for a total of eight days due to water pipeline failure. This loss in production amounted to an estimated loss in revenue of R30 million for the 2019 financial year. Further inspection was done regarding the pipeline failure. It was found that the case study mine had only one dewatering column to the neighbouring shaft. This dewatering column has been in use for many years and was deteriorating due to the harsh mining environment. Figure 13 illustrates the failing dewatering column captured during the inspection in the return airway (RAW) haulage.



Figure 13: Failing RAW pipeline⁶

Considering the loss in revenue for the 2019 financial year, and the failing dewatering column that was noted during inspection, it can be concluded that this case study provided enough scope to test the functionality of the developed methodology in Chapter 2.

3.3 Process 1: Obtain system information

3.3.1 System layout

Process 1.1 entailed the familiarisation with the case study operation to obtain a better understanding of the system. For the purpose of this study, the mine used as case study is referred to as Mine A. Mine A forms part of an integrated mining complex consisting of two neighbouring shafts. These neighbouring shafts are referred to as Mine B and Mine C respectively.

Mine A and Mine B form part of a dependant integrated mining operation. Mine B is basically an ore hoisting shaft for Mine A. Meaning all the ore extracted at Mine A gets distributed through the Railveyor to Mine B and hoisted to surface. The Railveyor is an ore train that runs between Mine A and Mine B. Mine A only dewateres to Mine B using a single dewatering column known as

⁶ A. Nell, Personal Photo, 2021

the RAW line (Point 1 in Figure 14). Through case study investigation it was concluded that the RAW pipeline fails on a regular basis due to its poor condition (Point 2 in Figure 14).

Through on-site investigations it was also found that Mine A utilises surface ice plants as refrigeration units (Point 3 in Figure 14). The working principle of ice plants can be found in Appendix A. The total amount of ice produced by the ice plants during full production periods amounts to 3 200 tons of ice per day. The ice produced on surface, is gravity fed into an ice dam (Point 4 in Figure 14) situated between 55 level (55L) and 59 level (59L). From the ice dam, chilled water is distributed to the mining block (Point 5 in Figure 14).

At Mine A, mining activities take place on 66L, 69L, 71L, 73L and 75L. After the chilled water has been utilised in the mining block, it is channelled back into the settlers situated on 77L (Point 6 in Figure 14). Mine A also makes use of mobile cooling units (MCUs) which utilise chilled water supplied by the ice dam. The working principle of mobile cooling units can be found in Appendix A. Fissure water also adds to the amount of water that enters the settlers. From the 77L settlers, water is pumped from the 77L pump station, in a controlled manner between the ice dam and Mine B through the RAW pipeline. The current control strategy is discussed in Section 3.4.3.

As mentioned previously, Mine A's dewatering system is integrated between two neighbouring shafts namely Mine B and Mine C. Mine B is the preferred option to dewater to due to the large quantity of water that can be handled at Mine B. There is also a Reverse Osmosis plant at Mine B where the used water is filtered and then reused at mining hostels.

Mine C forms part of the integrated mining complex but is independent of Mine A and Mine B. Mine A and Mine C are connected with a dewatering column on 66L (Point 7 in Figure 14) that is used when dewatering system failure occurs at one of the mines. This is not a sustainable solution because this pipeline can only be used to prevent the affected mine from flooding for a short period of time.

As recommended in Process 1.1, DXF layouts were obtained from the mine surveyor department and can be found in Appendix C. The locations of each dewatering component are clearly illustrated of the DXF files. There is an underground BAC with fridge plants and condenser ponds situated on 55L. This refrigeration circuit operates as a closed loop system and is independent of the dewatering system. Therefore, the 55L refrigeration system was excluded from this study. Figure 14 represents a schematic illustration of the dewatering layout at Mine A:

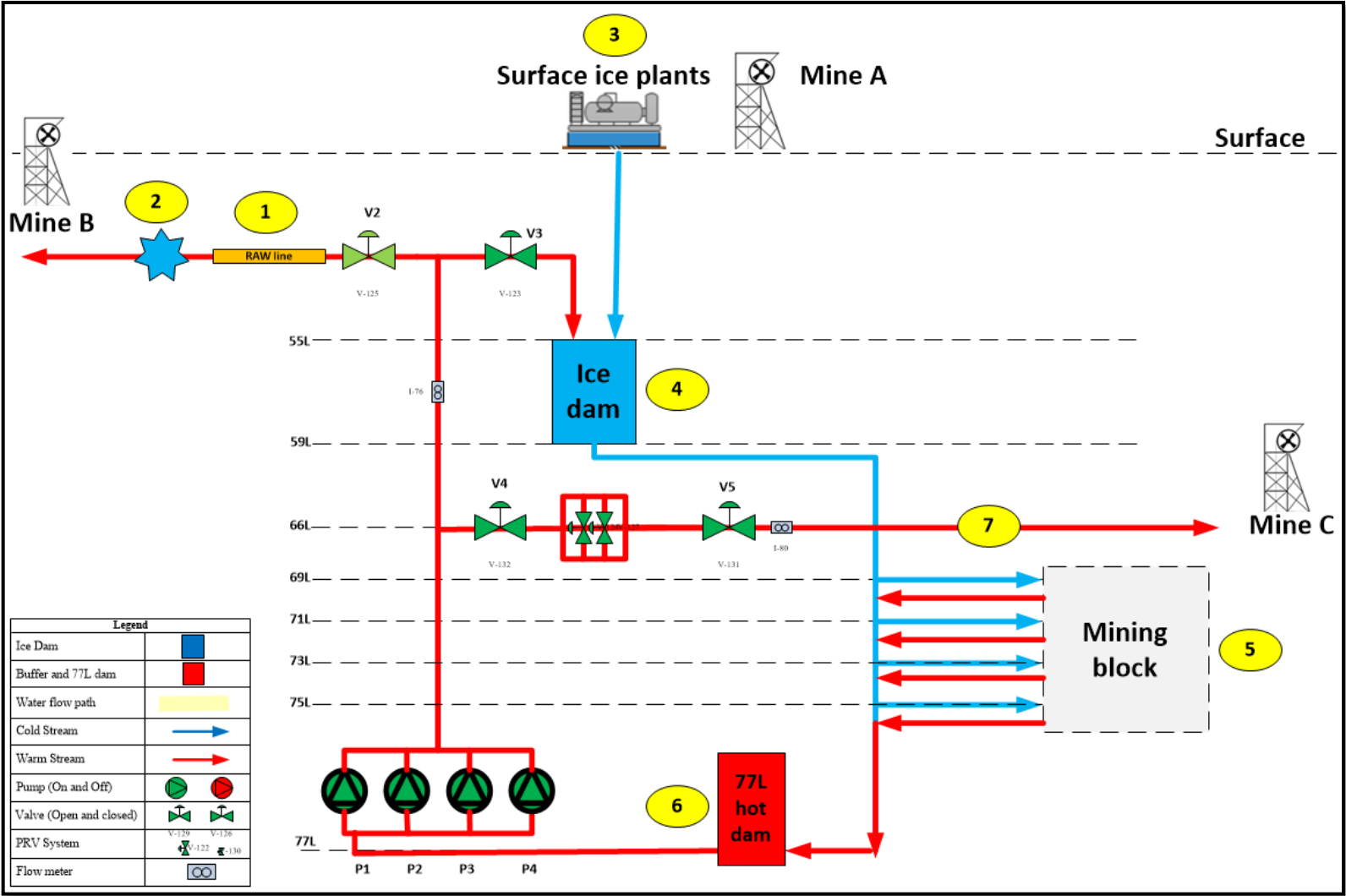


Figure 14: Case study water reticulation system schematic illustration

3.3.2 System design specifications

Process 1.2 entailed the gathering of critical component design specifications, pumping criteria, valve limitations and the quantity of water that needs to be dewatered. This information was provided by the Engineers on site. The different dam specifications are summarised in Table 8.

Table 8: Case study dam design specifications

Name	Location	Volume [m ³]	Top elevation [m]	Bottom elevation [m]	Maximum level [%]	Minimum level [%]
Ice dam	55L - 59L	2 350	- 2 150	- 2 271	83	55
Buffer dam	55L	1 000	- 2 153	- 2 154	90	30
Settlers	77L	780	- 2 845	- 2 851	80	30

Note that the buffer does not form part of the current dewatering system but is situated on 55L. The buffer dam was disconnected from the original dewatering system but is in a usable condition if needed. However, before the dam can be utilised, an effective dewatering control methodology needs to be developed.

The next important components to consider were the pumps used in the dewatering system. The values were obtained on the SCADA system as well as attending meetings with mine personnel. The pump design specifications are summarised in Table 9.

Table 9: Case study pump design specifications

Level	Pump	Power output [kW]	Flow rate [l/s]
77L	1	1 200	200
	2	1 200	200
	3	1 200	200
	4	1 200	200

Upon investigation of the chilled water consumers of the mine, it was found that the mobile cooling units (cooling cars) were the main chilled water consumers. The chilled water used for mining purposes, like water spraying and drilling, contributes to the excess water that is present on the ground. Fissure water that seeps through the rocks also contribute to this excess water. This water is channelled through the haulages to the 77L settlers.

The quantity of the excess water present on the case study was determined through a simple water balance which is discussed in Section 3.3.3. Table 10 lists the total number of chilled water-consuming cooling units at each active mining haulage.

Table 10: Chilled water consuming cooling units

Location	Quantity
66L – 35 X/C	1
66L – 36 X/C	1
69L – 38 X/C	1
69L – 74 X/C	1
69L – 74 A X/C	1
69L – 75 X/C	1
71L – South development	1
73L – South development	1
73L – 37 X/C	1
73L – 38 X/C	1
75L – South development 1	1
75L – South Development 2	1
75L – 35 X/C	1
75L – 38 X/C	1
75L – 40 X/C	1
75L – 73 X/C	1
75L – 75 X/C	1
75L – North development	1
Total	18

The rated operating conditions of the cooling units are listed below:

- Design cooling duty of 500 kW
- Water flow rate of 10 l/s
- Water inlet temperature of 11°C
- Air flow rating of 11 kg/s at 25 °C dry-bulb temperature on 100% relative humidity
- 45 kW fan installed

3.3.3 Real-time data acquisition

The next step was the data acquisition phase (Process 1.3). Mine A makes use of a SCADA system that communicates with REMS to control the dewatering system. Access to Mine A's

SCADA system was also obtained to ensure easy accessibility to real-time system data. The relevant data of several critical components had been logged and these data parameters were readily available. Each data parameter is stored in a separate tag name as explained in Section 2.3. Figure 15 illustrates the tag names for the critical dewatering components on Mine A. Note that some of the naming convention is hidden due to the privacy policy of the case study mine.

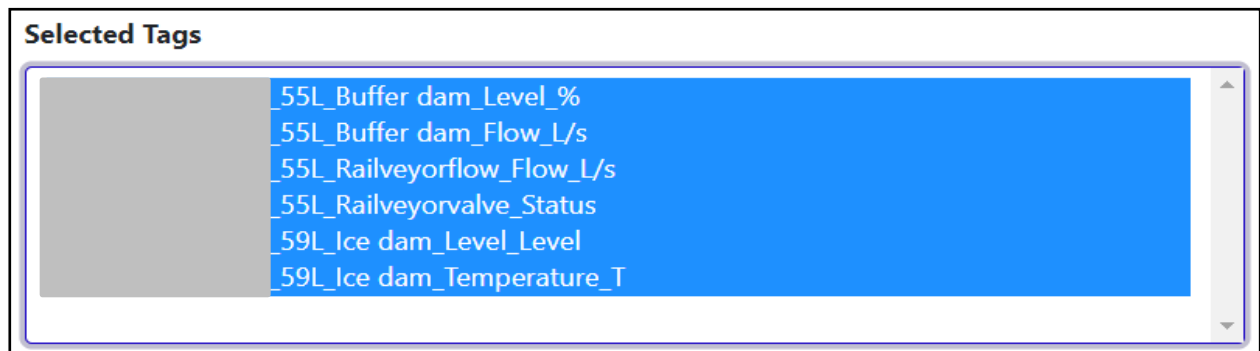


Figure 15: SCADA tag names

Manual audits for data acquisition purposes were unnecessary due to the accessibility of real-time SCADA data. However, manual audits were done to verify the installed instrumentation as suggested in Process 1.3. The average calculated error equalled to 4.3%. This result verified the instrumentation and proved that the real-time data was trustworthy. From evaluating the SCADA data sets, it was possible to determine the amount of additional water that was added to the underground system. This was done by comparing the amount of water that was sent down (in the form of ice) to the amount of water that was dewatered to Mine B. Note that the mass balance was done based on average data values obtained from the SCADA system. This mass balance is illustrated in Figure 16.

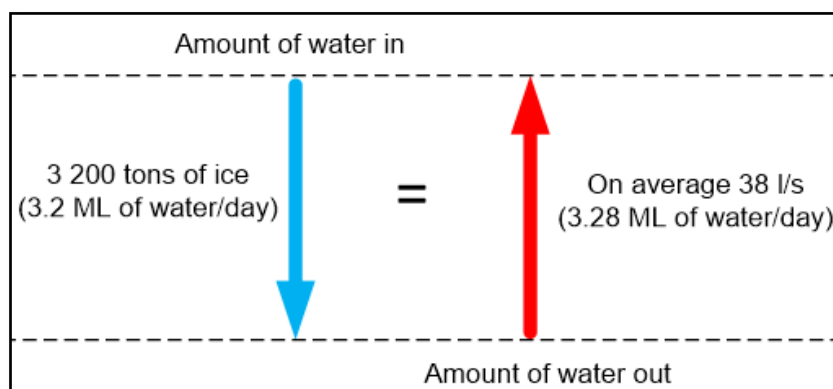


Figure 16: Dewatering mass balance

From the mass balance displayed in Figure 16, it is clear that there is an additional 0.08 ML of water that is dewatered to Mine B. This additional water is assumed to be fissure water for the purpose of this study. The identified additional water must be accounted for in the development of solutions section.

With all the critical information regarding the dewatering system of Mine A gathered and complete familiarity of the system operation gained, the problem identification phase could commence.

3.3.4 Critical risk assessment

During manual audits and in-depth system inspection as recommended by Process 1.4, it was noted that there was a risk of main dewatering column failure within Mine A's dewatering system. The RAW pipeline to Mine B was used as the main dewatering column. Several leaks were found on the RAW column. The leak locations are indicated in Figure 17.

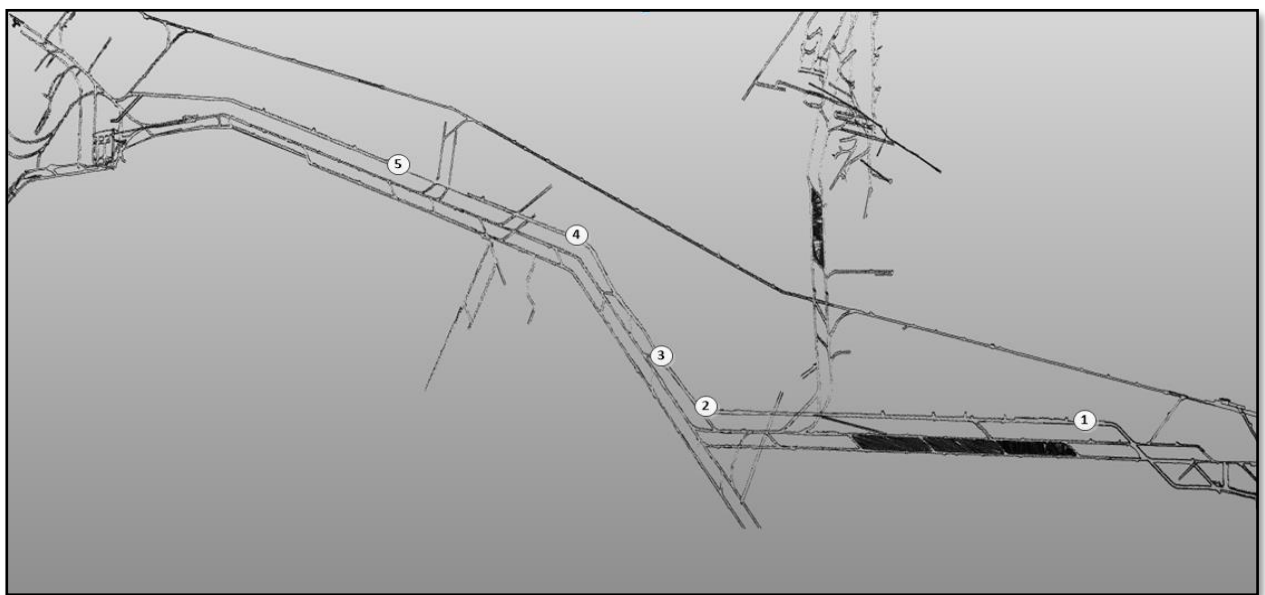


Figure 17: Leak identification layout

Table 11 summarises the leak type and an estimated leak flow that was noted during the leak identification audits. This information was supplied to Mine A and repairs were implemented immediately.

Table 11: Leak identification results

Location	Description	Leak flow [l/s]
1	10" flange	± 1
2	10" bend	± 0.5
3	4" connecting hose	± 1
4	4 mm hole in pipe	± 0.5
5	Crack in pipe	± 2

Regular repairs to the RAW pipeline are only a temporary solution and is not sustainable. Mine A was at great risk of flooding due to the deteriorating condition of the RAW pipeline. Another big concern was the lack of redundancy that was noted with only one dewatering column that was mainly used to dewater to Mine B. The Railveyor column was not capable of handling the total amount of water on its own. Therefore, the need clearly existed for a redundant alternative dewatering solution to reduce the risk of flooding within Mine A.

3.4 Process 2: Development of digital twin

Section 1.1.4 stated that the engineering environment has developed critical tools such as flow simulation software that can be used to accurately predict the outcome of changes to real-world systems. Recalling from Section 1.5.4, Process Toolbox (PTB) proved to be a user-friendly and very effective simulation software to use for transient and steady state simulations. Therefore, PTB was chosen as the simulation software for this study. A PTB component breakdown can be found in Table 23 in Appendix F.

3.4.1 Develop baseline model

Process 2.1 entails developing a direct simulation system replica which is commonly referred to as a digital twin model. With all the locations and design specifications of each critical dewatering component known, the construction of the components could commence.

The DXF files obtained during Process 1.1 was imported into PTB and the components were constructed (Process 2.1.1) and integrated (Process 2.1.2). The water pipelines from the ice dam were constructed on each level in accordance with the DXF layouts. All water pipes were connected to the identified mobile cooling units in the active crosscuts that are listed in Table 10. Figure 18 shows the connection setup at one of the mobile cooling units.

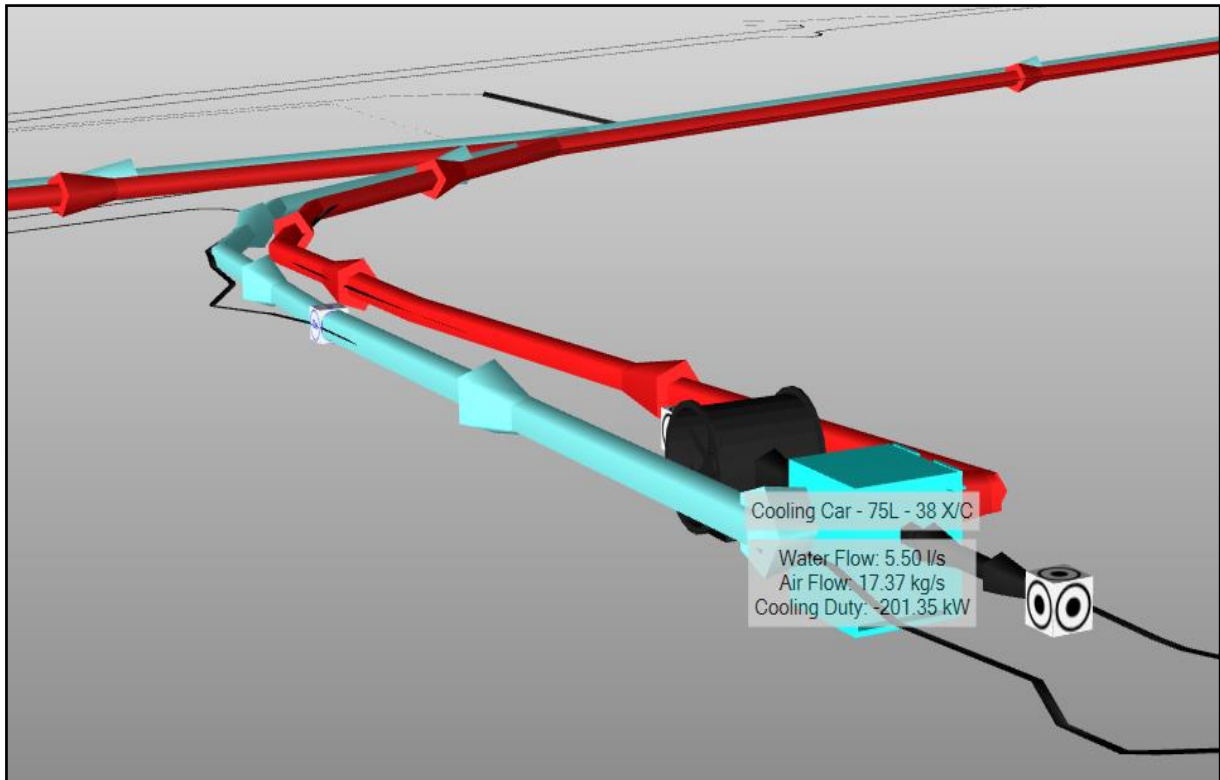


Figure 18: Cooling car connection

As seen from Figure 18, the chilled water pipeline is connected to the mobile cooling unit. A 45 kW fan is used to blow hot air through the cooling unit where the chilled water is circulated through cooling coils. The chilled water heats up due to the heat exchange that occurs between the hot air and the chilled water. The heated water flows out of the cooling car and is recirculated back to the dewatering system. To obtain an in-depth discussion on the thermodynamic principles of mobile cooling units, refer to Appendix A.

The dewatering components on 55L included the ice dam to be connected to the chilled water pipeline going to the mining block, as well as the hot water pipeline coming from 77L. The ice dam connection setup is illustrated in Figure 19.

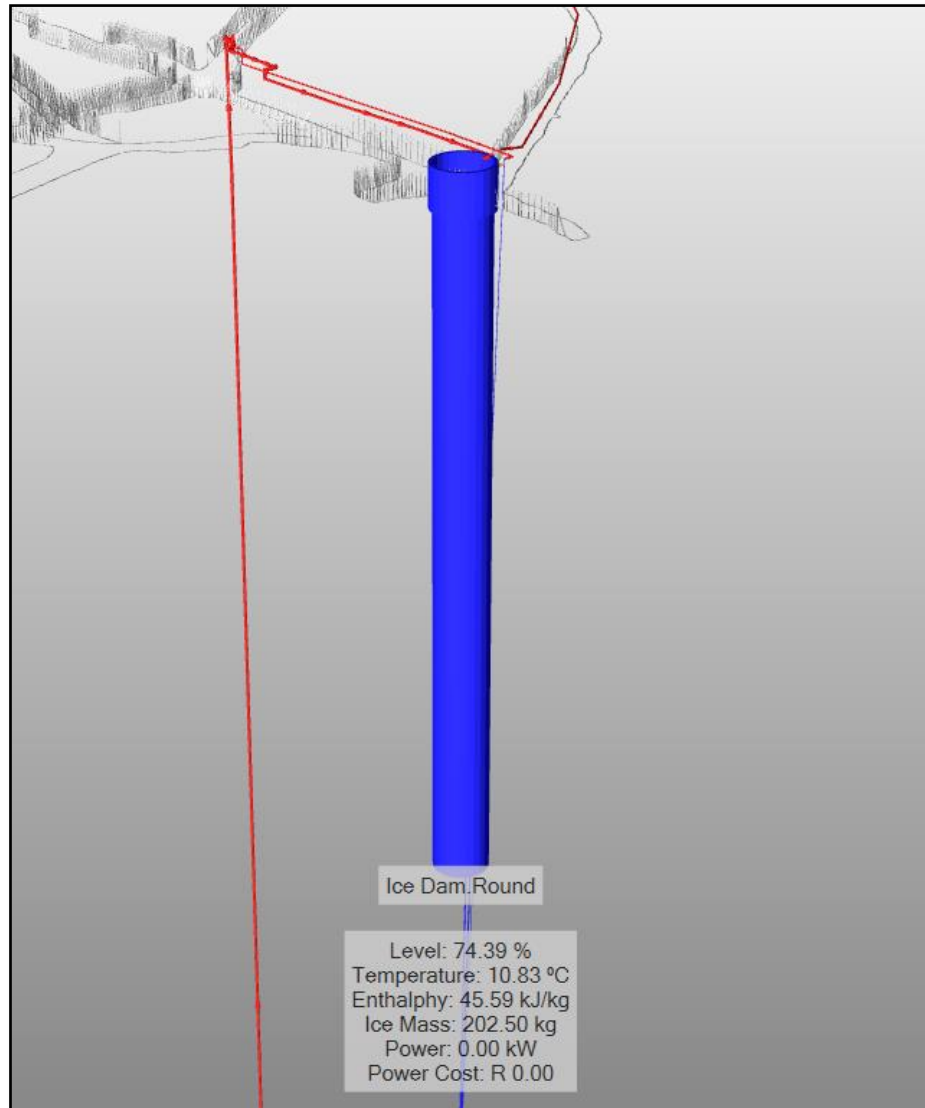


Figure 19: 55L ice dam connection setup

The 77L pump station as well as the settlers was integrated next. The hot water pipelines coming from the mobile cooling units were connected to the settlers situated on 77L. The 77L hot dam is not in use and serves as an additional storage dam when the settlers need to undergo maintenance. The 77L connection setup is illustrated in Figure 20.

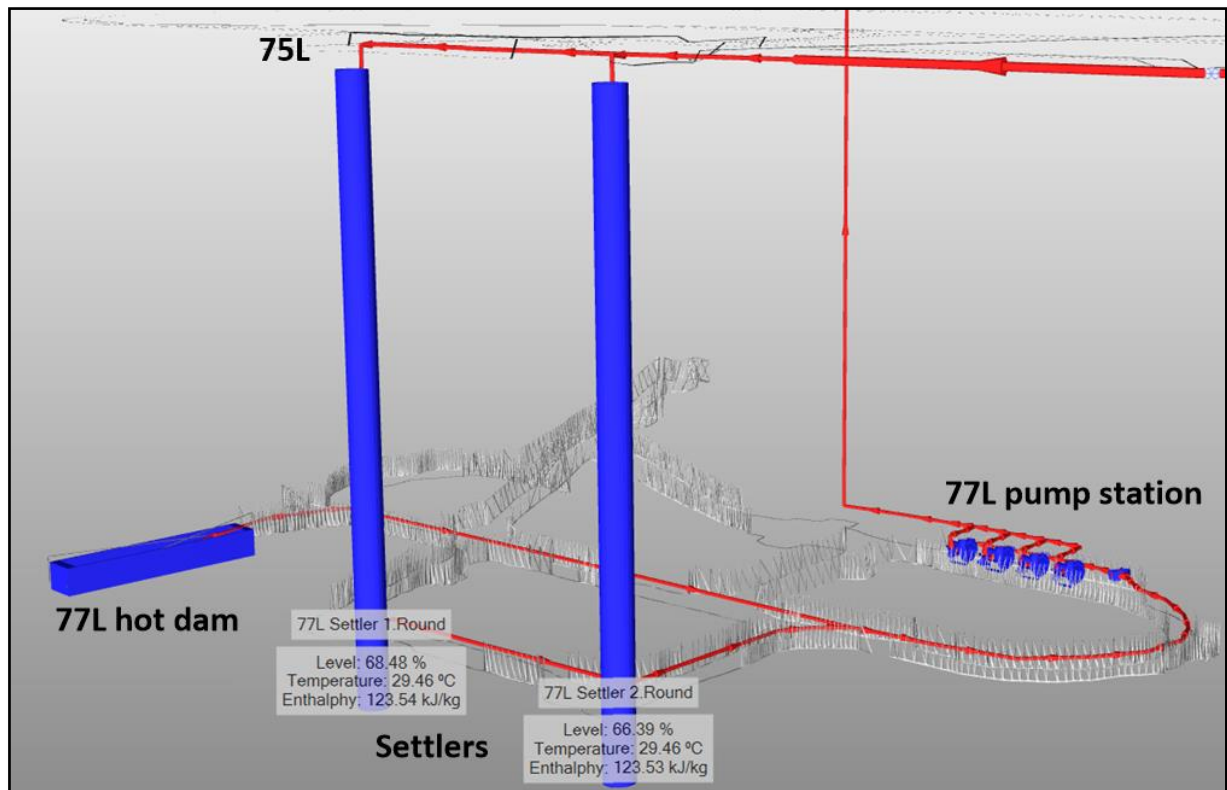


Figure 20: 77L settler and pump station connection setup

The final step in developing the baseline model was to import all the design specifications that were obtained in Process 1.2 into PTB (Process 2.1.3). This is crucial to ensure the simulated dewatering components represent the actual dewatering components. Note that PTB automatically assigns default values to certain properties. The default values may be changed during the calibration phase to achieve optimal accuracy, if needed.

Figure 21 illustrates the design specifications that were imported into the ice dam component in PTB that was obtained during Process 1.2. These design specifications are also listed in Table 8.

Properties			Import...	Export...
Name	Unit	Initial		
Pressure	kPa	100.000		
Temperature	°C	6.000		
Volume	m³	2350.000		
Level	%	74.000		
Heat	kW	...		
Top Elevation	m	-2150.000		
Bottom Elevation	m	-2271.460		
Heat Transfer Coefficient	kW/...	0.000		
Heat Transfer Area	m²	19.625		
Ambient Temperature	°C	32.000		
Ice Mass	kg	0.000		
Ice Flow	kg/hr	...		
Ice Mass Fraction		...		
Specific Energy	kWh/...	...		
Melting Rate	kg/hr	3000000...		

Figure 21: Ice dam design specifications

As mentioned before, there are two settlers on 77L. Both settlers have identical design specifications and are illustrated in Figure 22.

Properties			Calculate	Import...	Export...
Name	Unit	Initial			
Pressure	kPa	100.000			
Temperature	°C	30.000			
Volume	m³	780.000			
Level	%	41.000			
Heat	kW	...			
Top Elevation	m	-2845.000			
Bottom Elevation	m	-2851.246			
Heat Transfer Coefficient	kW/...	0.000			
Heat Transfer Area	m²	0.000			
Ambient Temperature	°C	0.000			

Figure 22: Settler design specifications

The 77L pump station consists of four identical dewatering pumps. Two pumps are in operation and two are additional pumps that serve as redundancy in case of pump failure. Figure 23 illustrates the pump curve which was obtained from the engineers on site. The pump curve was imported into each pump component in PTB.

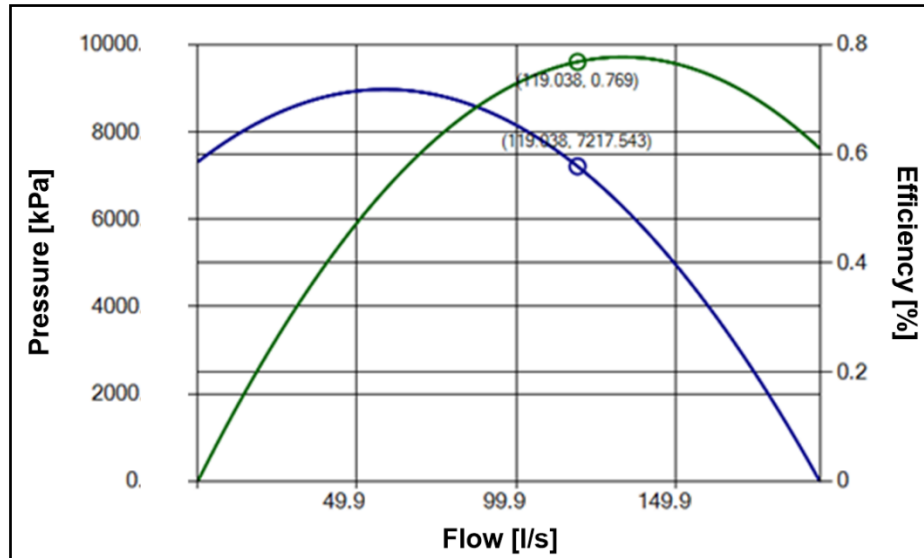


Figure 23: 77L pump curve

After the simulation model was constructed and all dewatering components were integrated with each respective design specification, the simulation could be simulated for the first time.

3.4.2 Simulate baseline model

The baseline model was simulated numerous times and all errors that occurred due to unconnected components were corrected. A total time period of 24 hours was simulated which represents one full production day. Figure 24 is an illustration of the complete baseline model.

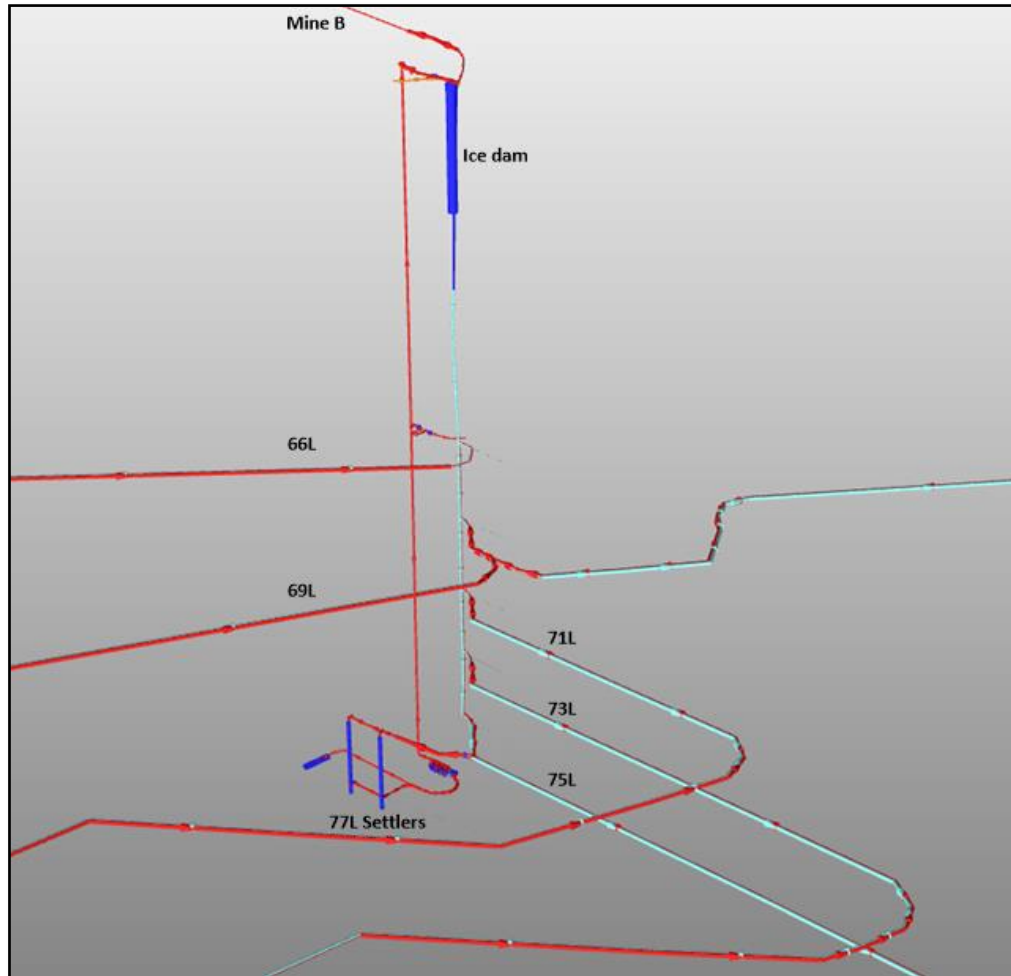


Figure 24: Baseline model

The ice dam is the root component of the dewatering system and therefore the most important component to control. The ice dam was instrumented with flow meters, temperature sensors and level indicators. All these instrumentation components were linked to the SCADA system and the data was easily accessible. The ice dam level and amount of water flowing into the ice dam were used as KPIs for the baseline to compare the level of accuracy of the model (Process 2.2.1).

3.4.3 Calibrate and verify simulation

The model was calibrated based on the current controls of the dewatering system at Mine A as suggested by Process 2.3.1 in Chapter 2. The valve statuses were integrated into the digital twin to determine the total water pumped to Mine B. The current set points of the valves were then integrated into the model. The following current setpoint controls were used for the respective valves:

Railveyor valve to Mine B:

This valve is used to control the amount of water that is dewatered to Mine B through the Railveyor pipeline. The valve control is dependent on the ice dam level. The setpoints for the control are indicated in Table 12.

Table 12: Valve to Mine B setpoints

Valve position	Ice dam level
Open	>77%
Close	<70%

Valve to the ice dam:

The valve to the ice dam serves as a safety precaution as it ensures that the ice dam does not flood. The ice dam level should not exceed 83% to prevent it from flooding and should not decrease below 55% to prevent the ice dam side wall from scaling due to the ice impact from surface. The setpoints for the control are indicated in Table 13.

Table 13: Ice dam valve setpoints

Valve position	Ice dam level
Open	>84%
Close	<80%

The control of the pumps on 77L was aligned with pump controls used in REMS by Mine A. The current pump statuses and the maximum flow per pump were used to simulate the water pumped from 77L to 55L. The pumps were controlled based on the 77L settlers' level. The setpoints used to calibrate the model are indicated in Table 14.

Table 14: 77L pump control

Pump	Pump status	77L dam level
1	Start	= 66%
	Stop	= 29%
2	Start	= 66%
	Stop	= 29%
3	Start	= 63%
	Stop	= 27%
4	Start	= 66%
	Stop	= 29%

The calibration was done using Proportional-Integral-Derivative (PID) controllers that are built into PTB. A basic description of the working principle of PTB components can be found in Appendix F.

The simulation was calibrated using actual data retrieved from Mine A's SCADA system as stated in Process 2.3.2. The ice dam level and the flow into the ice dam over a 24hour period were used as the main KPIs to compare the simulation output to actual data.

Figure 25 shows the trend of the actual ice dam profile vs the simulated ice dam profile for a 24hour period.

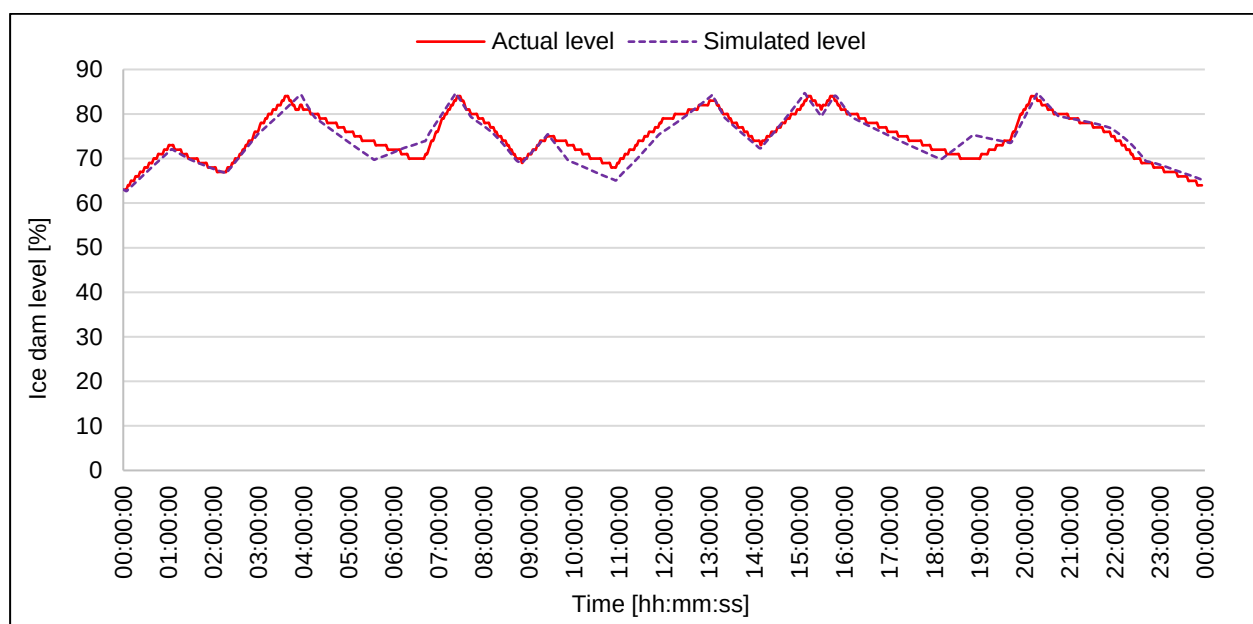


Figure 25: Ice dam level (Actual vs simulated)

As seen from Figure 25, the simulated ice dam level did not exceed the minimum and maximum ice dam levels of 55% and 83% respectively. The simulated ice dam level profile followed the actual ice dam level profile which was obtained from the SCADA data with an average error of 2%.

The slight deviation may be explained due to fluctuating water demand as underground water usage tends to be dynamic. Another contributing factor to the error deviation is the time delay present in the valve actuators. There could be a small-time delay between the set-point time period that is programmed into the REMS system and the reaction time period of the valve actuators.

The next KPI that was evaluated was the flow into the ice dam. Figure 26 shows the actual flow into the ice dam compared to the simulated flow into the ice dam.

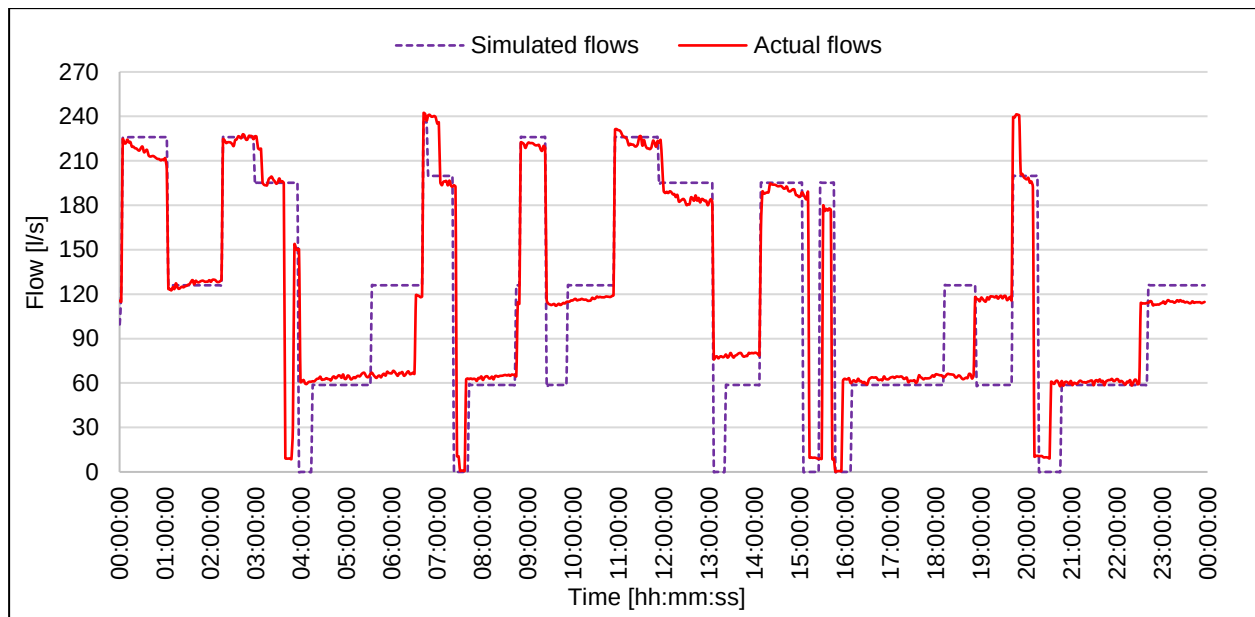


Figure 26: Flow into ice dam (Actual vs simulated)

The simulated flow profile was compared to the actual flow profile. This yielded an average error difference of 1.5% with a maximum error difference of 5.5%. This error difference is the result of inconsistent ice block sizes that are produced on surface and gravity fed into the ice dam underground. The ice produced on surface is in the form of an ice slurry consisting of melted ice and ice blocks of different sizes. Therefore, it proved challenging to simulate the exact quantity of water that entered the ice dam at each time period.

However, it is clear from Figure 25 and Figure 26 that the simulation is an accurate representation of the actual dewatering system. It is evident that the digital twin model is verified within the 10% error range as indicated by literature in Section 1.5.4.

3.5 Process 3: Develop alternative dewatering strategies

3.5.1 Route cause analysis

As discussed in Section 4.3.4, a possible risk within the current dewatering system was noted. There was only one dewatering column to Mine B which posed a great risk of failure due to regular leaks that were noted. To fully understand the cause of the problem, a root cause analysis was performed by continually asking the question “why?” (Process 3.1). This method was suggested

from past literature as mentioned in Section 1.4.5. Figure 27 illustrates how the root cause analysis was applied.

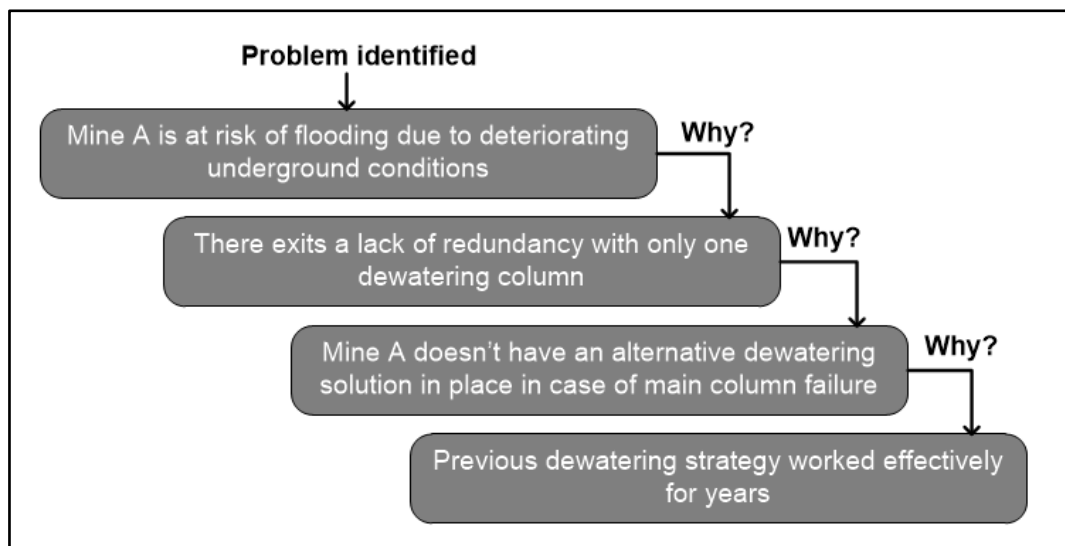


Figure 27: Root cause analysis [43]

The root cause analysis resulted in an interesting discovery. The current dewatering system has been performing effectively over the past couple of years. But due to the harsh mining environment, the main column is starting to fail. New leaks are regularly indicated, and the risk of flooding is busy escalating.

From the root cause analysis, it is concluded that an alternative dewatering solution consisting of a new dewatering column needs to be developed. The alternative dewatering solution must be redundant to prevent this problematic scenario from reappearing in the near future. Therefore, Process 3.2 entailed inspecting possible additional infrastructure that can be integrated into the dewatering system to serve as redundancy.

3.5.2 Additional infrastructure

During the site walkthrough phase (Process 1.1), it was noted that there was an additional dam on 55L connected to an additional pipeline in the Railveyor haulage to Mine B. The 55L dam, known as the buffer dam, was previously used as a storage dam to delay the outflow of water to Mine B when the RAW pipeline had to undergo maintenance. During such scenarios, the Railveyor pipeline was used to dump water to Mine B from the 55L buffer dam in a controlled manner. This was not a sustainable option due to the large volumes of water that the Railveyor pipeline had to tolerate.

Another additional pipeline to Mine C was noted during site inspection. This pipeline served as an emergency pipeline for Mine A and Mine C in case the dewatering system at either of the mines failed. This pipeline is currently disconnected because it had not been used for many years and started to disintegrate due to small volumes of water stagnating in the pipeline. A visit to Mine C resulted in obtaining the additional quantity of water that Mine C's dewatering system was capable of handling. This quantity was equal to 3.5 ML of water per day.

There are two possible options that can be integrated into Mine A's dewatering during the development of a fail-safe dewatering strategy.

3.5.3 Simulate possible solutions

As mentioned in Section 3.2, Mine A uses surface ice plants to generate ice that is gravity fed into an underground storage dam known as an ice dam. Chilled water is distributed to the mining block from the underground ice dam. The total amount of ice produced by the ice plants during full production periods amounts to 3 200 tons of ice per day, meaning 3.2 ML of water is being sent underground each day. It is evident that the ice dam is a critical component to consider with each possible dewatering solution.

Therefore, the main system performance outcomes of the solution had to comply with the following design specifications obtained from the engineers on site:

- The ice dam level should not exceed 83% to prevent it from flooding.
- The ice dam level should not decrease below 55% to prevent the ice dam side wall from scaling due to the ice impact from surface.
- Enable dewatering of 37 l/s to 41 l/s of water as a result of the addition of ice for cooling from surface.

Four possible scenarios were considered and simulated in order to meet the above-mentioned criteria. Table 15 provides a summary of the different scenarios developed and simulated.

Table 15: Scenario summary

Control	Description
Scenario 1	Dumping water to Mine C on 66L and Mine B through the RAW line on 55L. The maximum PRV flow on 66L was set at 60 [l/s].
Scenario 2	Dumping water to Mine C on 66L at a constant flow of 30 [l/s] and sending any excess water to Mine B through the RAW line.
Scenario 3	Dumping water through the Railveyor line to Mine B and integrating the 66L line to dump access water to Mine C.
Scenario 4	Integrating the 55L buffer dam into the dewatering system of Mine A. Pumping water through the Railveyor line to Mine B and access water through the 66L pipeline to Mine C.

Each scenario is discussed in more detail along with the obtained results in the sections below.

Scenario 1

Scenario 1 entailed using the existing RAW dumping control in conjunction with the additional pipeline on 66L to Mine C. A PRV was added to the model to ensure a maximum PRV flow of 60 l/s on 66L to Mine C, which correlates to the water handling capacity of Mine C.

The 77L pump control was kept the same as the baseline control to ensure the settler levels stay within the desired minimum and maximum levels. The 77L pump control is given in Table 16.

Table 16: Scenario 1 - 77L pump controls

Pump	Pump status	77L dam level
1	Start Stop	= 66% = 29%
2	Start Stop	= 66% = 29%
3	Start Stop	= 63% = 27%
4	Start Stop	= 66% = 29%

Figure 28 shows the flow profile towards Mine C on 66L as well as Mine B on 55L.

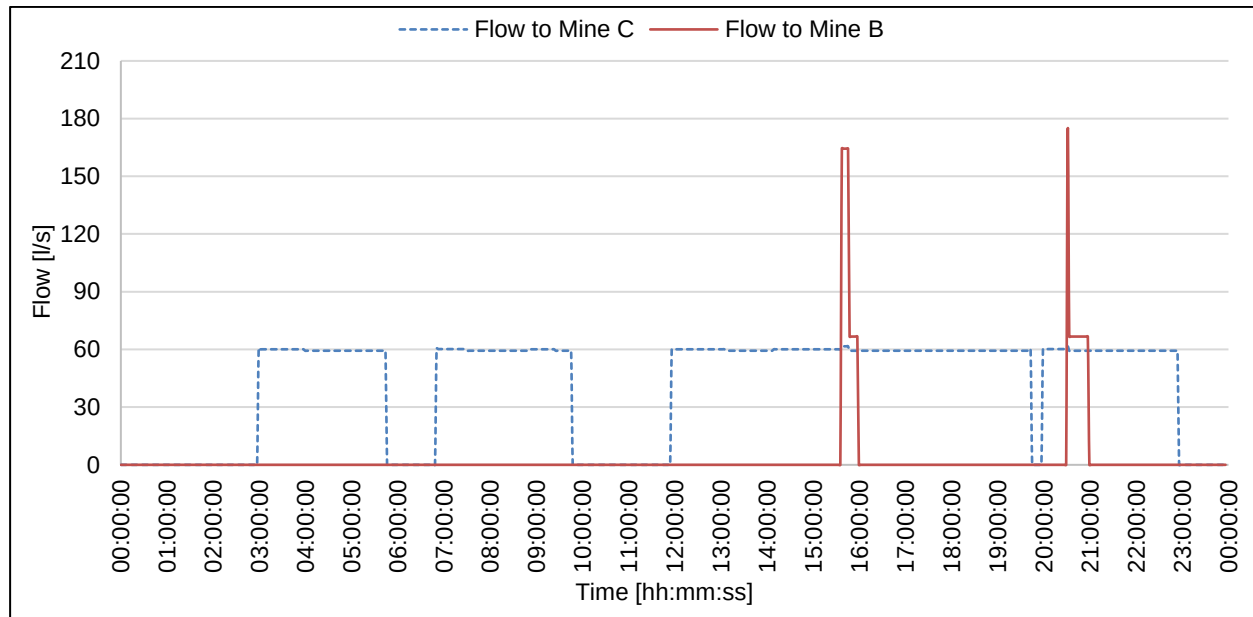


Figure 28: Scenario 1 - Flow profile to Mine B and Mine C

The daily average flow towards Mine C was seen to be 30 l/s and the daily average towards Mine B through the 55L RAW was seen to be 7 l/s. The pressure before and after the PRV was also evaluated to ensure the pipeline could handle it.

The maximum pressure before the PRV was seen to be 3 800 kPa whereas the maximum pressure after the PRV was 1 350 kPa. This was satisfactory due to the low-pressure piping used after the control valve that is rated at 1 600 kPa.

For instance, when the 66L control valve was closed, the pressure on the PRV discharge increased to 3 800 kPa. Therefore, the pipeline between the PRV and 66L control valve needs to be converted to high pressure piping if this scenario was to be considered. The set points for inlet and outlet 66L PRV pressures were 3 500 kPa and 1 200 kPa respectively. Figure 29 shows the PRV inlet and outlet pressures.

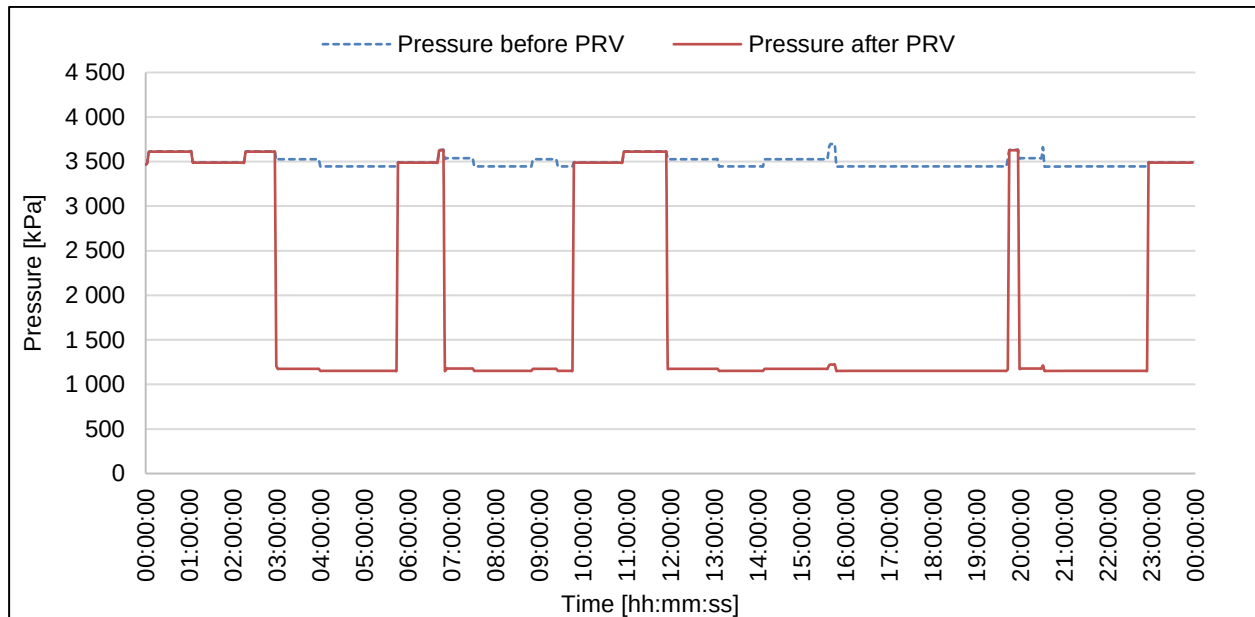


Figure 29: Scenario 1 - PRV pressures

As mentioned previously, it is of utmost importance to consider the response of the ice dam to the new dewatering control. The ice dam should always operate within the stated design specifications. The scenario results were compared to the baseline to ensure safe operation of the system. Figure 30 shows the response of the digital twin in terms of the ice dam level for Scenario 1.

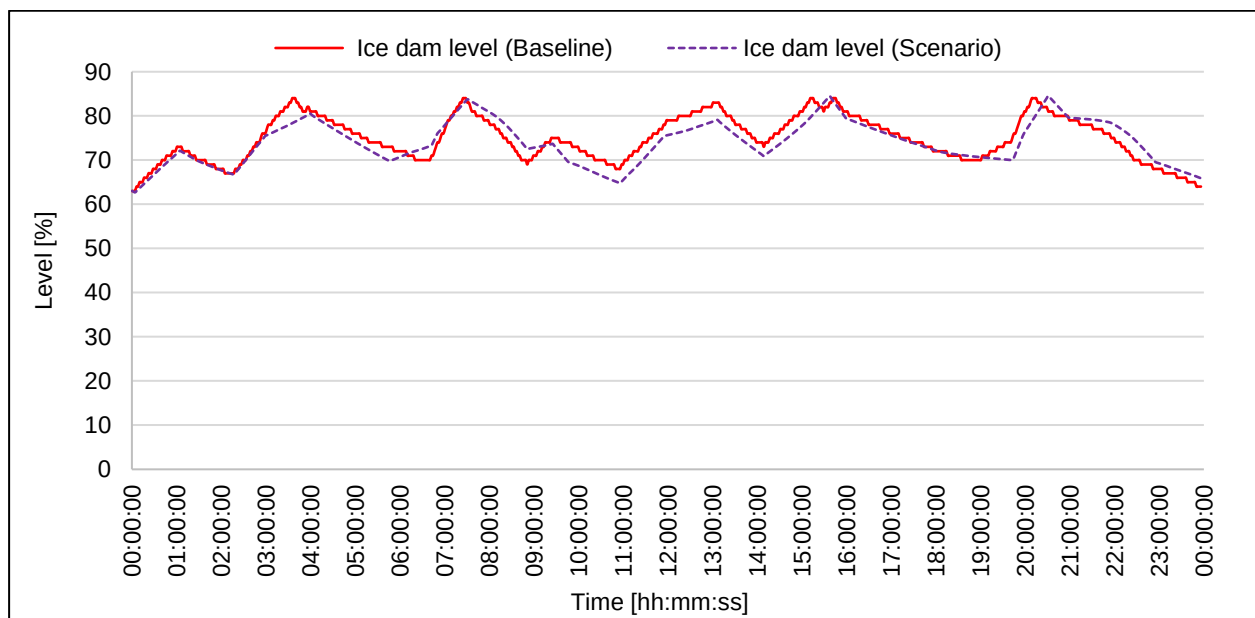


Figure 30: Scenario 1 - Ice dam levels

The design criteria, stated at the start of this section, specified that the ice dam should not exceed 83% or go lower than 55%. From Figure 30, it is clear that the maximum and minimum simulated ice dam levels were 83% and 65% respectively.

The simulated results were compared to the actual results to monitor the change in the average and maximum error of the model with the new integrated control. The simulated ice dam flow followed that of the baseline ice dam flow quite accurately. The average percentage error was equal to 1.5%. Figure 31 portrays the simulated flow to the ice dam compared to the actual flow (baseline).

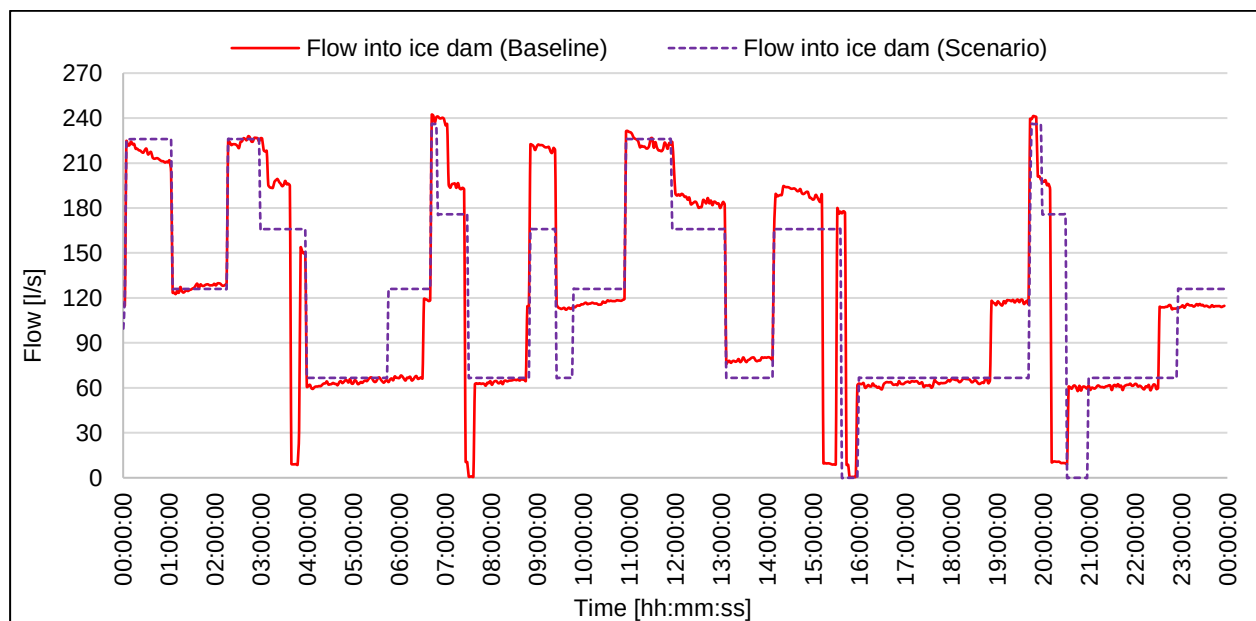


Figure 31: Scenario 1 - Flows into ice dam

Table 17 shows the set points which were used for the various control valves in order to optimise the control of the simulation model.

Table 17: Scenario 1 - Valve set points

Valve	Valve position	Ice dam level
66L Control Valve (V5)	Open	= 75%
	Closed	= 70%
Ice dam valve (V3)	Open	= 80%
	Closed	= 84%
RAW valve (V2)	Open	= 84%
	Closed	= 80%

The schematic illustration of Scenario 1 can be found in Figure 67 in Appendix D.

Scenario 2

Scenario 2 entailed reducing the flow to Mine C from 60 l/s to 30 l/s to ensure that Mine C could easily accommodate the additional water. Figure 32 shows the flow to Mine C and Mine B on 55L through the RAW pipeline.

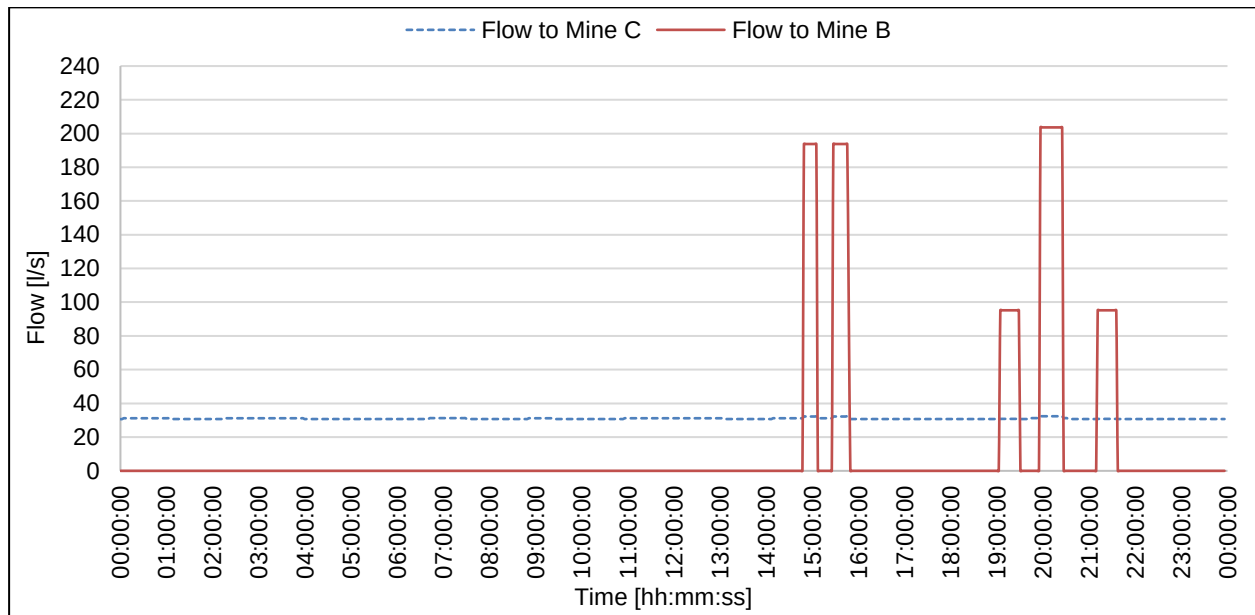


Figure 32: Scenario 2 - Flows to Mine B and Mine C

The average flow to Mine C is 30 l/s, while the average flow towards Mine B is 7 l/s. The maximum flow towards Mine B is 200 l/s. Figure 33 shows the inlet and outlet pressures on the 66L PRV.

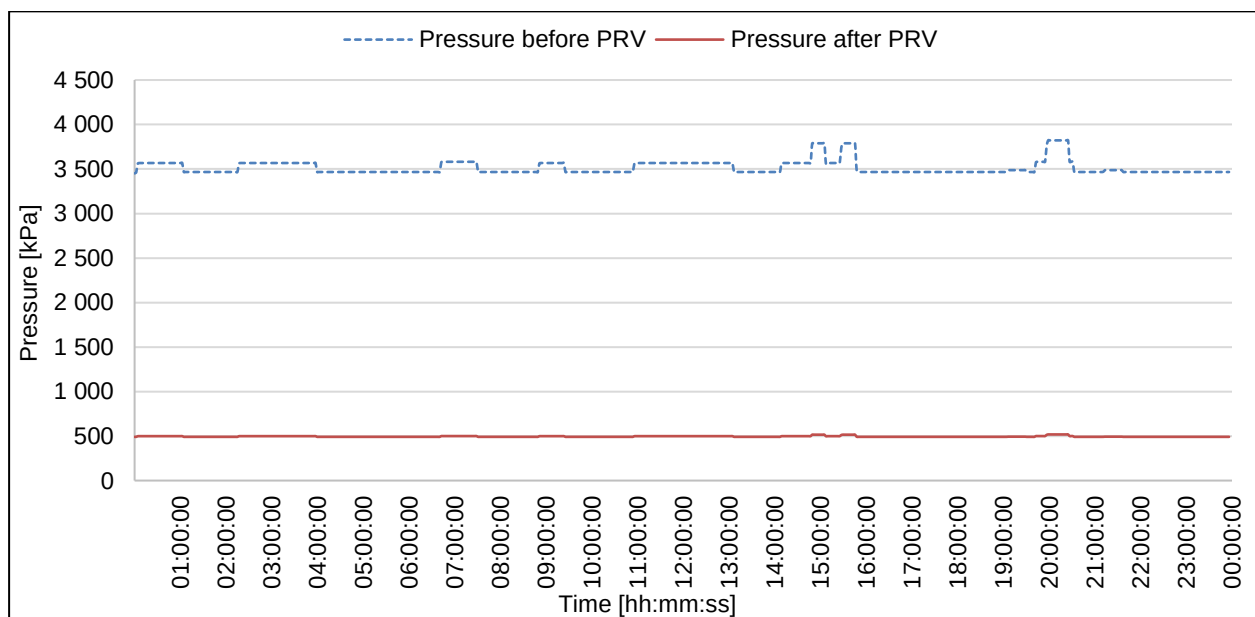


Figure 33: Scenario 2 - 66L PRV pressures

The pressure before and after the PRV was seen to be 3 600 kPa and 500 kPa respectively, which is satisfactory for the piping that is currently installed. Figure 34 shows the response of the ice dam due to the changes.

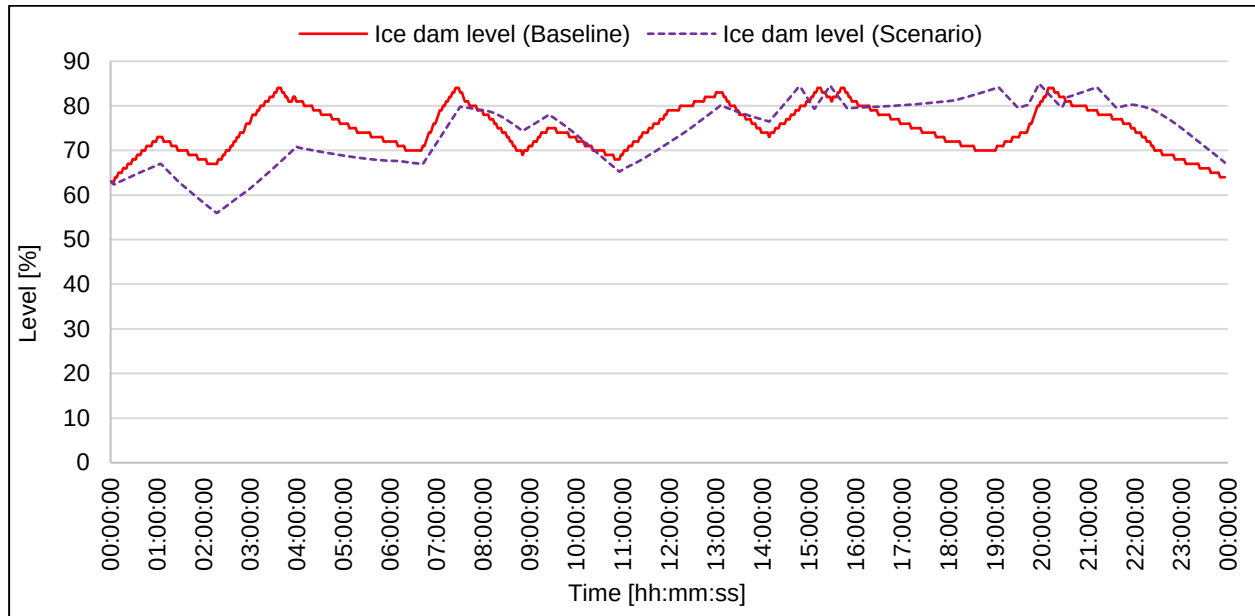


Figure 34: Scenario 2 - Ice dam levels

Figure 34 indicates that the maximum ice dam level is 83% and the minimum level 57%. These levels fall within the ice dam level boundaries. It is, however, clear that the simulated ice dam profile deviates from the baseline. Figure 35 shows the total water flowing into the ice dam.

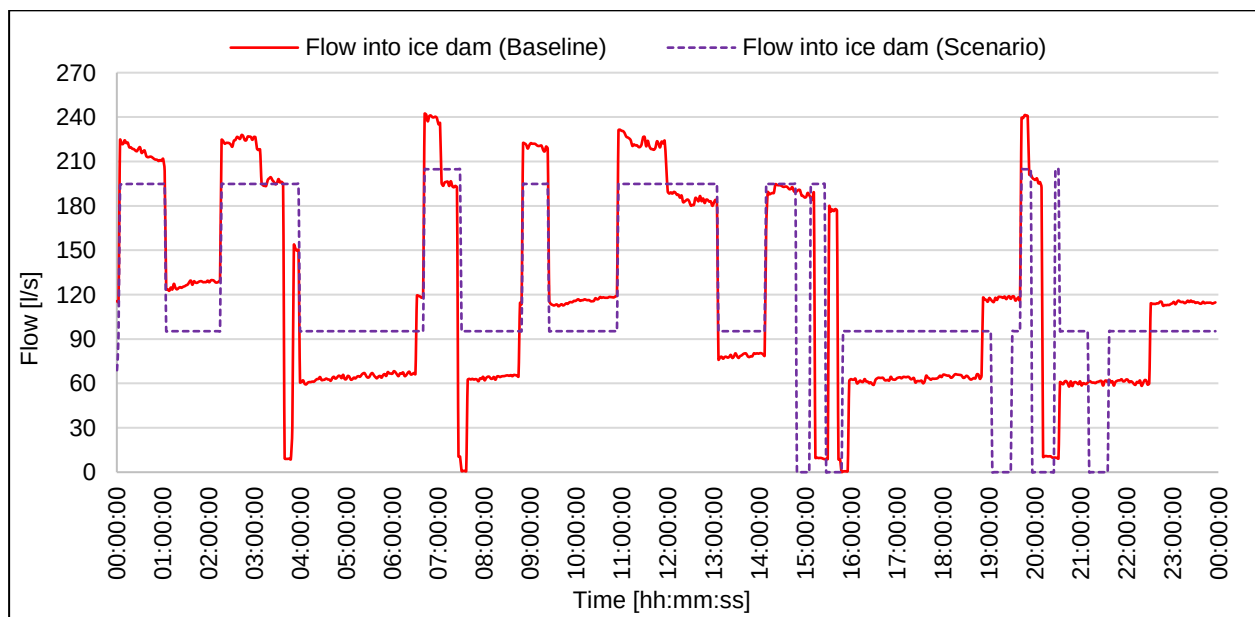


Figure 35: Scenario 2 - Flows into the ice dam

The maximum percentage difference between the baseline and the simulated scenario was 12%. The maximum error was due to the difference in setpoint controls for the valves. The simulated trends are based on the new setpoints displayed in Table 18 to allow for a constant flow of 30 l/s towards Mine C.

Table 18: Scenario 2 - Valve set points

Valve	Valve position	Ice dam level
66L Control Valve (V5)	Open	= 60%
	Closed	= 55%
Ice dam Valve (V3)	Open	= 80%
	Closed	= 84%
RAW Valve (V2)	Open	= 84%
	Closed	= 80%

The schematic illustration of Scenario 2 can be found in Figure 68 in Appendix D.

Scenario 3

Scenario 3 included the use of the Railveyor pipeline to Mine C. A 2.4 km pipeline was previously installed in the Railveyor haulage to handle the bulk of the water from Mine A and send it towards Mine B in a controlled manner during maintenance procedures on the RAW pipeline. However, the Railveyor pipeline is not capable of handling all the water that needs to be dewatered. Therefore, the 66L pipeline to Mine C was also incorporated into the proposed solution. The pipeline to Mine C consists of 8-inch and 10-inch pipe sections which can accommodate close to 160 l/s of flow. As mentioned previously, Mine B is the desired location to dewater most of the water to. This will also ensure that the Reverse Osmosis project can continue at Mine B.

A combined control was developed to send water to Mine B through the Railveyor pipeline and dumping access water to Mine C through the 66L pipeline. Figure 36 shows the water distribution between Mine B and Mine C.

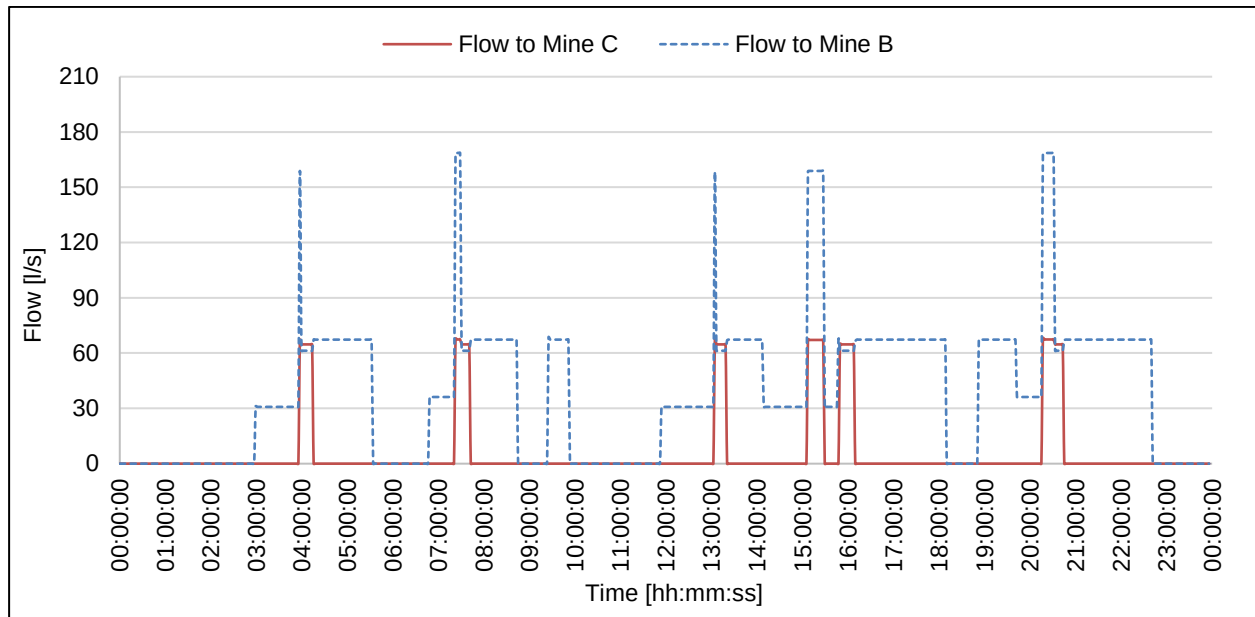


Figure 36: Scenario 3 - Water dumped to Mine B and Mine C

From Figure 36 an average water flow towards Mine B of 32 l/s through the Railveyor is obtained and the average water flow towards Mine C is 5 l/s. Figure 37 shows the pressure before and after the 66L PRV.

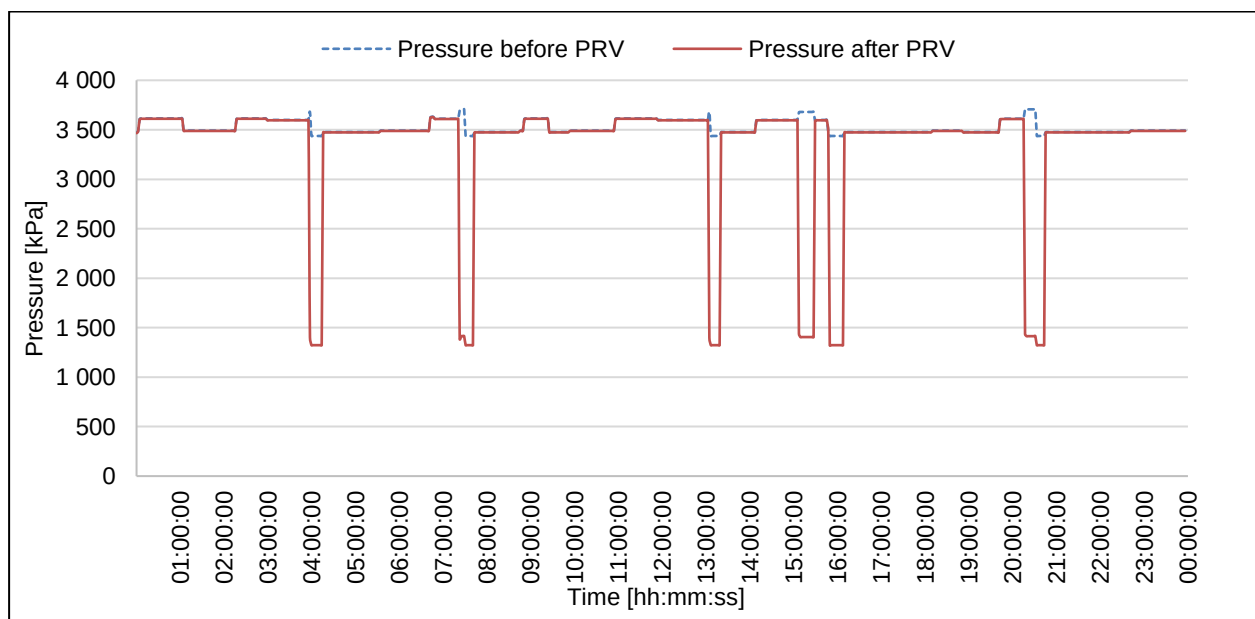


Figure 37: Scenario 3 - 66L PRV pressures

The PRV pressure setpoints before and after the PRV was 3 500 kPa and 1 200 kPa respectively. As seen from Figure 37, the maximum pressure before the PRV was 3 600 kPa when the 66L valve towards Mine C is closed and 1 350 kPa when the valve is open. Figure 38 shows the response of the ice dam level compared to the baseline.

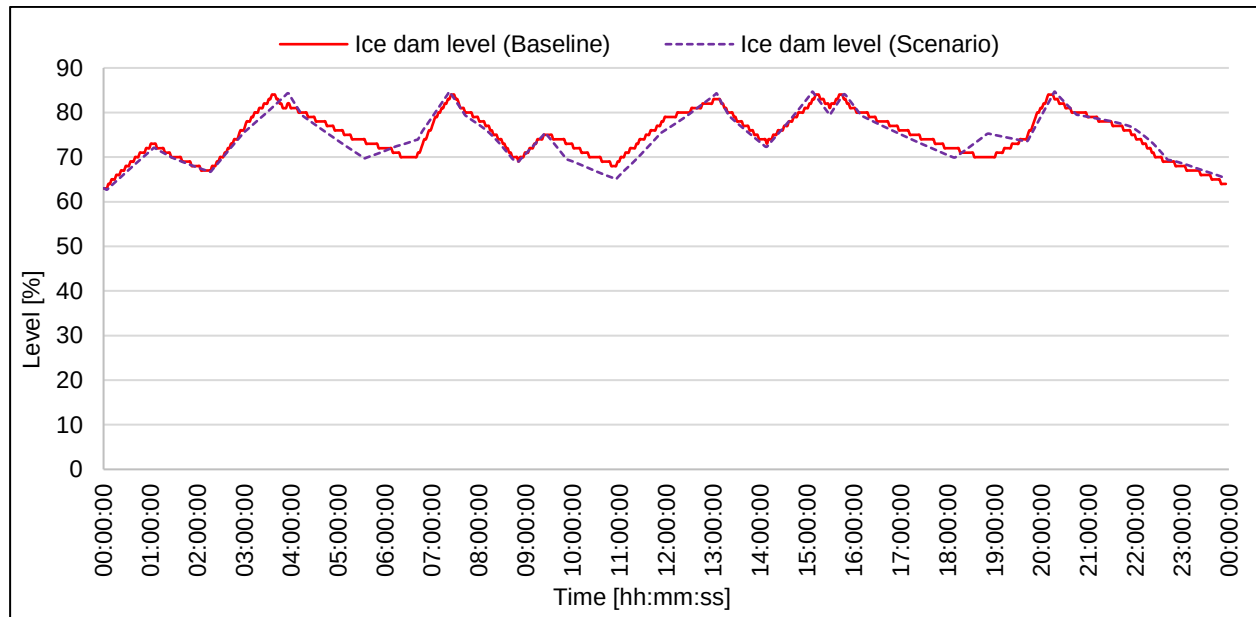


Figure 38: Scenario 3 - Ice dam level

The ice dam level followed the baseline level profile with reasonable accuracy. Again, it is clear that the ice dam would still operate within the maximum and minimum boundaries. Figure 39 shows the simulated water flow into the ice dam compared to the baseline flow.

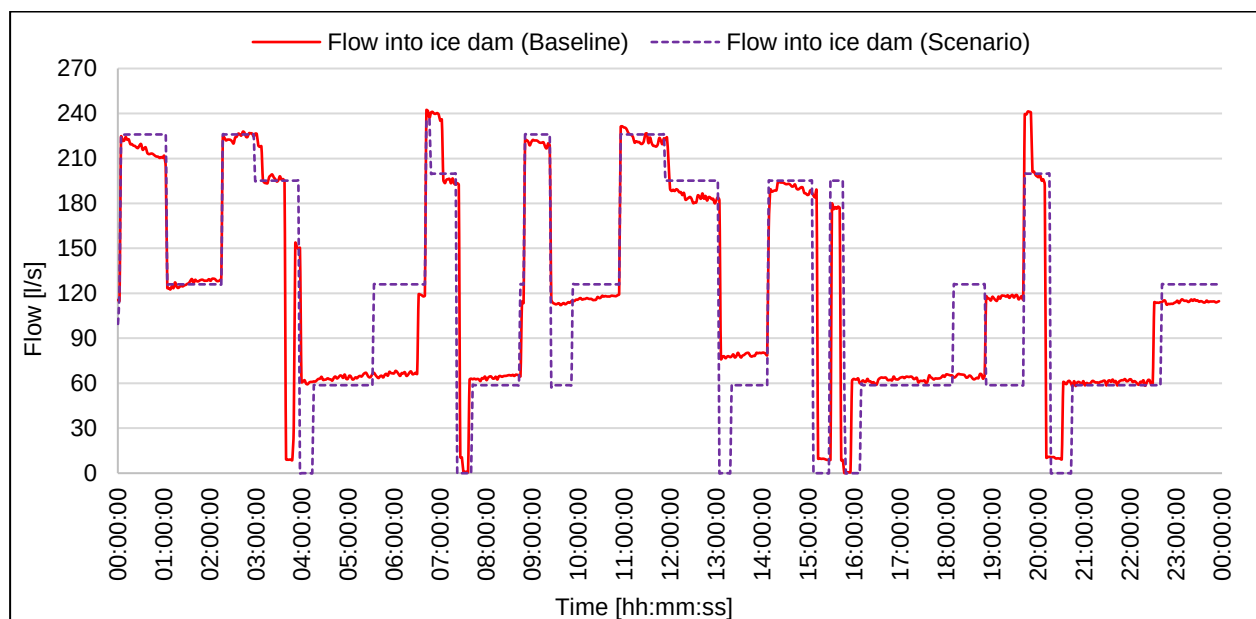


Figure 39: Scenario 3 - Flows into the ice dam

The simulated ice dam levels followed the baseline actual profile. The average percentage difference was seen to be 1.5% and the maximum percentage difference was seen to be 8.4% due to the change in the system configuration. The aim was to ensure that more water is pumped

towards Mine B as Mine B utilises the water at a Reverse Osmosis plant. Table 19 shows the setpoints simulated on the valves for the dewatering control.

Table 19: Scenario 3 - Valve set points

Valve	Valve position	Ice dam level
66L Control Valve (V5)	Open	= 84%
	Closed	= 80%
Ice dam Valve (V3)	Open	= 80%
	Closed	= 84%
Railveyor valve (V2)	Open	= 75%
	Closed	= 70%

The schematic illustration of Scenario 3 can be found in Figure 69 in Appendix D.

Scenario 4

Scenario 4 entails utilising an unused storage dam to allow for more centralised dewatering control capability. This storage dam is referred to as the buffer dam for this study. The buffer dam is situated on 55L. From this location, dewatering to Mine B and Mine C can be centrally controlled with more accuracy and ease.

Redundancy is key in a dewatering system; therefore, alternative dewatering solutions should be available during any dewatering component failure situation. The 55L Railveyor pipeline to Mine B is a redundant solution in scenarios where the RAW pipeline to Mine B fails. Therefore, the 55L Railveyor pipeline was included in this scenario.

The control of the buffer dam will make use of the 55L Railveyor pipeline to Mine B and the 66L pipeline to Mine C. This initiative consists of constantly dumping water through the Railveyor pipeline. The 66L pipeline to Mine C will handle the spikes in flow once the ice dam valve closes. The flow distribution between the Railveyor pipeline and the 66L pipeline can be seen in Figure 40.

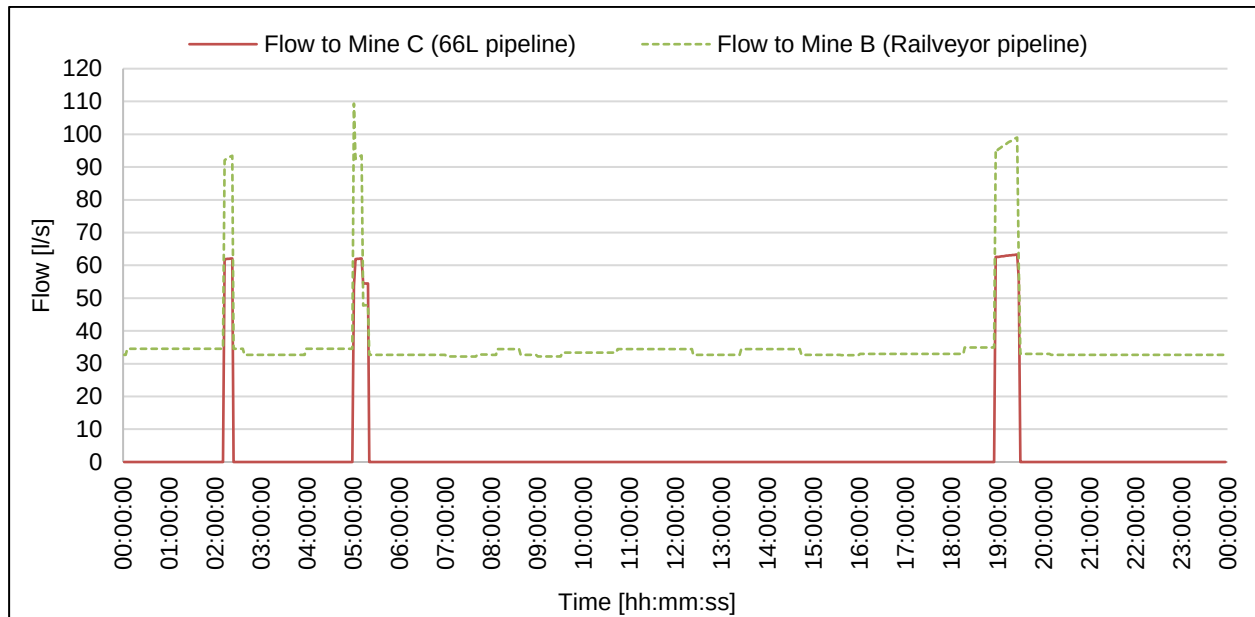


Figure 40: Scenario 4 - Water pumped to Mine C and Mine B through Railveyor pipeline

Figure 40 shows the constant dumping to Mine B through the Railveyor. The average flow through the Railveyor is 35.7 l/s. Most of the excess water will be dumped through this pipeline. The pipeline on 66L will only be used to help accommodate for more dumping capacity when the ice dam valve closes. The maximum flow to Mine C is 60 l/s when the ice dam valve closes.

The control of the flow of water into the buffer dam on 55L is formulated to delay the flow of hot water into the ice dam to some extent, so that the temperature of the water in the ice dam will decrease. Figure 41 shows the characteristics of the control of the buffer dam.

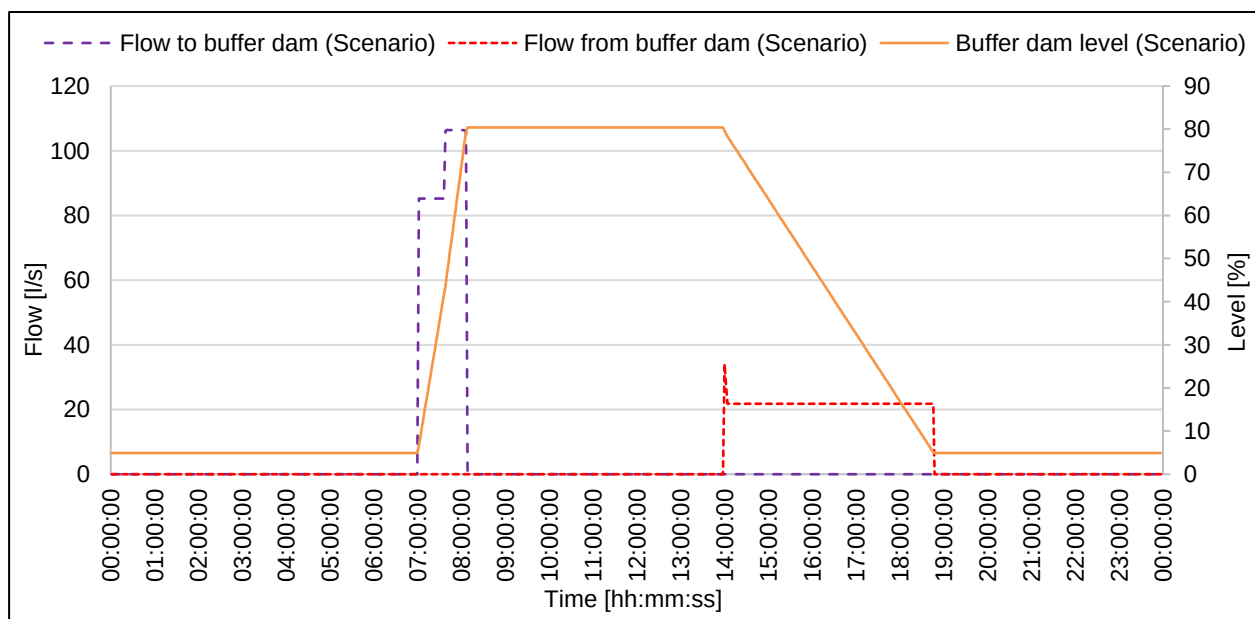


Figure 41: Scenario 4 - Buffer dam control

Figure 41 illustrates that the water flows into the buffer dam at 07:00 and stops just after 08:00 once the buffer dam level reaches 80%. The maximum flow into the buffer dam is 110 l/s. This means that there is a reduction of 110 l/s of hot water flowing into the ice dam during this time. The hot water is then reintroduced into the ice dam after drilling shift at 14:00.

The delay in flow does not mean that there is no hot water flowing into the ice dam. Figure 42 illustrates the difference in the flow into the ice dam as a result of the buffer dam.

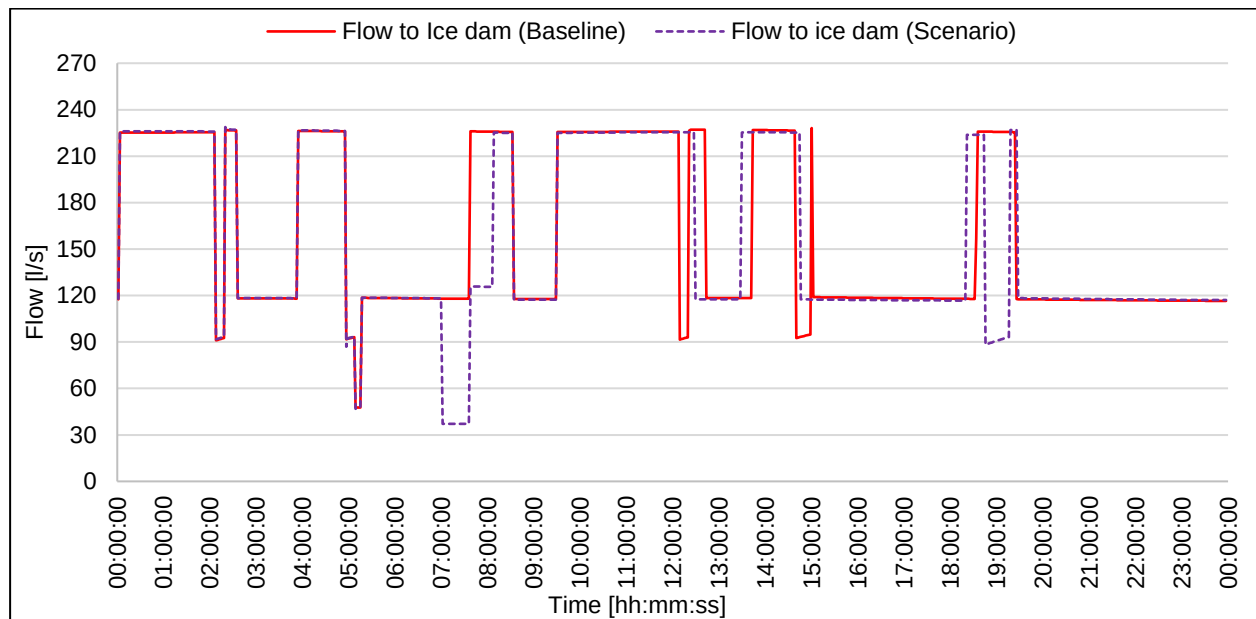


Figure 42: Scenario 4 - Flow into ice dam

Figure 42 illustrates that when the valve to the buffer dam is opened there is less water flowing to the ice dam during this time. This delay in water flowing into the ice dam will have an impact on the level of the water in the ice dam. Figure 43 illustrates this impact on the ice dam level.

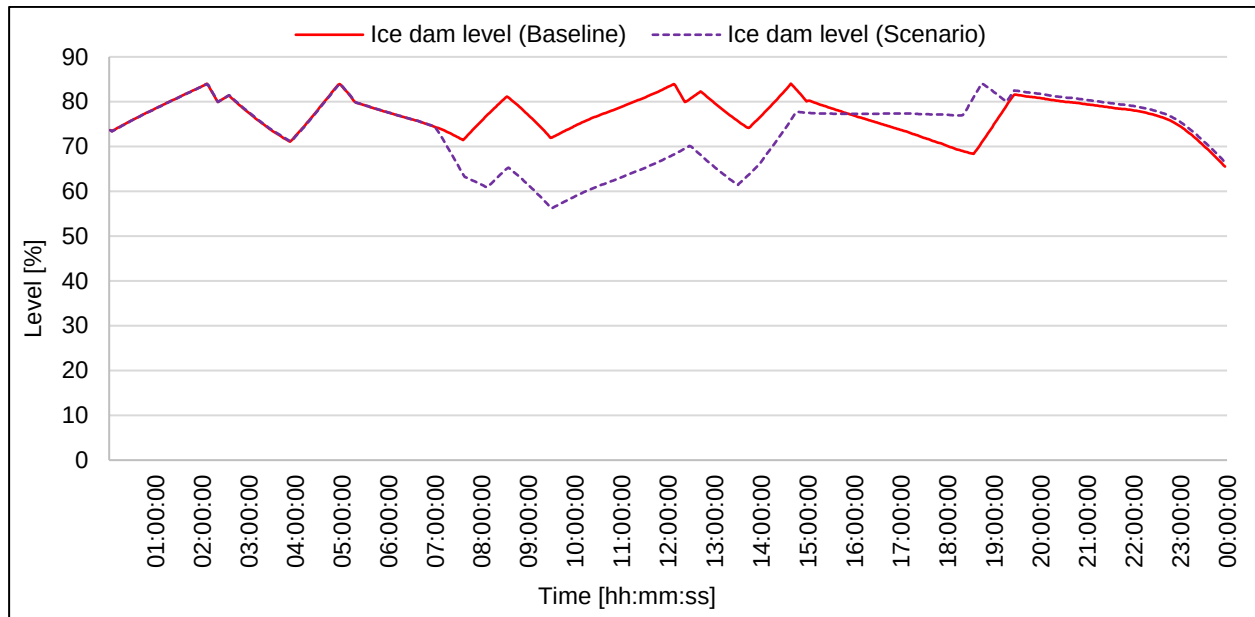


Figure 43: Scenario 4 - Ice dam level

Figure 43 illustrates the decrease in the level of the ice dam during drilling shift due to the fact that less water is flowing into the ice dam. The water stored in the buffer dam is always available to top up the ice dam if the temperature or level drops too low.

This decrease in level and the fact that there is less hot water flowing into the ice dam means that the ice dam temperatures will decrease, resulting in a lower ice dam temperature during drilling shift. Figure 44 illustrates the effect on the ice dam temperatures.

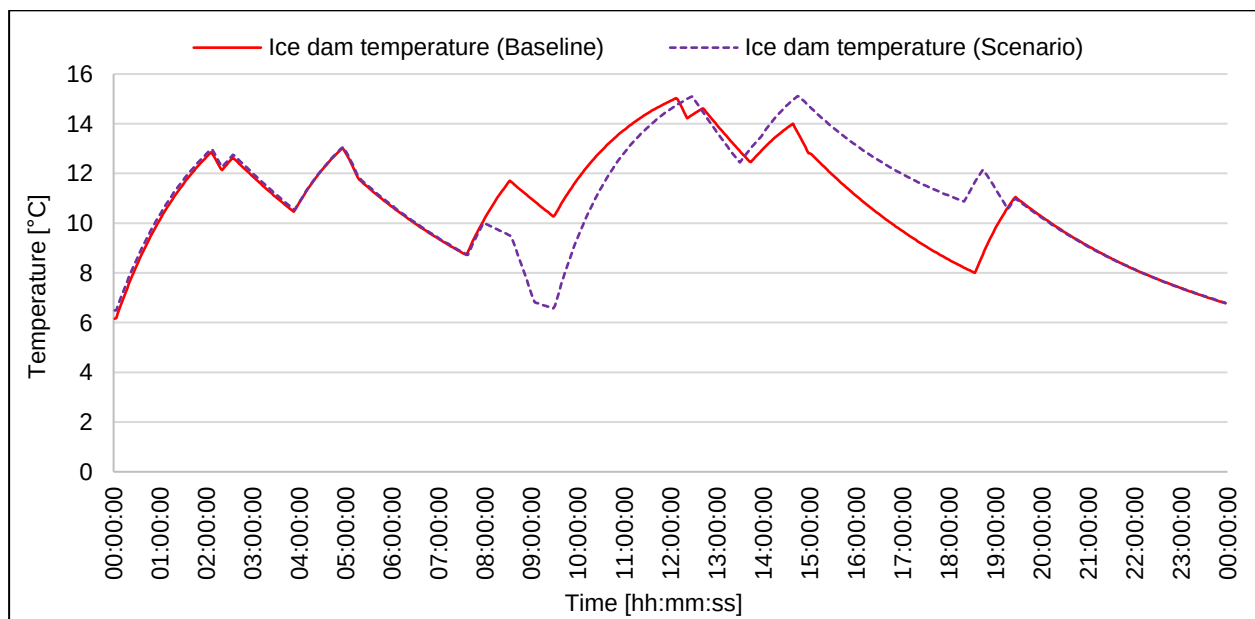


Figure 44: Scenario 4 - Ice dam temperatures

Figure 44 shows that the temperature of the ice dam decreased during drilling shift and increased after drilling shift due to the delay in hot water flow to the ice dam. The lowest temperature reached during drilling shift is 6°C. The average temperature decrease between 07:00 and 13:00 amounts to 1.4°C. This results to an increase in cooling duty during this time of 1.17 MW.

It is important to note that although there is less water flowing into the ice dam, the amount of water that is flowing out of the ice dam must remain the same. This is so that the activities within the mine remain unaffected. Figure 45 illustrates that there is no change in the demand from the mine.

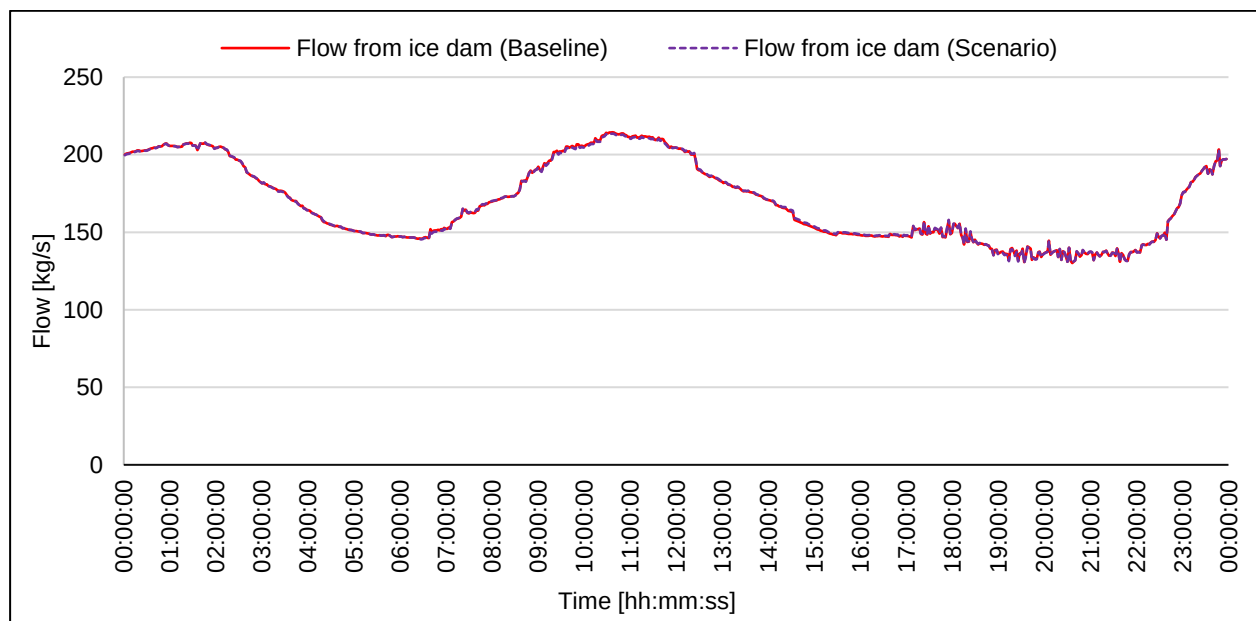


Figure 45: Scenario 4 - Flow from ice dam

Table 20 shows the setpoints implemented on the valves for the water control. The 66L PRV setpoints were kept the same as in Scenario 3. The aim was to ensure that more water is pumped towards Mine B as it is mostly used for the Osmosis plant.

Table 20: Scenario 4 - Valve and pump setpoints

Component	Status	Ice dam level	Buffer dam level
66L Control valve (V5)	Open Closed	= 84% = 80%	-
Ice dam valve (V3)	Open Closed	= 80% = 84%	-
Railveyor valve (V1)	Open	Always	-
RAW valve (V2)	Closed	Always	-
Buffer dam valve (V6)	Open Closed	- -	@ 07:00am = 80 %
5.5 kW pump control	Start Stop	- -	@ 14:00pm = 5%
22 kW pump control	Start Stop	= 45% -	- = 5%

The schematic illustration of Scenario 4 can be found in Figure 70 in Appendix D.

3.6 Process 4: Evaluate best solution

3.6.1 System constraint evaluation of possible solutions

To evaluate which scenario would be most suitable to consider, a scoring strategy was used. The scoring strategy worked as follows:

- If the scenario met the requirement, a score of 1 was allocated.
- If the scenario failed to meet the requirement, a score of 0 was allocated.

Note that all additional infrastructure that was identified was set as a requirement. The main outcome of this study is to develop a redundant dewatering solution. Therefore, the more dewatering options are included in the solution, the more redundant the solution becomes. As mentioned previously, Mine B is the preferred option to dewater most of the water to due to the Reverse Osmosis plant at Mine B. Therefore, dewatering to Mine B was also considered as a requirement.

The ice dam is the root of the dewatering system, therefore it was of utmost importance that it operated within the stated minimum and maximum level. This was also set a requirement. It was also required that the amount of water that was dewatering should be between 37 l/s to 41 l/s. The final requirement was to ensure flow spikes were kept below 180 l/s to prevent column failure due to high water pressures. Table 21 summarises the scoring results of each scenario.

Table 21: Scenario constraint comparison

Requirements	Scenario 1	Scenario 2	Scenario 3	Scenario 4
The ice dam level should not exceed 83%	1	1	1	1
The ice dam level should not decrease below 55%	1	1	1	1
Enable dewatering of 37 l/s to 41 l/s	1	1	1	1
Utilise RAW pipeline	1	1	0	1
Utilise Railveyor pipeline	0	0	1	1
Utilise 55L buffer dam	0	0	0	1
Utilise 66L pipeline	1	1	1	1
Dewater most water to Mine B	0	0	1	1
Flow spikes below 180 l/s	1	0	1	1
Total	6	5	7	9

From Table 21 it is clear Scenario 4 resulted in the highest score. All the scenarios listed above were presented to Mine A as discussed in Section 3.7.1. It was agreed upon that Scenario 4 was the best possible solution.

3.6.2 Cost implication of possible solution

After concluding that Scenario 4 proved to be the best possible solution, a detailed cost analysis was done regarding the additional infrastructure that would be required to implement the proposed solution (Process 4.2.1). A budget of R1 000 000 was approved by upper management for the proposed solution. Table 22 is a summary of the expected cost for the additional infrastructure that is required.

Table 22: Bill of materials (BOM)

Component	Quantity	Unit cost	Total
315 mm Butterfly valve (Ice dam valve & Buffer dam valve)	2	R3 651	R7 302
AUMA Actuator (4-20 mA), EPDM, PN16, Positioner and Gearbox (Ice dam valve)	1	R75 700	R75 700
315 mm AUMA Actuator open and close (Buffer dam valve)	1	R55 896	R55 896
22 kW PLC & VSD	1	R417 395	R417 395
Total			R556 293

Table 22 shows that the additional infrastructure would cost R556 293 which falls well within the approved budget for the project. The additional R443 707 could be used to fund the commissioning costs, labour costs and maintenance costs that will be needed to implement the proposed solution.

3.7 Process 5: Implementation

3.7.1 Project proposal

As suggested by Process 5.1.1, a project kick-off meeting was held with the management team of the mine. The management team consisted of the general manager, mine manager, engineers, mine captains and the shaft foremen. Each simulated scenario was discussed in detail and the limitations and concerns of each scenario were highlighted (Process 5.1.2).

From the results discussed with Mine A, it was decided upon that Scenario 4 would be implemented. After the approval of the control parameters, additional infrastructure and the BOM in Table 22, the project commissioning commenced.

3.7.2 Project commissioning

The complete implementation of the proposed solution took place over a time period of five months. The mine was fully responsible for the hardware commissioning phase which took place over a time period of four months (Process 5.2.1). However, regular inspection audits were conducted, and project progress was provided to Mine A on a bi-weekly basis.

A more hands-on approach could be followed with the control software commissioning. Mine A makes use of REMS to automatically control the dewatering system components. The pump and valve controls that were discussed in Scenario 4 were programmed into the on-site REMS system to ensure accurate system operation (Process 5.2.2).

Most underground dewatering components were instrumented, and real-time data was available on SCADA. However, during site inspection it was noted that the water flow meters at the buffer dam and the pressure loggers at the 66L PRV station were disconnected due to electrical issues. Therefore, these components could not be used for comparative purposes in the validation section of this study.

3.7.3 Validation of strategy

To validate the methodology that was developed in Chapter 2, the actual system performance had to be compared to the predicted results obtained from the simulation (Process 5.3.1). Note that the simulated flow profiles in this section may appear different compared to the simulated flow profiles illustrated in Section 3.5. The reason for this appearance deviation is the data interval difference between the simulation data and the SCADA data. The SCADA data logs half-hourly data whereas the simulation produces data in two-minute intervals.

In Section 3.5, the half-hourly SCADA data was used to calibrate and verify the simulation model. After the simulation was executed, the simulated baseline data was exported in two-minute intervals. The graphs plotted in Section 3.5 were based on the two-minute interval baseline data. In order to compare the actual SCADA data set (half-hourly data set) to the simulated data set (two-minute interval data set), the simulated data had to be converted to half-hourly data. This was done by calculating the average value of the two-minute interval data for half-hourly time periods. The half-hourly simulated data set is plotted against the half-hourly SCADA data in this section of the report.

The ice dam was used as one of the main KPIs to evaluate the system performance. The simulated ice dam level was compared to the actual ice dam level to validate the dam level prediction accuracy of the simulation model. As depicted in Figure 46, the actual ice dam level profile followed the simulated level profile with 4% accuracy. The ice dam level did not exceed the 83% maximum level and did not decrease below the 55% minimum level that was identified during Process 3. From this result it is evident that the ice dam operated well within the design specifications.

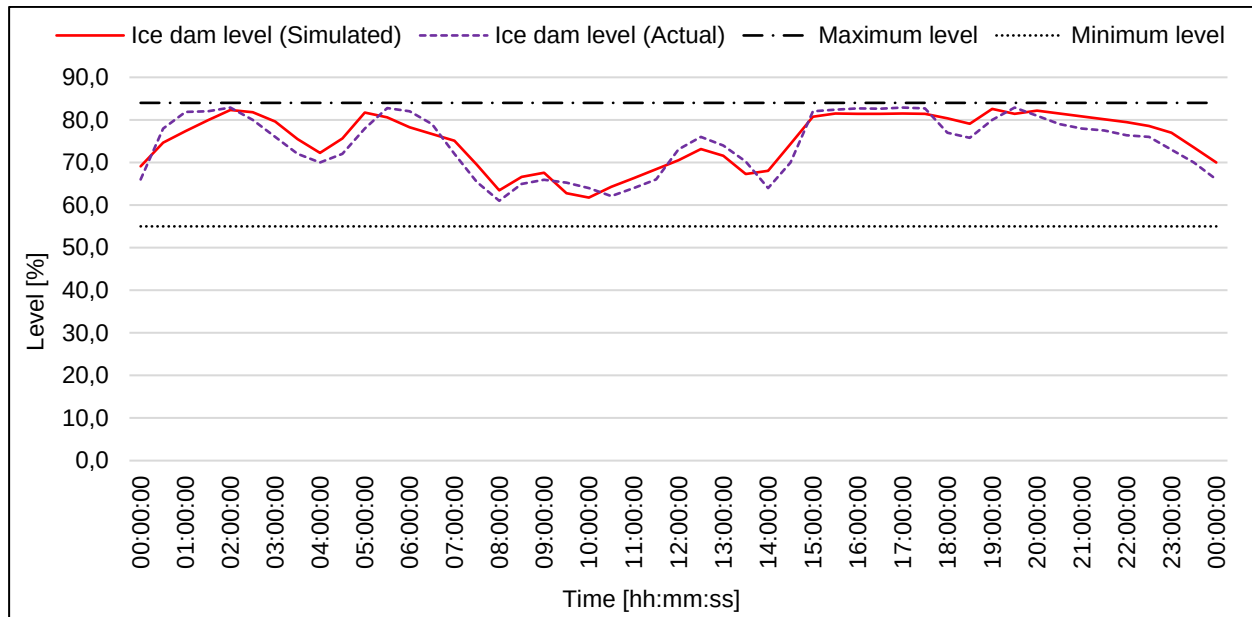


Figure 46: Ice dam level validation

The simulated ice dam temperature profile was also compared to the actual ice dam temperature profile to validate the accuracy of temperature prediction of the simulation model. As portrayed in Figure 47, the actual ice dam temperature profile tracked the simulated temperature profile with 4.6% accuracy. As predicted by the simulation model, the ice dam temperature decreased during drilling shift due to the delay in hot water flowing into the ice dam during this time.

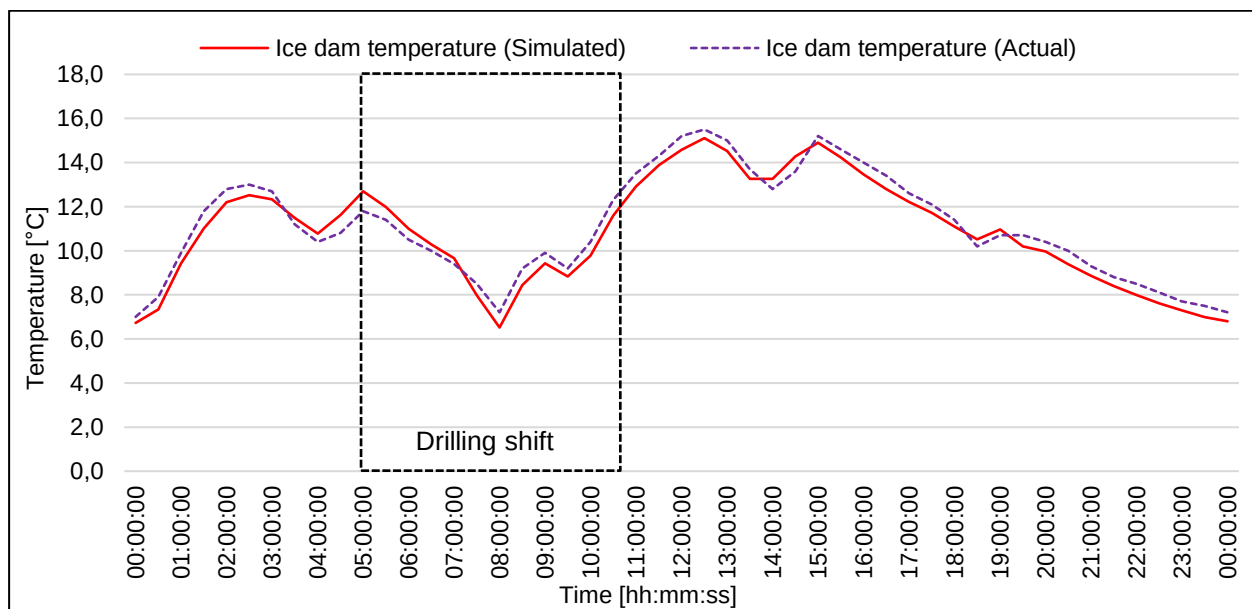


Figure 47: Ice dam temperature validation

The simulated flow into the ice dam was compared to the actual flow into the ice dam to validate the accuracy of flow prediction of the simulation model. From Figure 48 it is evident that the actual

ice dam flow profile deviated with a 6.1% average error compared to the predicted simulation ice dam flow profile.

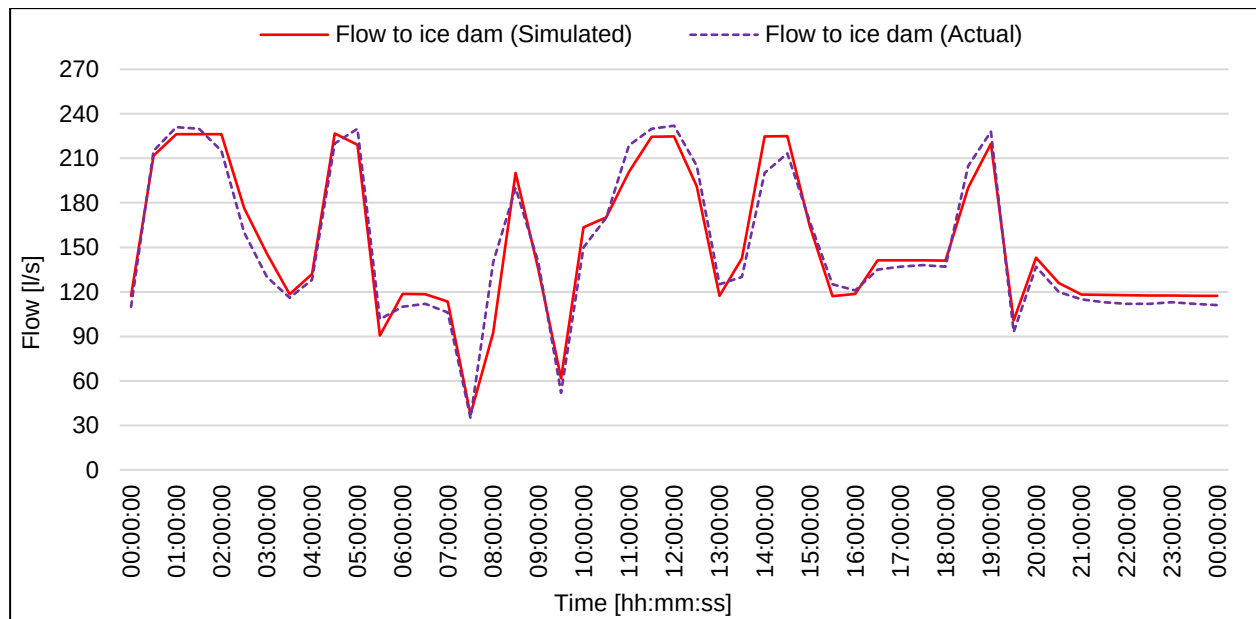


Figure 48: Flow to ice dam validation

To illustrate that the demand side of the dewatering system was unaffected by the implemented changes, the actual flow from the ice dam was compared to the baseline flow data. From Figure 49 it is clear that the actual demand flow profile followed the baseline flow profile with a 2% accuracy deviation.

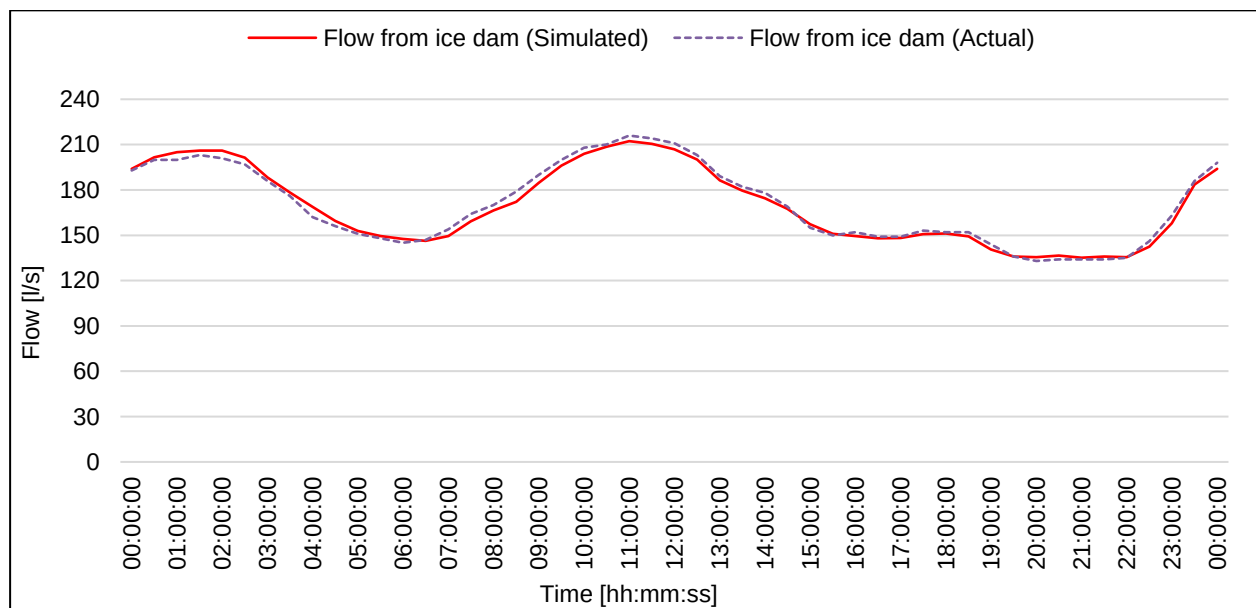


Figure 49: Flow from ice dam validation

The next KPI that was evaluated was the newly integrated 55L buffer dam performance. Note that reliable SCADA was not available for the flow rates in and out of the buffer dam due to unforeseen failure of the flow meter instrumentation that was installed at the inlet and outlet of the buffer dam. Therefore, only the buffer dam level was considered for comparative purposes. The predicted buffer dam level profile corresponded to the actual buffer dam level with an average error of 3%. The buffer dam level comparison is displayed in Figure 50.

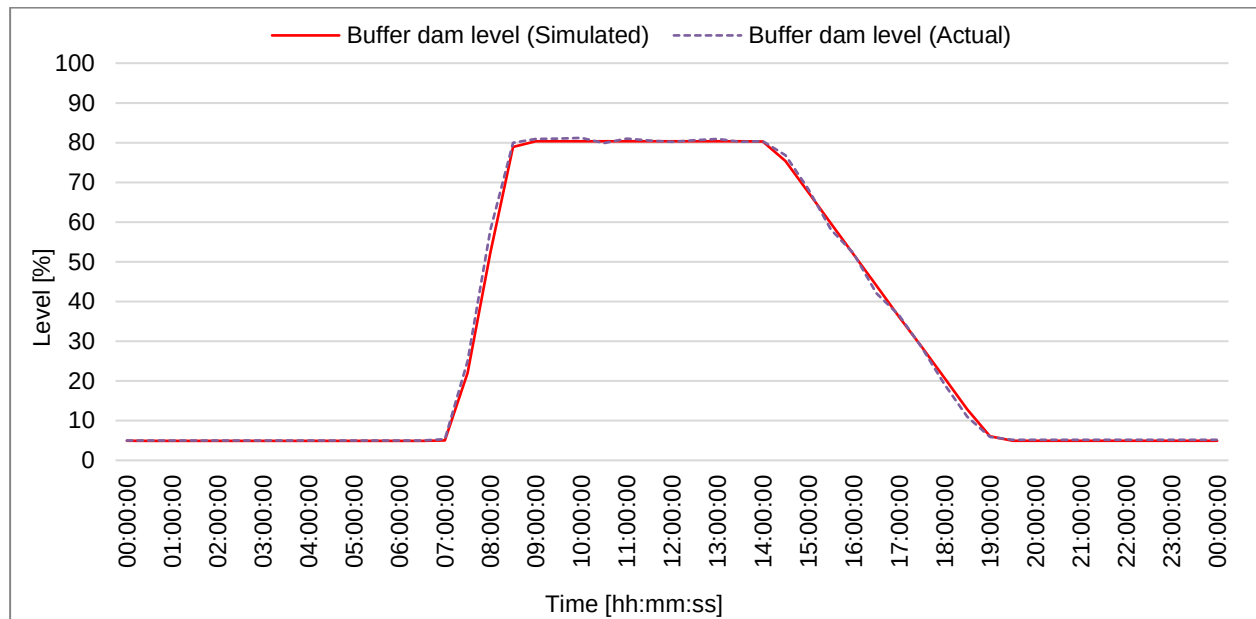


Figure 50: Buffer dam level validation

The main identified outcome of the adjusted dewatering system entailed the dewatering of 36 l/s to 40 l/s of water as a result of the addition of ice for cooling from surface. Therefore, the flow profiles to Mine B and Mine C were evaluated to ensure these criteria were met. Figure 51 illustrates the actual flow profile towards Mine C compared to the predicted simulated flow profile.

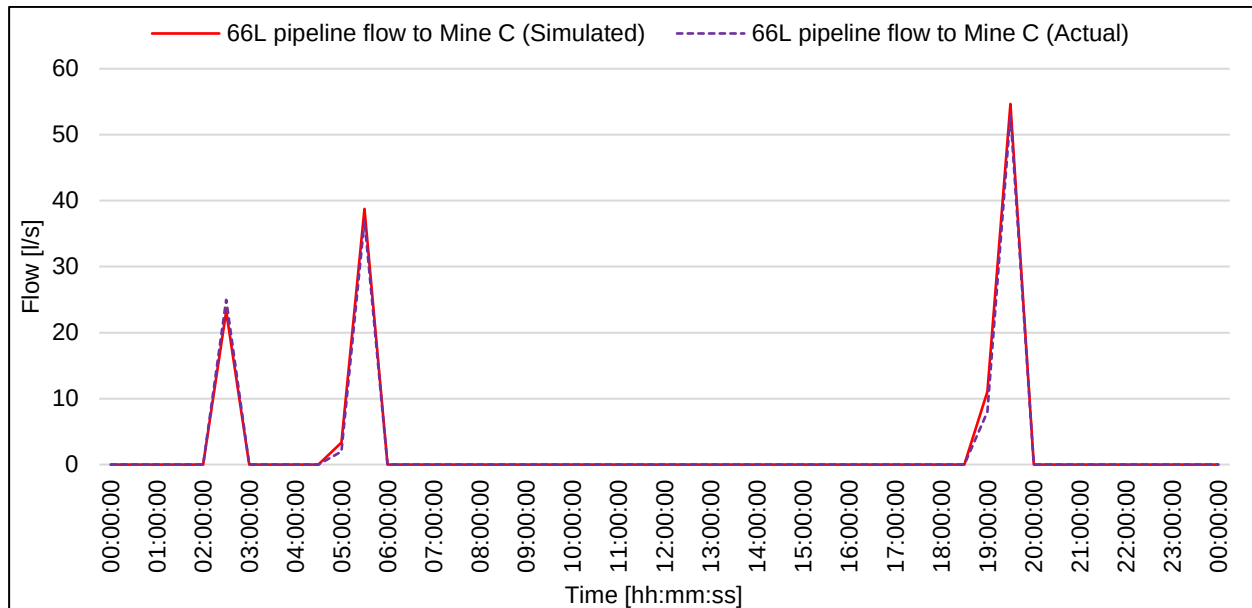


Figure 51: 66L pipeline flow to Mine C validation

As mentioned previously, the simulated flow profile displays slightly different from the simulated flow profile in Section 3.5 due to the two-minute interval time that had to be converted to a half-hourly interval time. However, from Figure 51, it is evident that the 66L pipeline towards Mine C successfully acts as a flow rate spike handler with an average performance error of 5.4% when compared to the simulation output. The average daily flow rate to Mine C equalled to 2.7 L/s or roughly 0.23 ML/day.

Mine B was the preferred option to dewater most of the excess water to due to the Reverse Osmosis water plant that is situated at Mine B. From the Reverse Osmosis plant, the water is re-used in mining hostels. Previously, water was dewatered to Mine B through the RAW pipeline. Recalling from Process 1.4, it was found that the RAW pipeline was busy failing due to the harsh underground conditions. Therefore, the idea was formulated to utilise an alternative pipeline on 55L which is referred to as the Railveyor pipeline.

The RAW pipeline underwent repairs and is still interconnected to the dewatering system of Mine A. However, the RAW valve is always closed and should only be opened when there are problems on the Railveyor pipeline. The RAW pipeline serves as a redundant dewatering component. No real-time data is available at this stage to show the performance of the RAW pipeline due to successful operation of the Railveyor pipeline.

The predicted Railveyor flow profile to Mine B corresponds to the actual Railveyor flow profile with an average error of 4.2%. The average daily water flow rate to Mine B equals 35 l/s or roughly 3 ML/day. Figure 52 depicts the actual flow profile compared to the simulation flow profile.

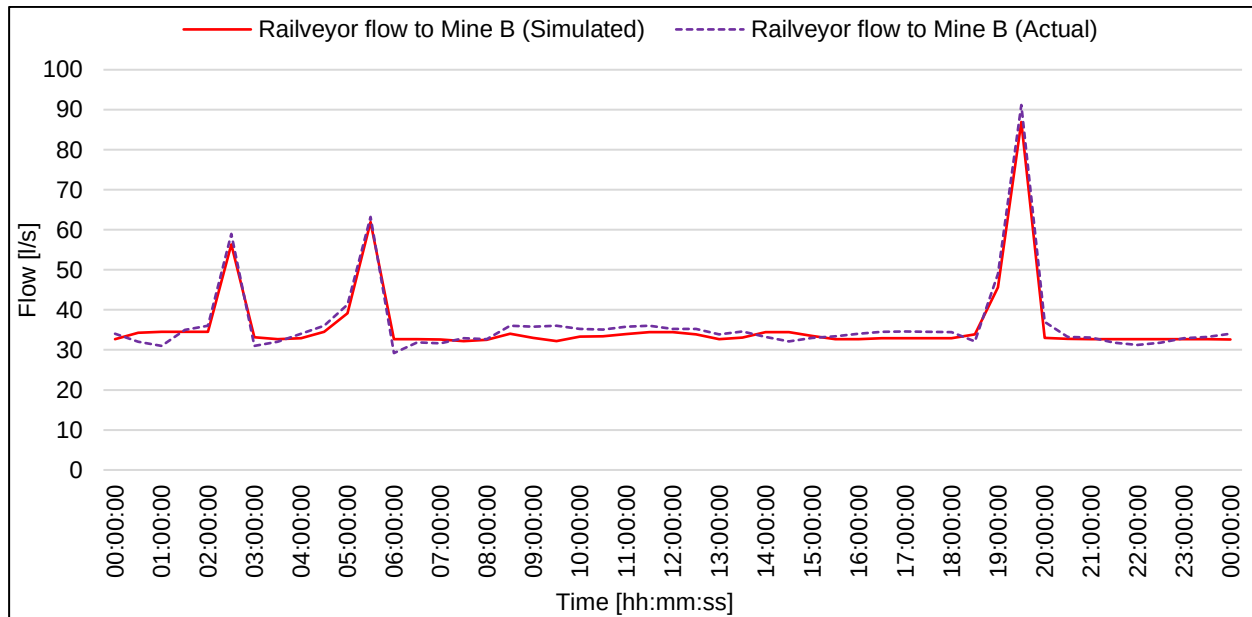


Figure 52: Railveyor flow to Mine B validation

The simulation model predicted the actual system outcome with great accuracy. The total average simulation error proved to be 4.2%. This accuracy is sufficient when considering the dynamic nature and severe complexity of the mine. This validates the use of simulation software to develop alternative dewatering strategies which was also the second objective of this study.

From the results discussed in this section of the report, it is evident that the control philosophy developed using simulation software was successfully executed on the case study. The developed dewatering solution (Scenario 4) has two redundant dewatering options included in the system design. These options include the RAW pipeline for when the Railveyor pipeline fails, and the 66L pipeline to Mine C for when Mine B experiences unforeseen problems to accommodate additional water.

As previously mentioned, Mine A experienced an estimated loss of R30 million for the 2019 financial year due to production that had to be stopped because of dewatering component failure. Mine A has not experienced a loss of production due to dewatering component failure since the implementation of the new dewatering control strategy developed in Section 3.5 for the 2020 financial year. This result further validates this study.

3.7.4 Maintenance procedures

Regular reporting on the system performance is an efficient method to evaluate the performance of the dewatering system as described in Process 5.4. Therefore, an automatic reporting system was introduced on the mine and was used to provide feedback on the system operation. The

reporting system is linked to the SCADA tags that receive real-time data of the actual system. The dewatering report containing the system performance data of the previous day (Process 5.4), is sent out on a daily basis.

Through evaluating the daily report on a regular basis, possible dewatering component failure will be prominent if sudden system performance changes occur. An example of the automatic daily performance report is included in Appendix E.

3.8 Conclusion

Chapter 3 discussed the results of the methodology described in Chapter 2 that was applied to a real-world case study. A full evaluation of the case-study dewatering system was done. The system layout and design specifications were discussed in Section 3.3 and the simulation skeleton model was developed accordingly using Process Toolbox simulation software.

The baseline simulation model was calibrated and discussed in Section 3.4. The baseline simulation was verified within 5% of the actual system using the ice dam level and flow into the ice dam as the main KPIs. The development and simulation of several different dewatering control strategies were discussed in Section 3.5. The most optimal solution was identified through a scoring evaluation strategy and was presented to the case-study mine in Section 3.6.

The proposed simulation solution was implemented on the case-study mine over a time period of six months. Real-time system performance data was compared to the predicted performance data from the simulation model and was discussed in Section 3.7. It was evident that the predicted simulation results deviated with an average error of 4.2% when compared to the actual system performance data. This average error is sufficient when considering the dynamic nature and severe complexity of the mine.

The new developed dewatering solution proved to be redundant and fail-safe due to the different alternative dewatering options that were included in the system design in case of dewatering component failure. This was the main objective of this study. From the validation results, it is evident that the dewatering control philosophy of the proposed solution that was developed through simulation, was successfully implemented on a case-study. The case-study was de-risked from flooding and a loss in production was prevented that can be seen as enormous savings achieved. All the study objectives were successfully met, and this clearly validates this study.

CHAPTER 4: CONCLUSION

4.1 Study overview

The challenges in underground mining operations are continuously increasing throughout the globe due to the increase in mining depth. An increasing heat load is directly proportional to the increase in mining depth. Therefore, several cooling systems that use chilled water are utilised to mitigate the heat load to ensure a safe and tolerable working environment. Chilled water is sent underground and is used in cooling systems, as well as several other mining purposes that were discussed in Chapter 1.

The chilled water that is sent underground needs to be removed from the mine to prevent flooding. Flooding is considered as a critical hazard and therefore dewatering systems were developed to maintain a water balance within the mine. Mining operations are increasing in size and the increase in chilled water usage is inevitable. Therefore, dewatering systems require more sophisticated and redundant dewatering control strategies in case of dewatering component failure. When critical dewatering components fail, the whole integrated water reticulation system fails. To maintain an effective dewatering system, optimal dewatering control philosophies needed to be designed to maintain redundancy at all times.

This study therefore focused on the development of alternative dewatering strategies through the use of simulation software with the main objective to prevent flooding in deep-level mines. The following sub-objectives were formulated to address the above-mentioned need:

1. Identifying possible risks for component failure
2. Develop and verify a simulation of the current system
3. Develop alternative dewatering strategies through the use of simulation software
4. Implement flood prevention strategy to maintain redundancy

Investigation was done into the current industry approach regarding current flood prevention techniques. It was concluded that previous studies failed to provide a methodology that primarily focused on the development of an alternative dewatering control strategy with the main objective to maintain redundancy in case of critical dewatering component failure. However, past literature proved that simulation software could be used to accurately predict the outcome of real-world system changes. The chosen software for this study was PTB. Several studies were previously done using PTB with great success as discussed in Section 1.5.4.

The first step was the familiarisation of the case-study system. During on-site inspection the risk of possible dewatering column failure was noted which was also the first sub-objective of this study. Using PTB, a digital twin of the current dewatering system was constructed. Each dewatering component was calibrated according to the component design specifications. The calibrated components were integrated, and the digital twin model was verified with an average error difference of 1.5% and a maximum error difference of 5.5% compared to real-time data of the current system. From this result it is clear that the second sub-objective for this study was met.

To satisfy the third sub-objective of this study, the calibrated simulation model had to be used to develop and test several possible solutions to the identified problem. Four different scenarios were developed and simulated. Redundancy was kept in mind throughout the scenario development process. A scoring technique was used to determine the most suitable solution which proved to be Scenario 4. Scenario 4 had two redundant dewatering options included in the system design. These options included the use of the RAW pipeline for when the Railveyor pipeline fails, and the 66L pipeline to Mine C for when Mine B experiences unforeseen problems to accommodate additional water.

The proposed solution was implemented on a case-study mine that experienced a loss in production for a total of eight days due to flooding. The loss in production amounted to an estimate loss in revenue of R30 million for the 2019 financial year. The simulated control strategy was programmed into the on-site REMS system to ensure immediate system response to key setpoint changes. The predicted simulation results deviated with an average error of 4.2% when compared to the actual system performance data. This result was adequate when considering the dynamic nature and severe complexity of the mine.

The case study mine has not experienced a loss of production due to dewatering component failure since the implementation of the new dewatering control strategy. The mass balance within Mine A was also maintained effectively with 3.23 ML of water per day that was removed from Mine A. Recalling that 3.2 ML of ice is sent underground per day, the excess 0.03 ML of water was assumed to be fissure water. From these results it is evident that the last sub-objective of this study was met, and ultimately the main objective of this study as well.

4.2 Recommendations for further study

The objective of this section is to provide recommendations for further studies to possibly improve the results obtained from this study, and to apply this method on other industries. Five recommendations are listed below and are discussed in more detail in the latter part of this section.

- Development of a model to predict fissure water for life of mine planning.
- Derive a model to predict optimum mixing ratios between warm water and ice in an ice dam.
- A method to quantify the impact dewatering strategies has on the primary ventilation system.
- Test the developed methodology on municipal water systems.
- Implement the developed methodology on sanitary sewerage systems.

As mentioned in Section 4.3.3, the amount of fissure water present in the dewatering system was theoretically calculated by performing a simple mass balance over the water reticulation system. This quantity which amounted to 0.08 ML/day was incorporated into the simulation model and was assumed to be a constant value of fissure water on the specific case study. However, as mining operations expand, the amount of fissure water present will increase. Therefore, a method to predict the quantity of fissure water that needs to be accounted for in the dewatering system design is needed. Through such a method, the dewatering system can be simulated and adapted for the whole life of mine (LOM).

During manual underground spot checks, it was noted that the ice dam temperature was inconsistent depending on the location of the temperature reading. The SCADA ice dam temperature probe on this case study was situated at the bottom of the ice dam. The ice dam proved to be cooler at the upper section compared to the temperature at the bottom section of the ice dam. This is an indication that there is insufficient mixing in the ice dam between the water and ice that is gravity fed from surface. Therefore, investigation should be done on methods to ensure optimal mixing between the ice and water in an ice dam. The recommended study should particularly be done on case studies where surface ice plants are utilised as refrigeration units.

Chilled water is mainly used for cooling purposes underground. A future study should consider developing a model that integrates the water reticulation system consisting of the refrigeration system with the primary ventilation system. To quantify the impact of water control strategies on

the refrigeration system and ventilation system will ensure that no system is negatively affected with certain system changes.

The mining environment is not the only industry that acquires water control methods to prevent flooding. A study is recommended to implement the devised methodology on a municipal water system that needs to be handled in a controlled manner. A test should be conducted to determine if the execution of this methodology on municipal water systems could lead to water saving initiatives to help address the water crises around the globe. It is however recommended that the case study have an automatic control system installed to eliminate human error.

Another industry that requires effective automatic system control is sanitary sewerage systems. The flooding of sewerage systems is an everyday occurrence in South Africa and this method could help mitigate this unhygienic scenario.

BIBLIOGRAPHY

- [1] August. V. Greth, "Evaluating Mine Cooling Systems and Mine Ventilation Strategies to be Applied in Deep and Hot US Mines," Thesis, Master of Science in Mining Engineering," University of Nevada, 2018.
- [2] D. G. Krige and C. P. S. Barnard, "Gold-mine productivity as affected by the average wet-bulb temperature of the underground working places," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 81, pp. 117–121, 1981.
- [3] T. Maurya, K. Kareena, H. Vardhan, M. Aruna, and M. G. Raj, "Potential Sources of Heat in Underground Mines – A Review," *Procedia Earth and Planetary Science*, vol. 11, pp. 463–468, 2015.
- [4] T. Maurya, K. Kareena, H. Vardhan, M. Aruna, and M. G. Raj, "Potential Sources of Heat in Underground Mines – A Review," *Procedia Earth and Planetary Science*, vol. 11, pp. 463–468, 2015.
- [5] D. J. Brake, "The application of refrigeration in mechanised mines," *AusIMM Proceedings*, vol. 306, pp. 1–9, 2001.
- [6] A. Greth, P. Roghanchi, and K. C. Kocsis, "A review of cooling system practices and their applicability to deep and hot underground US mines," *16th North American Mine Ventilation Symposium*, vol. 11, pp. 1–9, 2017.
- [7] L. Mackat, S. Bluhm, and J. Van Rensburg, "Refrigeration and cooling concepts for ultra-deep platinum mining," *The Southern African Institute of Mining and Metallurgy*, vol. 4, pp. 285–292, 2010.
- [8] H. Wagner, "The management of heat flow in deep mines," *Geomechanik und Tunnelbau*, vol. 4, pp. 157–163, 2011.
- [9] X. Nie, X. Wei, X. Li, and C. Lu, "Heat Treatment and Ventilation Optimization in a Deep Mine," *Advances in Civil Engineering*, pp. 1–12, 2018.
- [10] J. C. Vosloo, "A new minimum cost model for water reticulation systems on deep mine", Thesis, Philosophiae Doctor in Electrical Engineering, North-West University, 2008.

- [11] J. G. Pretorius, M. J. Mathews, P. Maré, M. Kleingeld, and J. Van Rensburg, "Implementing a DIKW model on a deep mine cooling system," *International Journal of Mining Science and Technology*, vol. 29, pp. 319–326, 2019.
- [12] A. J. Schutte, M. Kleingeld, and H. J. Groenewald, "A holistic energy-cost evaluation of ice vs chilled water in mining," *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 118–122, 2016.
- [13] T. Janus and B. Ulanicki, "Hydraulic Modelling for Pressure Reducing Valve Controller Design Addressing Disturbance Rejection and Stability Properties," *Procedia Engineering*, vol. 186, pp. 635–642, 2017.
- [14] D. Stephenson, "Distribution of water in deep gold mines in South Africa," *International journal of mine water*, vol. 2, pp. 21–30, 1983.
- [15] H. J. van Staden, J. F. van Rensburg, and H. J. Groenewald, "Optimal use of mobile cooling units in a deep-level gold mine," *International Journal of Mining Science and Technology*, vol. 30, pp. 547–553, 2020.
- [16] P. F. H. Peach, M. Kleingeld, and J. I. G. Bredenkamp, "Optimising deep-level mine refrigeration control for sustainable cost savings," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 1–8, 2017.
- [17] J. Bandrowski, J. Hehlmann, H. Merta, and J. Ziolo, "Studies of sedimentation in settlers with packing," *Chemical Engineering and Processing: Process Intensification*, vol. 36, pp. 219–229, 1997.
- [18] M. I. Witham, A. F. Grabsch, A. T. Owen, and P. D. Fawell, "The effect of cations on the activity of anionic polyacrylamide flocculant solutions," *International Journal of Mineral Processing*, vol. 114–117, pp. 51–62, 2012.
- [19] S. Kosharna, A. Stetsenko, V. Glon, and L. Kozakova, "Reliability of parallel and serial centrifugal pumps for dewatering in mining process," *Acta Montanistica Slovaca*, vol. 23, pp. 119–131, 2018.
- [20] P. Maré, J. H. Marais, and J. Van Rensburg, "Improved implementation strategies to sustain energy saving measures on mine cooling systems," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 102–109, 2015.

- [21] R. Venter, "Reconfiguring deep-level mine dewatering systems for increased water volumes", Thesis, Master of Mechanical Engineering, North-West University, 2020.
- [22] F. Felfelani and R. Kerachian, "Municipal water demand forecasting under peculiar fluctuations in population: A case study of Mashhad, a tourist city," *Hydrological Sciences Journal*, vol. 61, no. 8, pp. 1524–1534, 2016.
- [23] G. Gokilakrishnan, S. Divya, R. Rajesh, and V. Selvakumar, "Operating torque in ball valves: a review," *International Journal For Technological Research In Engineering*, vol. 2, pp. 311–315, 2014.
- [24] Emerson Fisher, "Control valve handbook 5 edition," *Emerson Automation Solutions*, 2005.
- [25] Ming. J. Chern, Ping. H. Hsu, Y. Cheng, Po. Y. Tseng, and Chang. M. Hu, "Numerical Study on Cavitation Occurrence in Globe Valve," *Journal of Energy Engineering*, vol. 139, pp. 25–34, 2013.
- [26] S. L. Shen, H. M. Lyu, A. Zhou, L. H. Lu, G. Li, and B. B. Hu, "Automatic control of groundwater balance to combat dewatering during construction of a metro system," *Automation in Construction*, vol. 123, pp. 1–11, 2021.
- [27] I. Halkijevic, Z. Vukovic, and D. Vouk, "Frequency pressure regulation in water supply systems," *Water Science and Technology: Water Supply*, vol. 13, pp. 896–905, 2013.
- [28] S. Singh *et al.*, "Data management for developing digital twin ontology model," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 235, no. 14, pp. 2323–2337, 2021.
- [29] N. B. Gorev, V. N. Gorev, I. F. Kodzheshirova, I. A. Shedlovsky, and P. Sivakumar, "Simulating Control Valves in Water Distribution Systems as Pipes of Variable Resistance," *Journal of Water Resources Planning and Management*, vol. 144, no. 11, pp. 1–16, 2018.
- [30] S. Oshurbekov, V. Kazakbaev, V. Prakht, and V. Dmitrievskii, "Increasing service life and system efficiency of parallel pumps using combined pump regulation," *Water (Switzerland)*, vol. 13, 2021.
- [31] B. Pascoe, J. Van Rensburg, and R. Joubert, "Dewatering processes to sustain savings when a critical system fails," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 1–5, 2019.

- [32] A. J. H. Nel, J. F. van Rensburg, and C. Cilliers, "Improving existing DSM initiatives on mine refrigeration systems for sustainable performance," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 1–7, 2017.
- [33] R. Pelzer, E. H. Mathews, D. F. le Roux, and M. Kleingeld, "A new approach to ensure successful implementation of sustainable demand side management (DSM) in South African mines," *Energy*, vol. 33, pp. 1254–1263, 2008.
- [34] J. Vosloo, L. Liebenberg, and D. Velleman, "Case study: Energy savings for a deep-mine water reticulation system," *Applied Energy*, vol. 92, pp. 328–335, 2012.
- [35] K. Rózkowski, R. Zdechlik, and W. Chudzik, "Open-pit mine dewatering based on water recirculation—case study with numerical modelling," *Energies*, vol. 14, p. 4576, 2021.
- [36] W. Schoeman, N. Oosthuizen, and J. F. Van Rensburg, "Optimum water distribution between pumping stations of multiple mine shafts," *Proceedings of the 10th Industrial and Commercial Use of Energy Conference*, Cape Town, pp. 1–4, 2013.
- [37] A. Romero, D. Millar, M. Carvalho, J. M. Maestre, and E. F. Camacho, "A comparison of the economic benefits of centralized and distributed model predictive control strategies for optimal and sub-optimal mine dewatering system designs," *Applied Thermal Engineering*, vol. 90, pp. 1172–1183, 2015.
- [38] K. T. Witthüser, M. Holland, T. Seidel, and C. M. König, "Numerical modelling of mine dewatering and flooding in the Evander Gold Basin, South Africa," *South African Journal of Geology*, vol. 118, pp. 71–82, 2015.
- [39] J. Szczepiński, "The Significance of Groundwater Flow Modeling Study for Simulation of Opencast Mine Dewatering, Flooding, and the Environmental Impact," *Water*, vol. 11, 2019.
- [40] P. Maré and P. J. H. Marais, "Novel simulations for energy management of mine cooling systems", Thesis, Philosophiae Doctor in Mechanical Engineering, North-West University, 2017.
- [41] B. M. Friedenstien, C. Cilliers, and J. van Rensburg, "Simulating operational improvements on mine compressed air systems," *South African Journal of Industrial Engineering*, vol. 29, pp. 69–81, 2018.

- [42] X. Luo, M. Dooner, W. He, J. Wang, and Y. Li, "Feasibility study of a simulation software tool development for dynamic modelling and transient control of adiabatic compressed air energy storage with its electrical power system applications," *Applied Energy*, vol. 228, pp. 1198–1219, 2018.
- [43] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure", Thesis, Master of Mechanical Engineering, North-West University, 2017.
- [44] P. M. Williams, "Techniques for Root Cause Analysis," *Baylor University Medical Center Proceedings*, vol. 14, pp. 154–157, 2001.
- [45] W. Bouwer, "Designing a Dynamic Thermal and Energy System Simulation Scheme for Cross Industry Applications", Thesis, Philosophiae Doctor in Mechanical Engineering, North-West University, 2004.
- [46] K. S. More, C. Wolkersdorfer, N. Kang, and A. S. Elmaghraby, "Automated measurement systems in mine water management and mine workings - A review of potential methods," *Water Resources and Industry*, vol. 24, p. 100136, 2020.
- [47] T. Smith, H. P. R. Joubert, and J. F. Van Rensburg, "Automated control of mine dewatering pumps to reduce electricity cost," *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 62–69, 2015.
- [48] P. J. Oberholzer, "Best practices for automation and control of mine dewatering systems", Thesis, Master of Mechanical Engineering, North-West University, 2014.
- [49] D. H. Velleman, J. Venter, and R. Pelzer, "Automated demand side management of clear water pumping and storage for shifting load out of Eskom's domestic peak in the mining industry," *Proceedings of the 9th Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 17–20, 2012.
- [50] P. F. H. Peach, J. F. Van Rensburg, and J. I. G. Bredenkamp, "Control integration of deep-level mine water reticulation sub-systems," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 1–7, 2019.
- [51] C. A. Alves de Araujo Junior, J. M. Mauricio Villanueva, R. J. S. de Almeida, and I. E. Azevedo de Medeiros, "Digital twins of the water cooling system in a power plant based on fuzzy logic," *Sensors*, vol. 21, pp. 1–22, 2021.

- [52] S. Taljaard, J. F. Van Rensburg, and H. J. Groenewald, "Comparative study of mine dewatering control systems," *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 1–7, 2018.
- [53] W. Van Der Wateren, H. P. R. Joubert, and M. Kleingeld, "Optimising energy recovery in mine dewatering systems," *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 1–8, 2019.
- [54] C. Wei *et al.*, "Selection of optimum biological treatment for coking wastewater using analytic hierarchy process," *Science of the Total Environment*, vol. 742, p. 140400, 2020.
- [55] H. P. R. Joubert, J. F. Van Rensburg, and M. Kleingeld, "Improved risk management processes for South African industrial ESCos," *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, pp. 29–36, 2016.
- [56] H. L. Grobbelaar, "Maintenance procedures on DSM pumping projects to improve sustainability", Thesis, Master of Mechanical Engineering, North-West University, 2014.
- [57] L. Gao *et al.*, "A systems model combining process-based simulation and multi-objective optimisation for strategic management of mine water," *Environmental Modelling and Software*, vol. 60, pp. 250–264, 2014.
- [58] L. Zhao, W. J. Cai, and Z. H. Man, "Neural modeling of vapor compression refrigeration cycle with extreme learning machine," *Neurocomputing*, vol. 128, pp. 242–248, 2014.
- [59] C. K. Lee, "A simplified explicit model for determining the performance of a chilled water cooling coil," *International Journal of Refrigeration*, vol. 43, pp. 167–175, 2014.
- [60] B. E. V. E. Smith, "An Introductory Guide to Valve Selection," p. 216, 1995.
- [61] R. K. Arifulin, I. M. Kashtanov, and N. A. Antonov, "Shut-off device for well-head equipment," vol. 48, pp. 23–26, 2012.
- [62] S. J. Oh, J. H. Yoon, and S. P. Kim, "A study on the flow characteristics of butterfly valve with baffles," *Journal of Mechanical Science and Technology*, vol. 35, pp. 1065–1073, 2021.
- [63] P. Naseradinmousavi and C. Nataraj, "Nonlinear mathematical modeling of butterfly valves driven by solenoid actuators," *Applied Mathematical Modelling*, vol. 35, pp. 2324–2335, 2011.

APPENDIX A: REFRIGERATION PLANTS

Refrigeration plants

The primary purpose of refrigeration plants is to supply chilled water to air-cooling systems like BACs and several other mining activities which are discussed in more detail in Chapter 1. Refrigeration plants work on the thermodynamic vapour-compression cycle. The vapour-compression cycle is a closed loop cycle consisting of four main components: condenser, evaporator, compressor, and expansion valve [58]. Figure 53 shows the main components of the vapour-compression cycle.

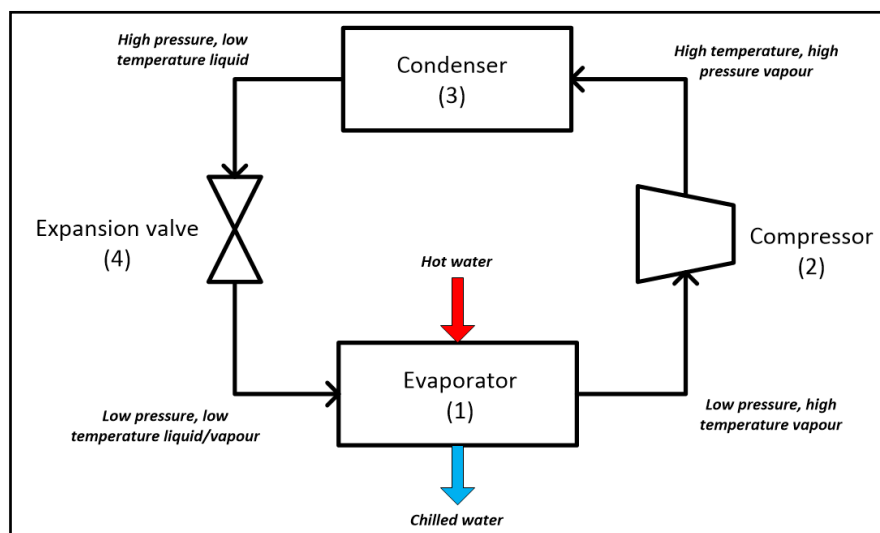


Figure 53: Vapour-compression cycle⁷

The evaporator (component 1) is a refrigerant reservoir in a shell-and-tube heat exchanger (HTX) configuration. The hot water entering the evaporator flows over tubes where a liquid refrigerant is present. The refrigerant is used to extract heat from the water flowing through the evaporator. The refrigerant evaporates after enough heat is absorbed. A compressor (component 2) introduces mechanical work to the cycle. The refrigerant vapour is compressed resulting in a refrigerant vapour pressure and temperature increase. The high pressure and high temperature refrigerant enter the condenser.

The condenser (component 3) is also a shell-and-tube HTX which is used to remove heat from the refrigerant. An expansion valve (component 4) is used to decrease the pressure of the

⁷ Adapted from Figure 1 from [58]

refrigerant before entering the evaporator again [11]. The repetition of this cycle results in chilled water reaching temperatures of about 3 °C [10]. The chilled water produced by the refrigeration plants is used to supply BACs on surface and underground, depending on the depth of the mine.

Ice plants are also used in ultra-deep mines to provide chilled water. They are more efficient than refrigeration plants at mines exceeding depths of 2 300 m [7], [12]. Ice plants provide cooling in the form of ice slurry that is produced by the ice plant on surface. The ice slurry is distributed down the shaft and falls into an ice dam underground [12]. Ice plants also work on the vapour-compression cycle.

Mobile cooling units (MCUs)

Mobile cooling units/cooling cars/spot coolers are tertiary cooling components used in deeper mining areas where the primary and secondary cooling systems are inefficient. MCUs are normally situated at cross-cut intake areas when the environmental temperatures become intolerable. MCUs are indirect contact heat exchangers and consist of booster fans integrated with cooling coils that work on the same principle as a radiator [59].

A liquid coolant (chilled water) flows through the cooling coils while the booster fan blows hot air through the cooling car and over the cooling coils. Convective heat transfer takes place between the chilled water and the hot air that is flowing over the cooling coils. As a result of this heat transfer method, cold air is supplied to key working areas [15]. A typical MCU is displayed in Figure 54.



Figure 54: Typical mobile cooling unit⁸

⁸ Adapted from Figure 9 from [7]

As mentioned before, the chilled water removes heat from the hot air flowing over the cooling coils. To calculate the heat added to the chilled water, a mass balance over the MCU can be done as indicated in Figure 55:



Figure 55: Water balance⁹

The heat added to the chilled water can be calculated by using energy Equation 1.

Equation 1: Heat added to chilled water [21]

$$\text{Heat added } (\dot{q}) = \dot{m}C_p(T_{out} - T_{in})$$

Where

$\dot{q}$	=	Heat added	kW
$\dot{m}$	=	Water mass flow	kg/s
T_{in}	=	Inlet water temperature	$^{\circ}C$
T_{out}	=	Outlet water temperature	$^{\circ}C$
C_p	=	Specific heat of water	$J/kg^{\circ}C$

⁹ Adapted from Figure 2.8 of [21]

APPENDIX B: CONTROL VALVE TYPES

Gate valve

Gate valves make use of a gate that moves perpendicular to the flow of the fluid. Gate valves are used in applications where very little pressure loss is required [60]. The position of the gate is controlled by a screw thread that is connected to a rotating wheel on top of the valve. Gate valves are frequently used as shut-off valves and are designed for fully open or fully closed scenarios. These valves should not be used as control valves [61]. Figure 56 provides a sectional view of a gate valve.



Figure 56: Gate valve illustration¹⁰

Ball valve

A ball valve has a one-way valve configuration with a ball-shaped disk installed in line with the flow passage. The ball has a large hole through it to allow for flow through it. As seen from Figure 57, the ball rotates from parallel to perpendicular with reference to the flow direction of the fluid, when the valve is closed. This valve configuration is ideal for on/off applications and is also suitable for throttling [24].

¹⁰ Obtained from: Zetkama. [Online]. Available: www.zetkama.com/industrial-valves/gate-valves-zgat/

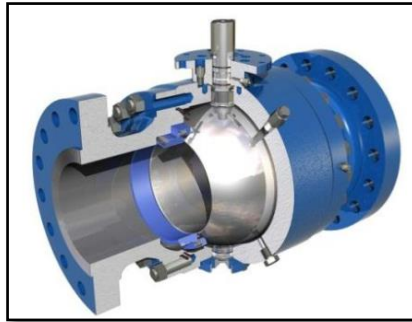


Figure 57: Ball valve illustration¹¹

When ball valves are used for throttling purposes over extended periods of time, erosion of the exposed seat becomes a possibility due to the high velocity flow through the valve [23].

Globe valve

Globe valves are mostly used in throttling applications. They are also suitable for flow and pressure regulation, as well as complete shut-off of flow [24]. Globe valves can control the flow of the fluid through the valve by simply adjusting the handwheel. Special cage trims are designed to change the characteristics of the valve. Cage trims refer to energy-dissipating disks that create smaller pressure drops over the valve. These cage trims also prevent cavitation in globe valves [25]. Figure 58 represents a typical globe valve.

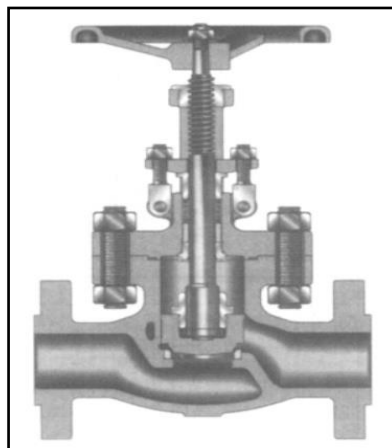


Figure 58: Globe valve illustration¹²

Due to the tortuous flow path of the fluid, large pressure drops can be expected over globe valves. Globe valves have a much larger pressure drop compared to gate valves or ball valves [24], [25].

¹¹ Obtained from: Global valve & Controls. [Online]. Available: www.globalvalveandcontrols.com

¹² Obtained from: ScienceDirect. [Online]. Available: www.sciencedirect.com/topics/engineering/globe-valve

Butterfly valve

Butterfly valves are used in a wide variety of applications due to their low manufacturing cost and ease of installation [62]. A butterfly valve allows for a flow through a straight passage and is ideal for on/off applications. This valve is also suitable for throttling due to the tight shut-off capability. There is a pressure loss through the valve even in an open configuration due to the rotating disk that is present in the flow path [63]. Figure 59 represents a butterfly valve.



Figure 59: Butterfly valve illustration¹³

There is a drawback in control applications using butterfly valves. The liquid passing through the valve induces a torque on the rotating disk. Due to this occurrence, large actuators with high output power are needed in high pressure applications [48].

¹³ Obtained from: Weir. [Online]. Available: www.weirpowerindustrial.com

APPENDIX C: MINE A DXF LAYOUTS

Figure [59-65] in Appendix C illustrates the DXF layouts that were obtained from the mine for each mining level.

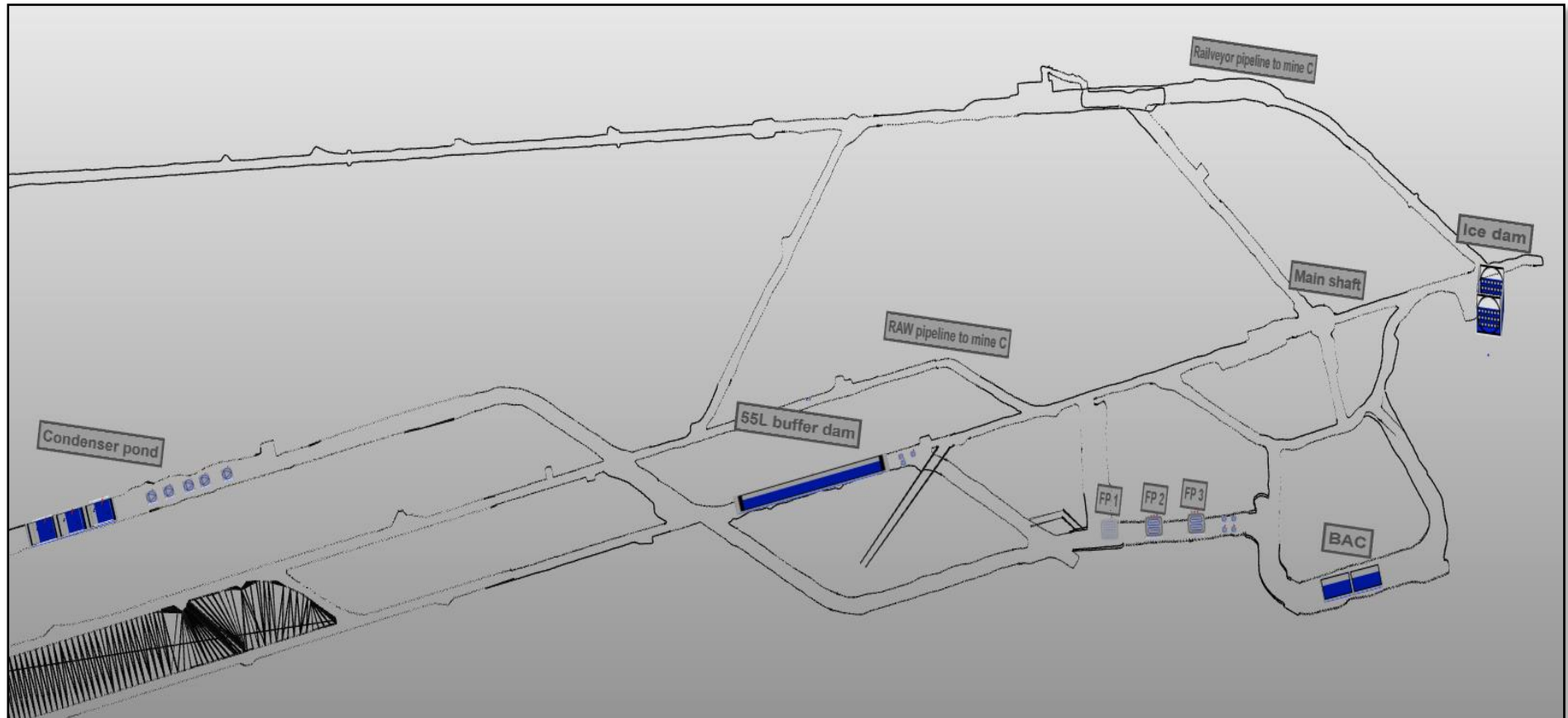


Figure 60: 55L DXF layout

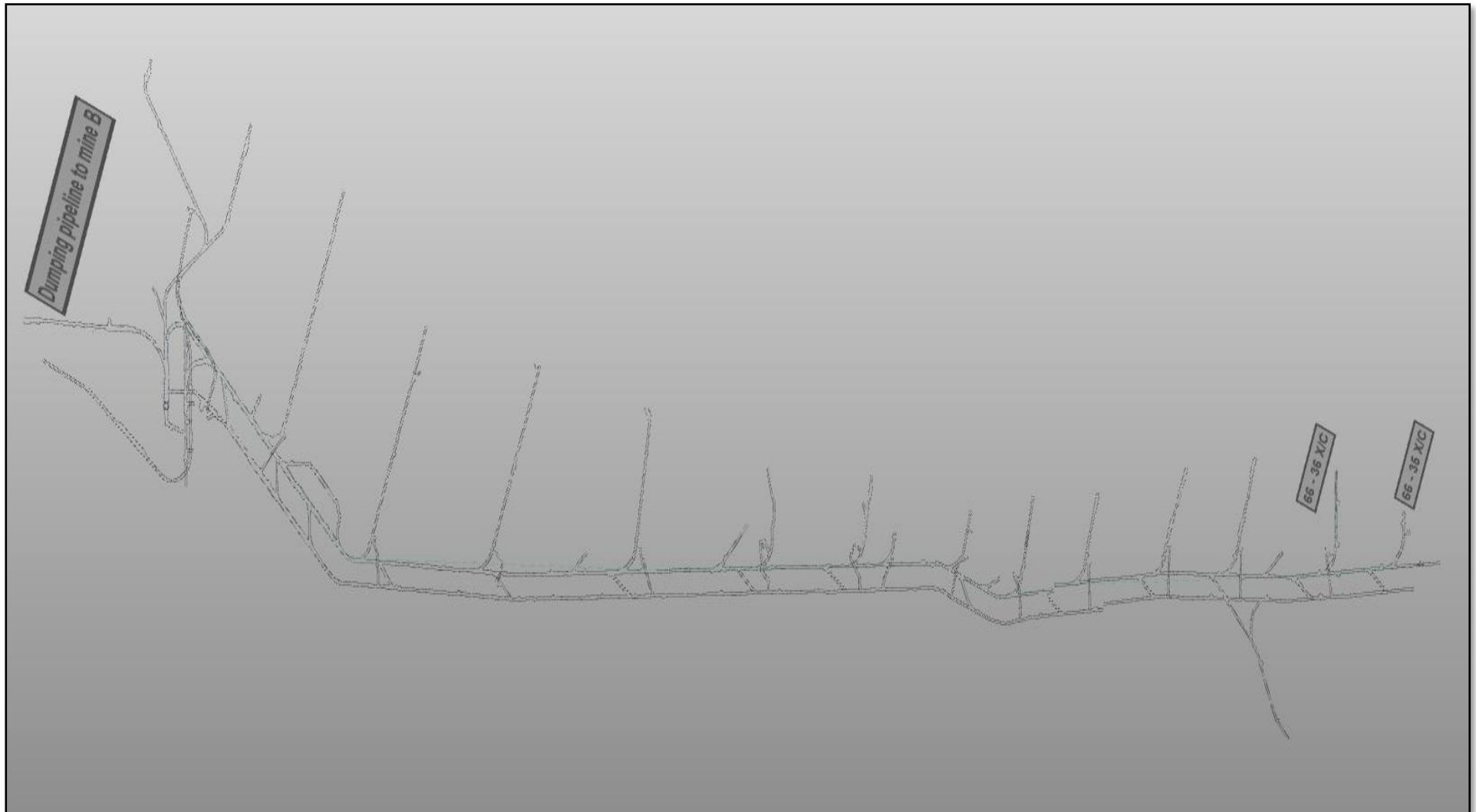


Figure 61: 66L DXF layout

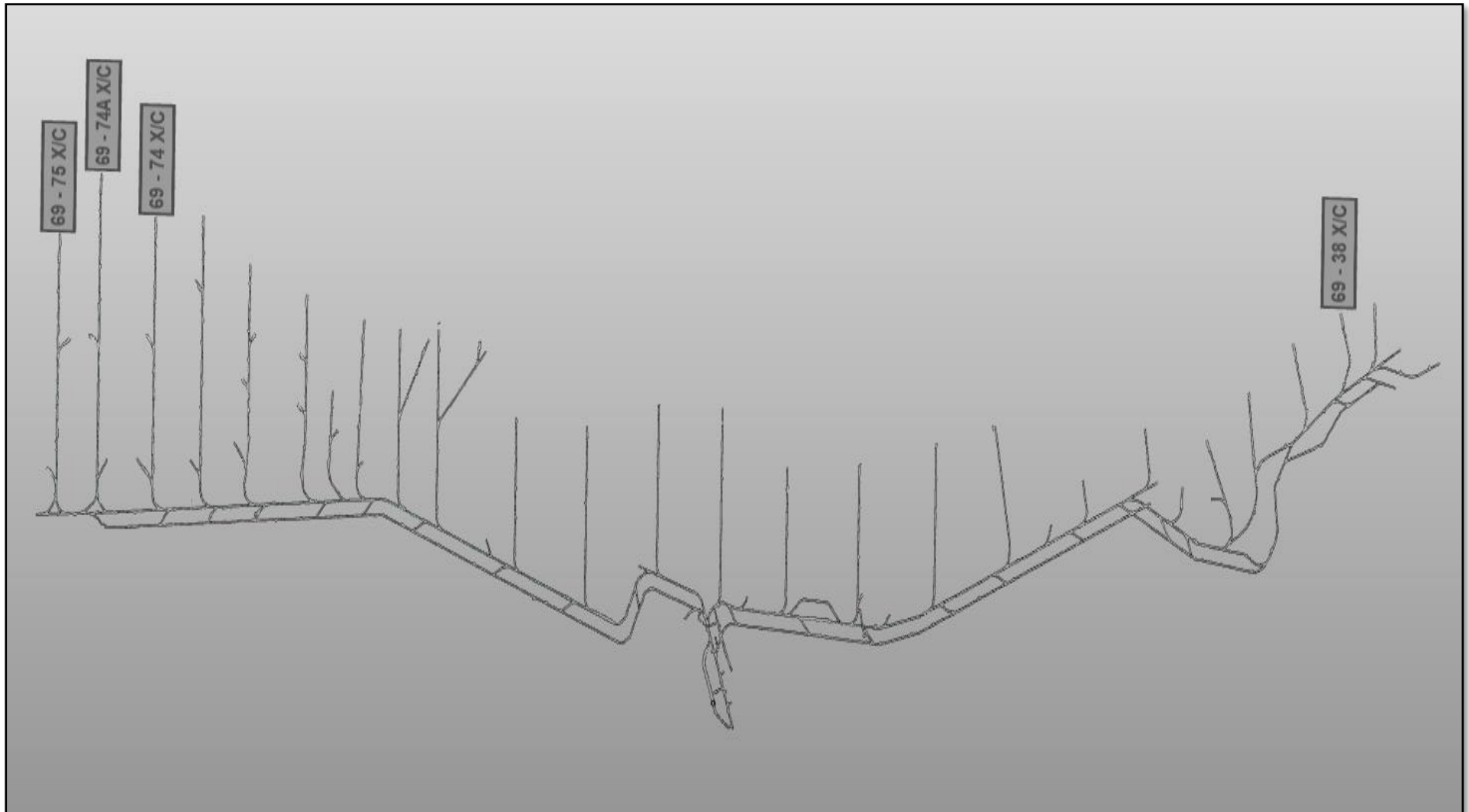


Figure 62: 69L DXF layout

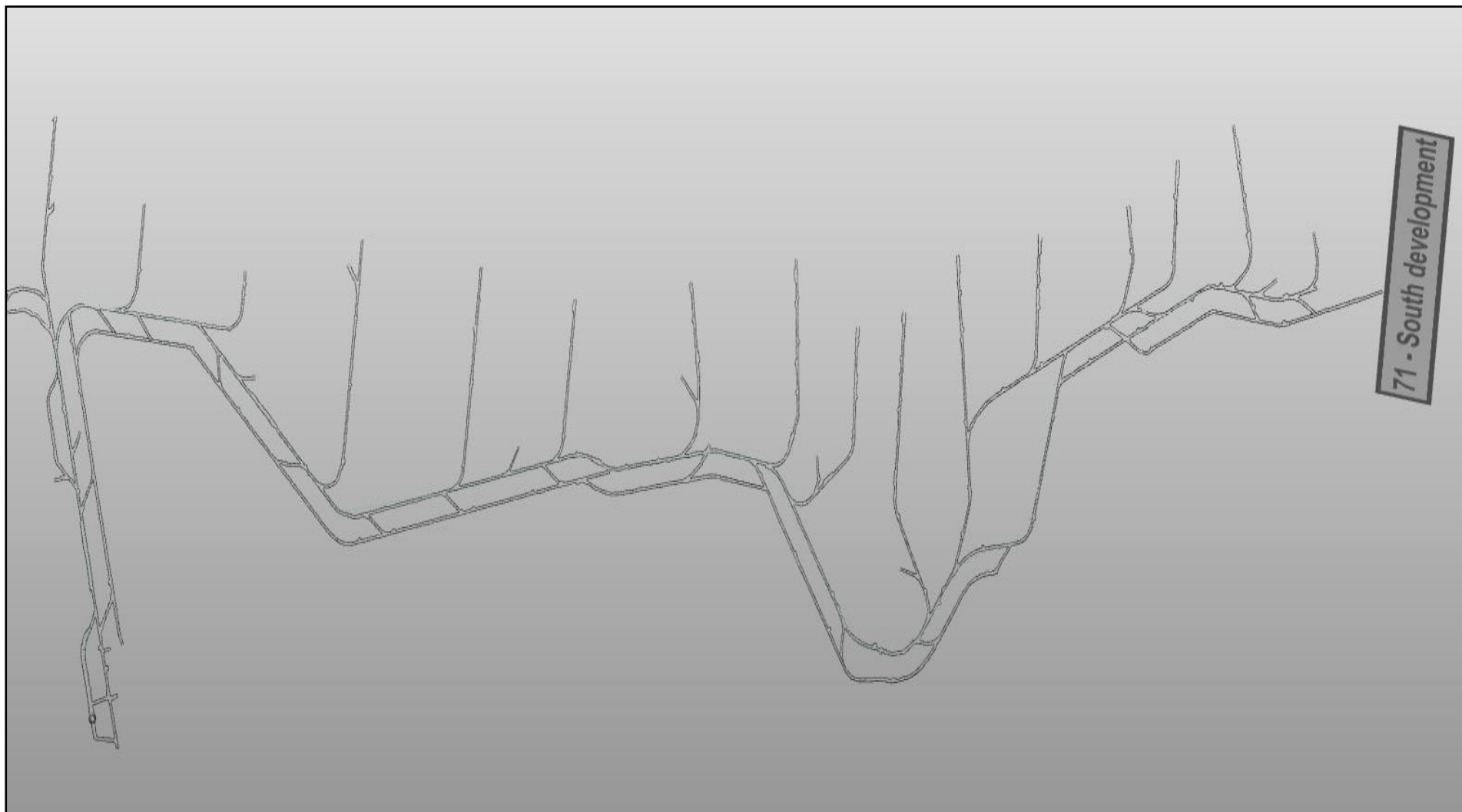


Figure 63: 71L DXF layout

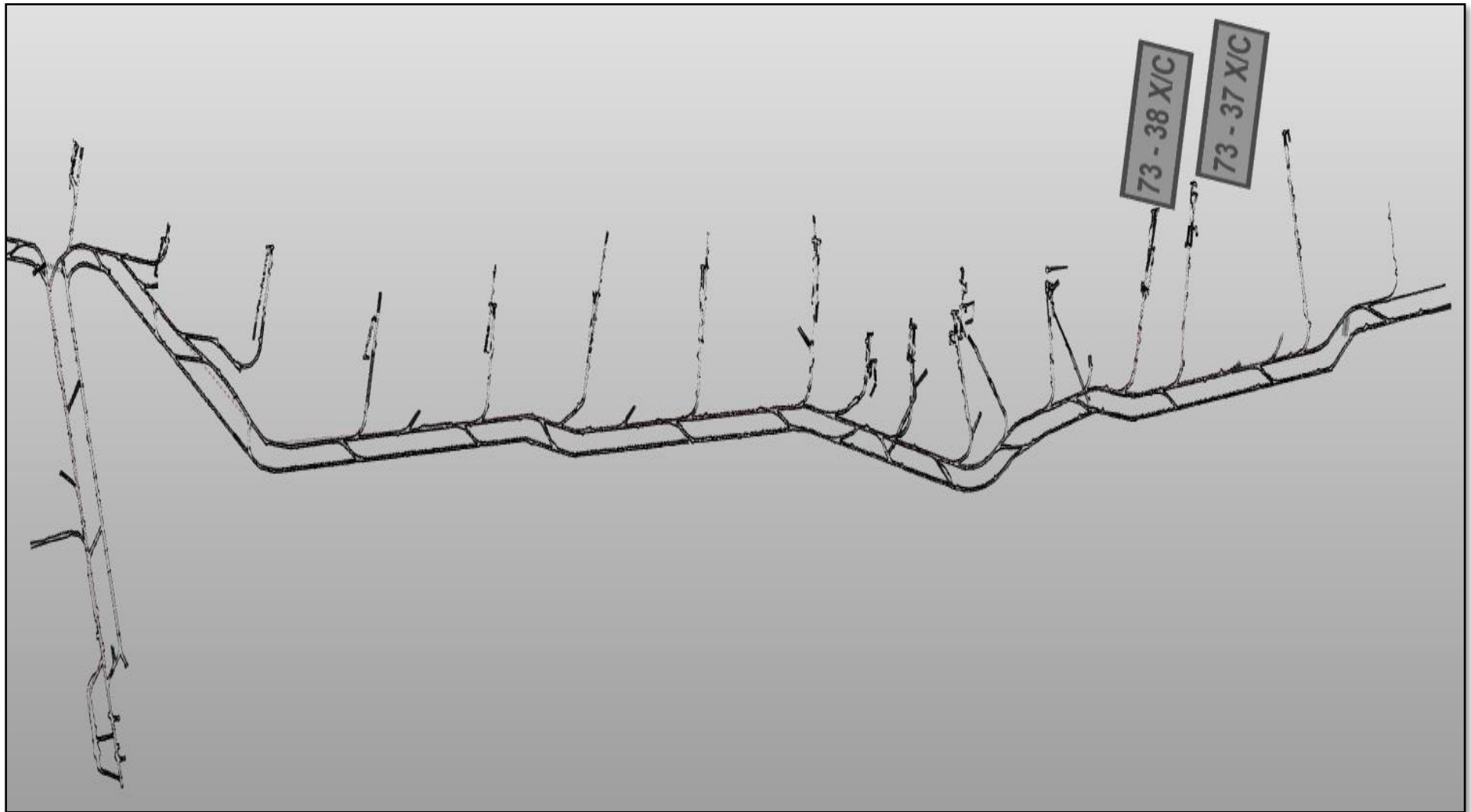


Figure 64: 73L DXF layout

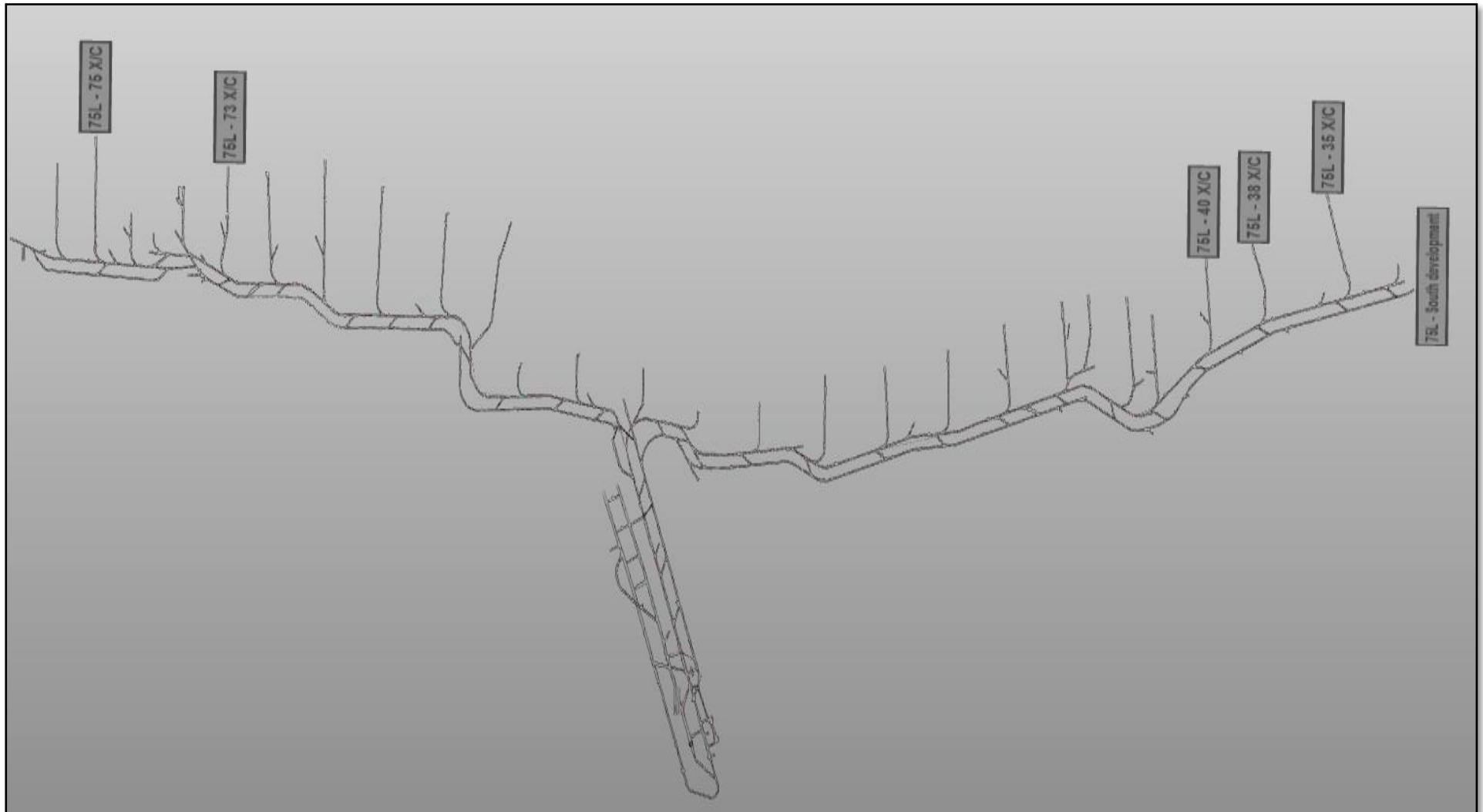


Figure 65: 75L DXF layout

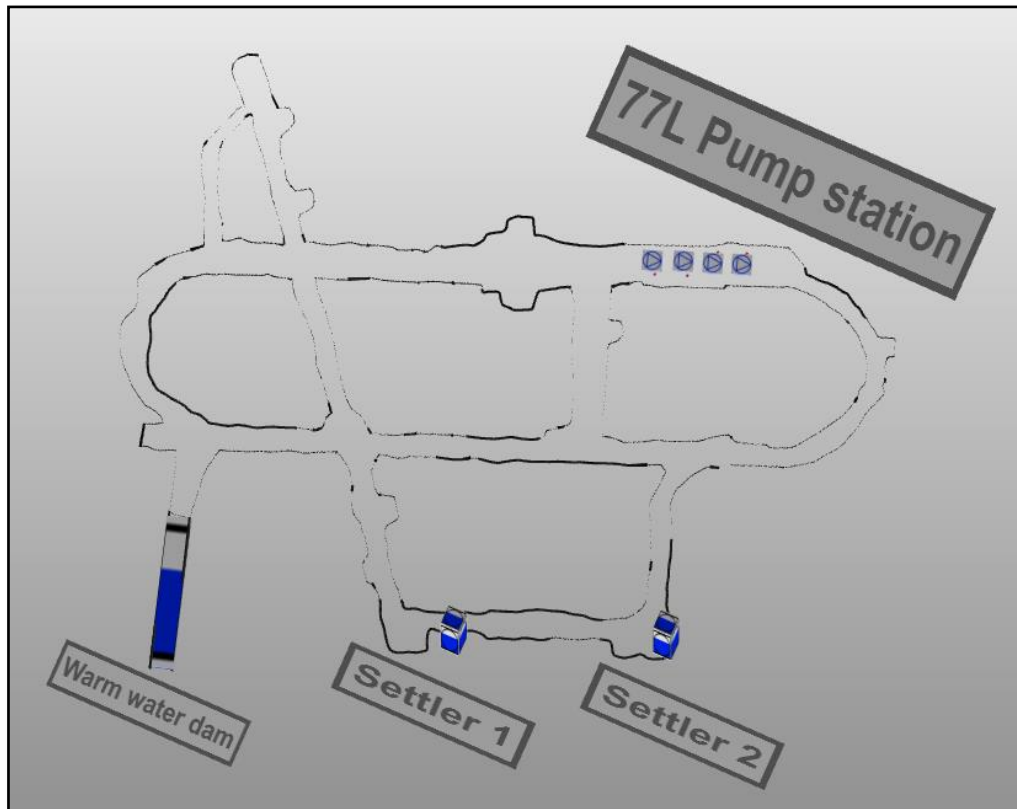


Figure 66: 77L DXF layout

APPENDIX D: SCENARIO SCHEMATIC ILLUSTRATIONS

Figure [66-69] in Appendix D is schematic dewatering system representations of each simulated scenario that was discussed in Section 3.5.3.

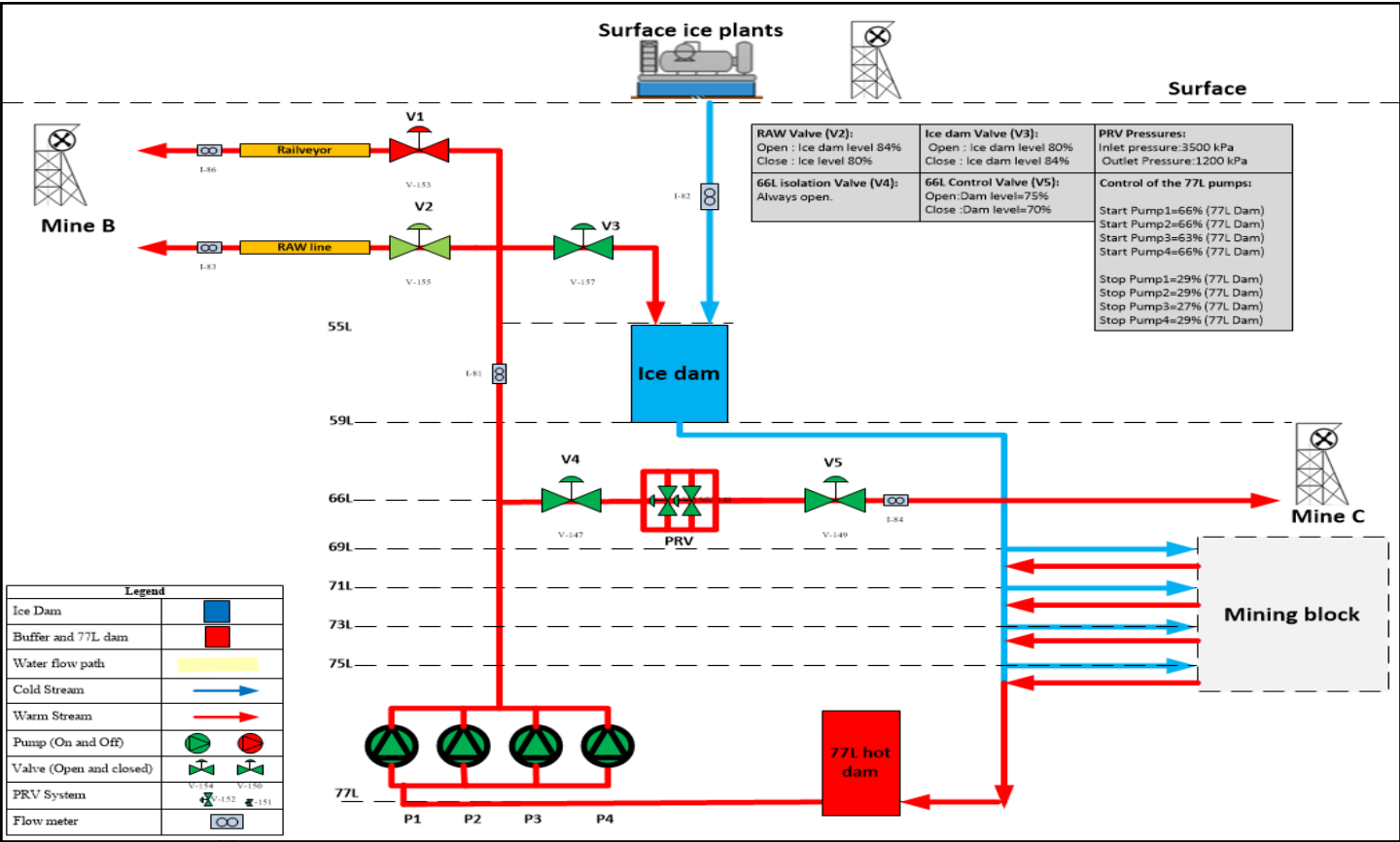


Figure 67: Schematic illustration - Scenario 1

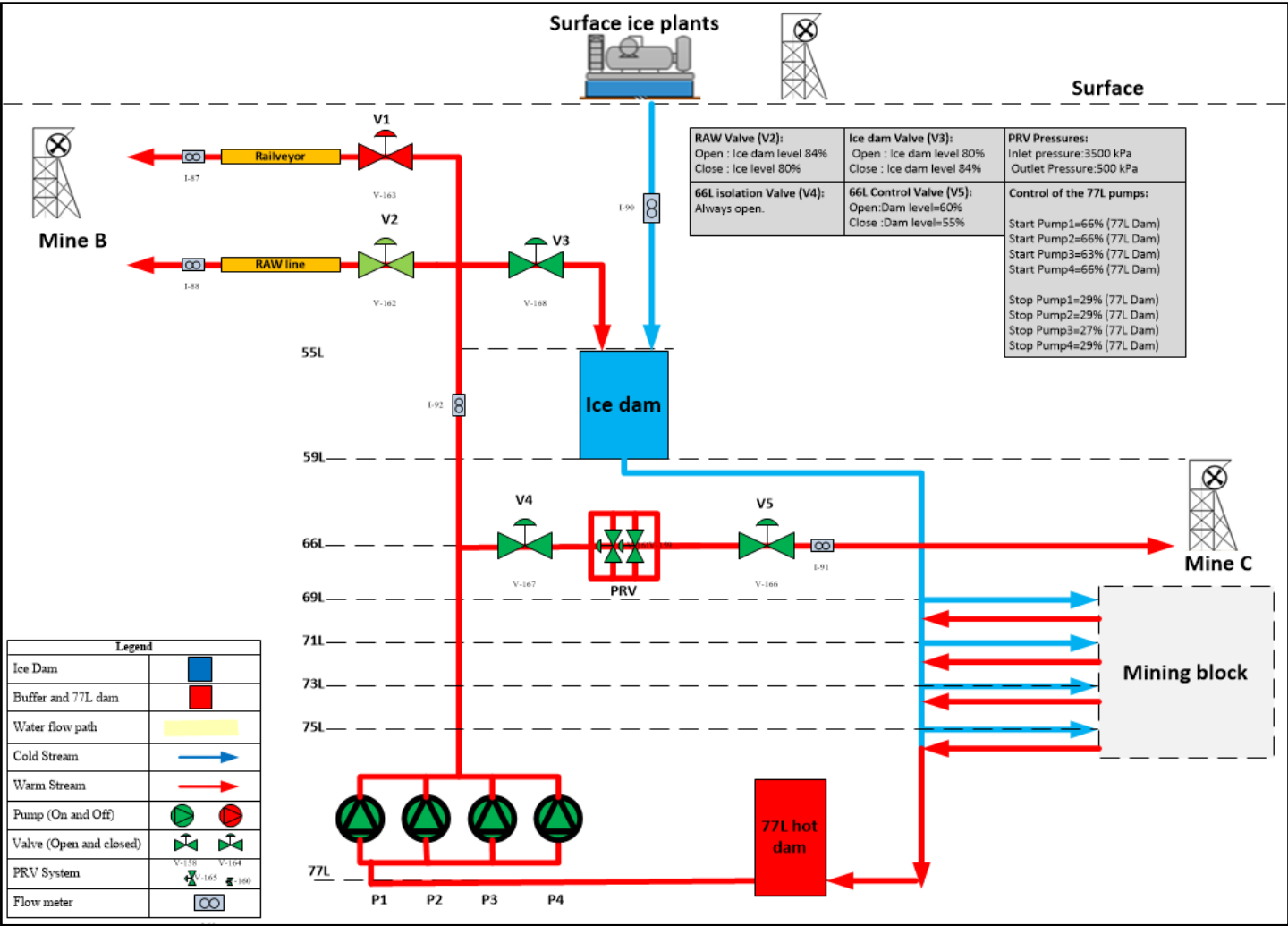


Figure 68: Schematic illustration - Scenario 2

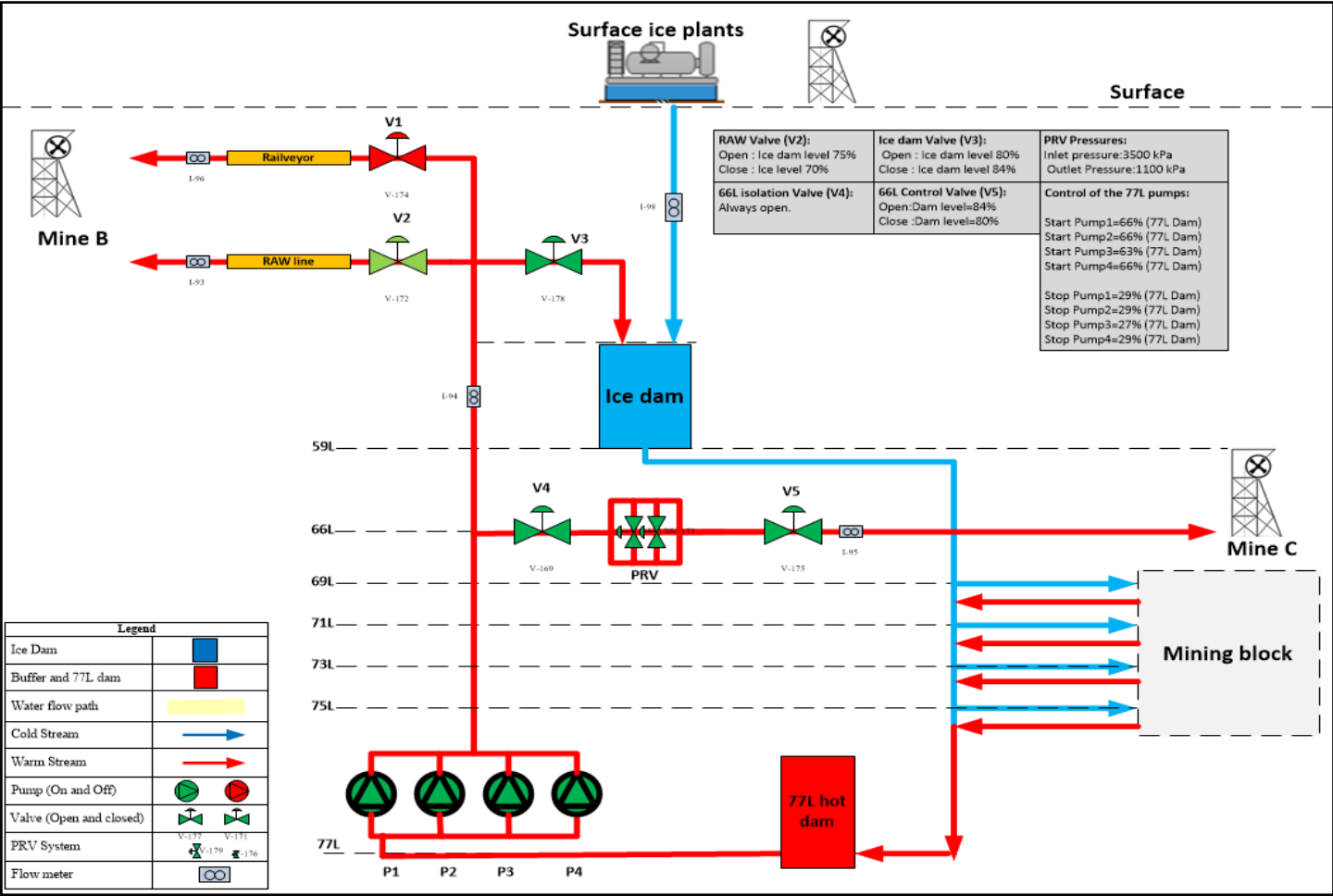


Figure 69: Schematic illustration - Scenario 3

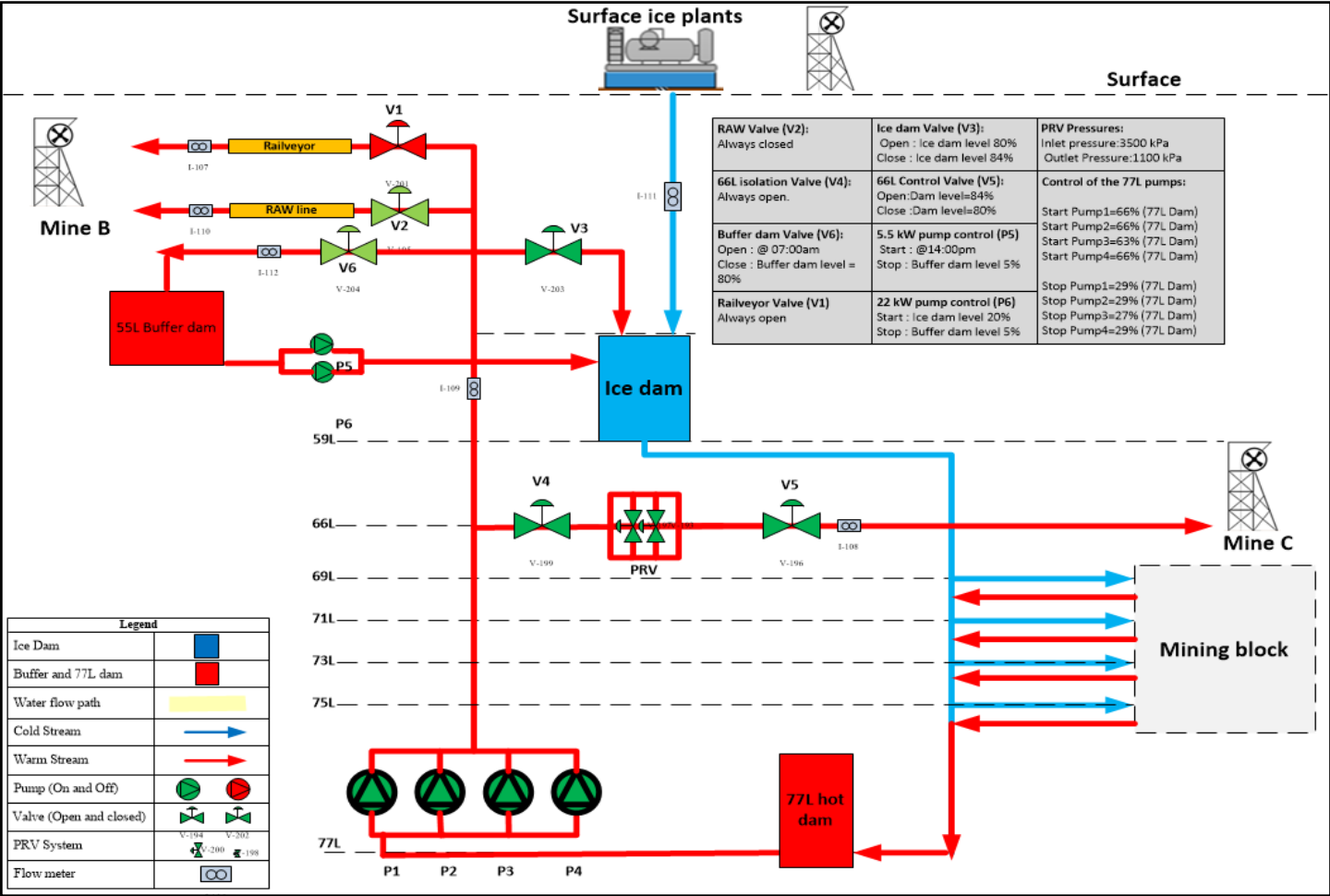


Figure 70: Schematic illustration - Scenario 4

APPENDIX E: MINE A REPORTING EXAMPLE

Figure 71 and Figure 72 illustrate the automatic daily report that is send to the mine as suggested in Process 5.4 in Section 2.7.

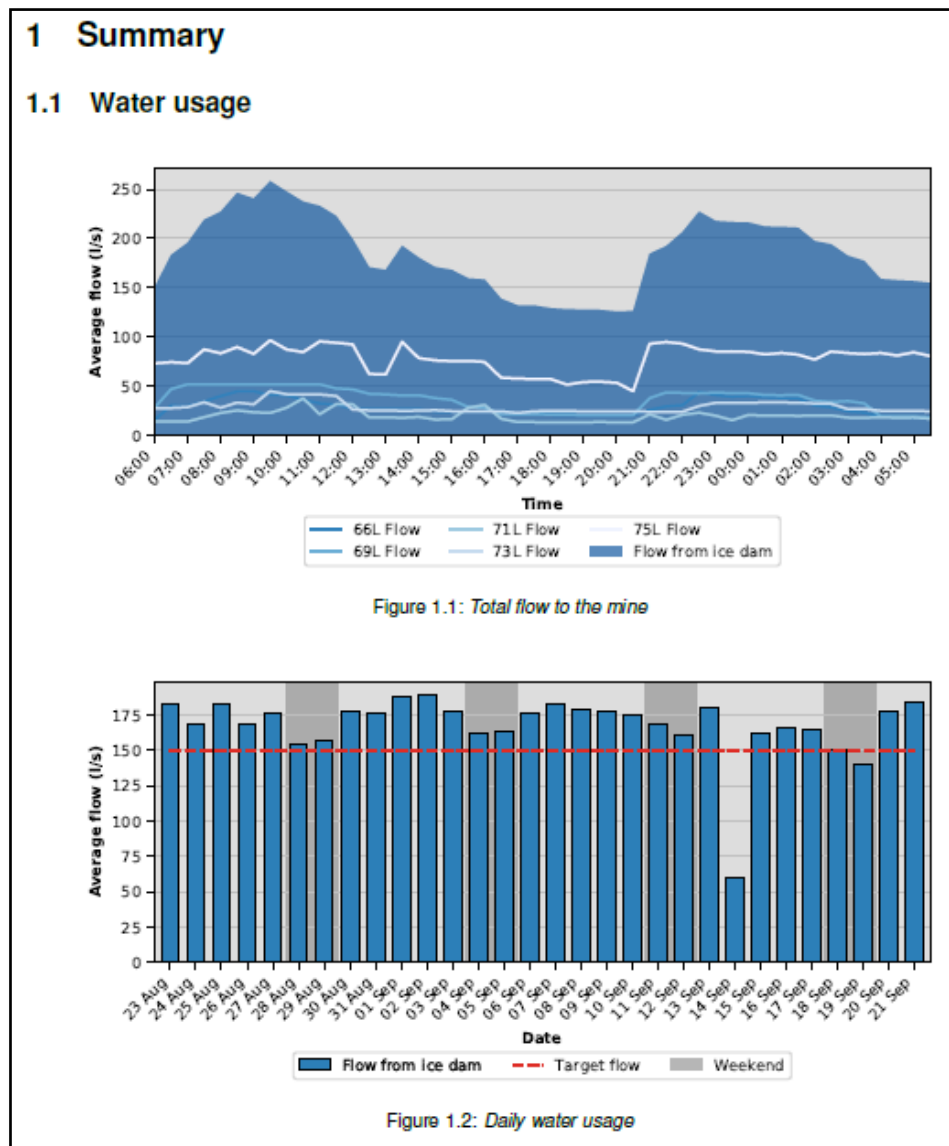


Figure 71: Automatic daily dewatering report example 1

3 Storage dams

3.1 55L Buffer dam

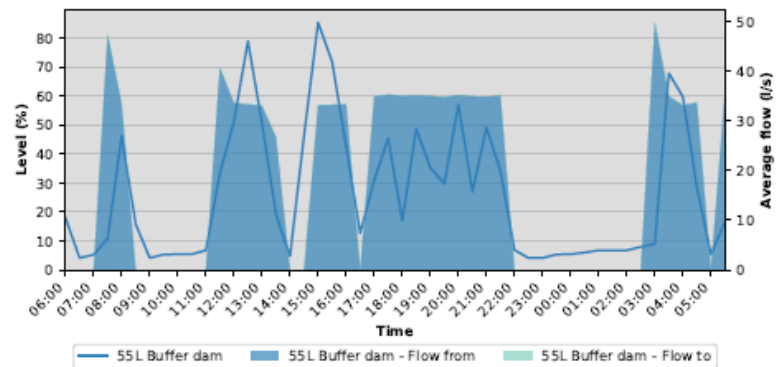


Figure 3.1: 55L Buffer dam information

3.2 77L Settlers

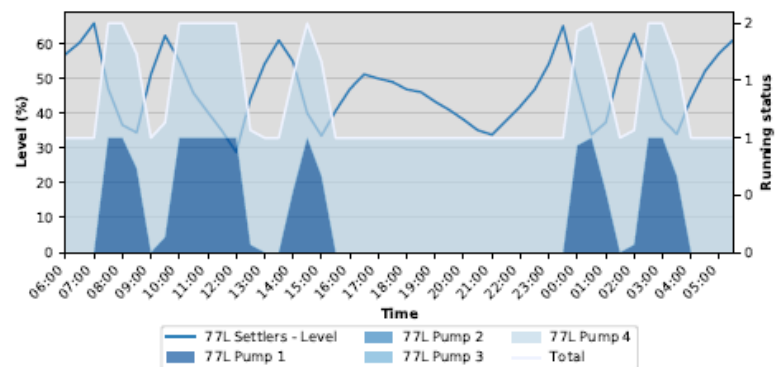


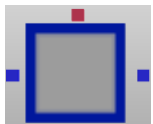
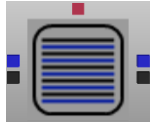
Figure 3.2: 77L settler information

Figure 72: Automatic daily dewatering report example 2

APPENDIX F: PTB WATER COMPONENT BREAKDOWN

Table 23 provides a Process Toolbox (PTB) breakdown of each simulation component.

Table 23: PTB water component breakdown

Type	Component	Function
Water pressure boundary		The water pressure boundary allows for specific property inputs for each time increment. (Temperature, Pressure)
Water node		The change in fluid volume flow are specified in water nodes. The water node also calculates water network properties. (Pressure, Temperature, Enthalpy)
Water pipe		Network pressure losses are calculated. Accommodates the flow of fluid between water nodes. (Mass flow)
Water air heat exchanger		Represents a counter flow indirect contact heat exchanger. Can also be used to represent a mobile cooling unit. (UA, Duty)
Water dam		Represents a water storage unit where inlet and outlet flows are independent of each other. (Volume)
Water pump		Adds potential energy to a fluid and induces a pressure difference to allow for water flow. (Mass flow, Power, Pressure)
PI controller		A proportional and integral controller takes two input signals to calculate the control error. This is done to reach a user specific setpoint in alignment with the input.