Model-based localisation of water-use inefficiencies in deep-level mines

JM van Coller

orcid.org/ 0000-0001-9818-7122

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Supervisor: Dr JH Marais

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ABSTRACT

Title: Model-based localisation of water-use inefficiencies in deep-level mines

Author: JM van Coller

Supervisor: Dr JH Marais

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Keywords: Deep-level mining, model-based, water, inefficiencies, energy management

The South African deep-level gold mining sector is facing profitability challenges due to increasing operating costs and declining production trends. Electricity costs can account for over R16 billion of the annual cost of operating a deep-level mine. This is a concerning factor and has led to the early closure of some South African mining companies. Integrated water reticulation systems, which consist of refrigeration, water distribution, and dewatering, contribute to around 28% of the overall electricity consumption of deep-level mines. Research has shown that improving energy efficiency can contribute to reducing operating costs of companies, leading to better profits.

An area presenting the potential to lower operating costs in deep-level gold mines is by addressing inefficiencies in the water reticulation system. These inefficiencies are represented in the water reticulation system in all three phases (refrigeration, pumping and water distribution). By reducing the wastage in the water reticulation system, refrigeration systems can deliver chilled water successfully for underground use and the volume of water required to be dewatered by pumping systems is reduced. This results in more chilled water for mining and cooling, better production rates, and a safer working environment.

Harsh underground conditions and flow rates of around 300 L/s result in poor conditions of pipe networks used for water distribution. The water distribution network presents an opportunity to improve efficiency of the water reticulation system. This is achievable by reducing water inefficiencies in the complex distribution network.

However, these water distribution networks currently require manual labour to walk up to 20 km along the underground pipelines to find and report on the found water inefficiencies.

It is evident that a need exists to develop a model to assist with the localisation of water inefficiencies in deep-level mines using the available infrastructure and instrumentation.

A method was developed to identify anomalies, classify the type of water-use inefficiency, and address these water inefficiencies in the water distribution network. The method incorporated guidelines and procedures for effectively locating water inefficiencies. For context, the process of limiting inefficiencies to a particular area is referred to as localisation. The localisation of water inefficiencies assists in reducing the need to walk along each pipe in the water reticulation system during underground audits.

Mine A was subjected to the developed method. Water inefficiencies could be detected from surface monitoring of available data. Validation of these results was obtained by evaluating the accuracy of the model by comparing located inefficiencies with false alarms. The model had a precision rate of 93%, thus identified, classified, and assisted with locating 93% of the 68 detected flow anomalies.

The investigation implemented on Mine A indicated that the average water distribution network inefficiency resulted in a flow increase of approximately 11 L/s when open ends occurred. This increase in flow effectively led to a reduction of chilled water available to perform mining activities. Chilled water that was wasted before could be used and an additional electrical cost saving of R8.6 million per annum was realised after corrective action was taken.

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NOMENCLATURE

Symbol	Description	Unit
Q	volumetric flow rate	m^2/s
P_{inside}	pressure experienced inside the pipe	Pa
$P_{outside}$	pressure experienced outside the pipe	Pa
A_t	Area of leak	m^2
α	Fluid coefficient of flow	-
ρ_{water}	Density of fluid	kg/m^3
$\bar{x}$	the average reading in the sample	-
N	is the sample size	-
σ	the estimated standard deviation of the individual values	-
$SH(i)$	The high CUSUM value for positive anomaly detection of the ith point	-
$SL(i)$	The low CUSUM value for negative anomaly detection of the ith point	-
X_i	The result for the ith data point	-
μ	The target value	-
σ	The allowable standard deviation	-
P_{ph}	Hydraulic power	kW
Q	Pump volumetric supply flow rate	$m3/h$
L/s	Liters per second	L/s
ρ	Density of water (assumed constant)	kg/m^3
g	Gravitational acceleration constant	m/s^3
h	Pump head requirement	m
n_{eff}	Pump efficiency factor	-
(P_P)	Pump motor energy	-
$t_{running}$	Total running hours	-
P_F	Power consumption of fridge plant	kW
$\dot{m}_w$	Water mass flow of fluid being cooled	kg/s
$C_{p,w}$	Specific heat constant of water	$kJ/kg \cdot K$
ΔT	Change in temperature of fluid being cooled	K
COP	Coefficient of performance	-

Symbol	Description	Unit
$E_{daily\ cost}$	Daily monetary cost of reduced pumping or refrigeration in the respective demand seasons	(R) ZAR
t_s	The tariff based on the time-of-use and demand season	c/kWh
t_{peak}	The average time the machine was operational in the peak tariff period	hrs
t_{std}	The average time the machine was operational in the standard tariff period	hrs
t_{off}	The average time the machine was operational in the off-peak tariff period	hrs
P_P	The reduced power consumption due to less pumping	kWh
$Cost_{annual}$	The annual cost saving of reduced pumping or refrigeration in the respective demand seasons	(R) ZAR
P_F	The reduced power consumption due to less chilled water supplied	kWh
$E_{daily\ average}\ (R)$	Average reduced pumping or refrigeration costs per day, incorporating weekdays, Saturdays, and Sundays	(R) ZAR
$E_{weekday}\ (R)$	Average reduced pumping or refrigeration costs per weekdays during the corresponding demand seasons	(R) ZAR
$E_{Satuday}\ (R)$	Average reduced pumping or refrigeration costs per Saturday during the corresponding demand seasons	(R) ZAR
$E_{Sunday}\ (R)$	Average reduced pumping or refrigeration costs per Sunday during the corresponding demand seasons	(R) ZAR
$E_{daily\ summer\ cost}$	The daily cost saving during summer demand season	(R) ZAR
$E_{daily\ winter\ cost}$	The daily cost saving during winter demand season	(R) ZAR
TPR	True positive rate	-
TP	Total correctly detected system anomaly events	-
FP	Total number of false system anomaly events	-
P_{feed}	Power measured by the power feeder	MW_{eq}

LIST OF ABBREVIATIONS

BAC	Bulk air cooler
CUSUM	Cumulative sum chart method
DSM	Demand-side management
ESCO	Energy service company
FPs	Fridge plants
FTPs	File transfer protocols
GDP	Gross domestic product
HMI	Human machine interface
HOD	Head of department
km	Kilometres
kPa	Kilopascal
LCL	Lower control limit
LDSA	Leak detection simulated annealing
ML	Megalitre
mm	Millimetre
MPa	Megapascal
NB	Nominal bore
PLCs	Programmable logic controllers
RAW	Return air way
SCADA	supervisory control and data acquisition
SI	Système Internationale
SPC	Statistical process control

SQL	Structured query language
TOU	Time-of-use
TWh	Terawatt-hour
UCL	Upper control limit
VPN	Virtual private network
VSDs	Variable speed drives

Chapter 1: Introduction

Figure 1: Typical mining shaft in South Africa[1].

[1] Photo by: "Daily Maverick". [Accessed: 23-December-2020]. [Online]. Available: https://www.dailymaverick.co.za/article/2020-12-23-mponeng-sale-a-milestone-in-sa-mining/.

1. INTRODUCTION AND LITERATURE

1.1. Background

The significance of gold

Gold was discovered in South Africa in 1886 and has played a monumental role in the history of the country's development. South Africa has been a primary contributor to global gold production ever since [1].

Gold is an important asset to a country due to the value added to the economy, particularly due to the historical role gold plays in the value of a country's currency and economy [2]. Most of the fabricated gold is used to produce jewellery. However, gold is used in electronics due to its corrosive qualities and high electrical conductivity. Before the benefits of gold in electronics were known, the precious metal was primarily considered a monetary metal to be stored in bank vaults [3].

During financially uncertain times, a country would use gold to protect its currency and resist losing its value. This is known as the gold standard, where a country would peg their monetary system to the value of gold [4], [5].

The importance of gold mining is supported by the world economic influence of gold. [6]. The unemployment rate and the gross domestic product (GDP) are both directly influenced by the price of gold[7], [8]. The contribution of the mining and quarrying industry to the GDP growth increased by 2.1% from 2021 to 2022. The gross domestic product (GDP) of South Africa had a contribution of just over 4.5% from mining and quarrying [7].

In 2021 South Africa produced around 4.2% of the annual world gold output and relied on around 13% of South Africa's revenue to be produced from minerals [1]. This is concerning since South Africa used to be one of the leaders in contributions to global gold production during the 1970s [9], [10].

Production uncertainty for deep-level gold mines

Apart from two years with substantially good production, gold mining in South Africa has shown a downward trend that has been consistent since 1994. Gold production in South Africa has been on a decline since the peak of the industry in the 1970s [10]. The output in production has faced numerous challenges and this downward trend is cause for concern in the industry. Figure 2 illustrates the decline in the gold mining production trend since 2010.

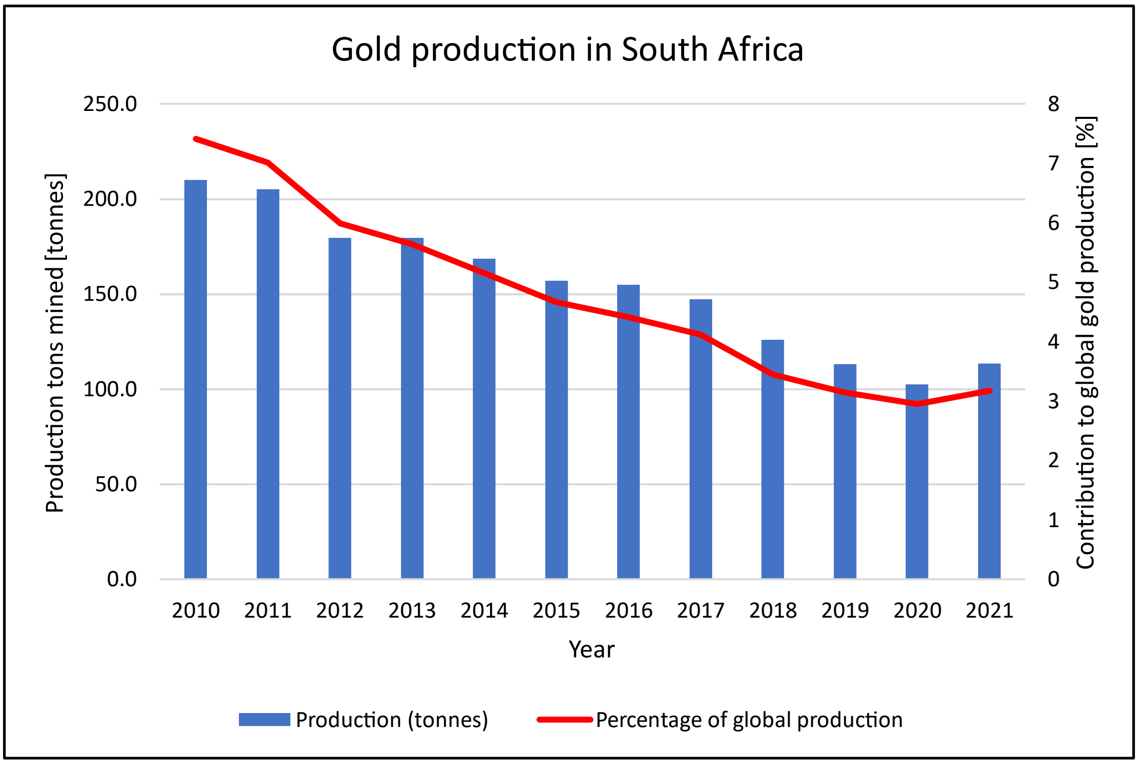


Figure 2: Gold production in South Africa (Adapted form [9]).

This constant decline in gold production suggests an uncertain future for the industry of gold industry and deep mining in South Africa [11]. The Mineral Council of South Africa reported in 2018 that, due to the declining gold reserves, an estimated 75% of mines in South Africa were declared unprofitable [12]. The reason for the downward trend in the production of gold can be attributed to various challenges presented to the industry.

Difficulties faced by South African gold mining

South Africa led the industry by delivering the highest gold production worldwide until around 1994, when gold mining started facing challenges. The decrease in South African gold output can be divided into the following main contributors [11]:

- Cost of labour.
- Labour-related issues.
- Increasing production costs.

Cost of labour

South African gold mining has been a victim of frequent union strikes [10]. The political action for equality based on race and social status has drastically influenced productivity and eventually led to an increase in wages [13]. Agreements between mining companies and worker unions have been met, but only proved to be beneficial in the short term [14]. Labour unrest indicates there exists conflict between goals that are set by the company and the expectations of the labour force.

Labour-related issues

Human labour is an essential part of the gold mining industry due to technical constraints. The stoping width limits operations to equipment that will suit the narrow working space, this essentially makes the industry highly reliant on labourers [11]. The working environment of an underground deep-level miner can include a stoping width as low as 1 m [15]. Shown in Figure 3 is a mineworker within the narrow stoping environment.

Figure 3: Stoping area of a deep-level gold mine (Adapted from [15]).

Considering the large scale of underground operations in the gold mining sector, the productivity of labourers is affected by variables such as travel time to the working area, with some underground mining levels spanning up to 20 km [10].

This contributes to the low working efficiency of drill operators and the availability of equipment [16]. In some mining operations, the underground working areas can take up to an hour to reach from the surface [11].

Increasing production costs

High operating costs are a concerning factor for gold mines in South Africa as it leads to a shorter life of mine [17]. The costs of operating a gold mine in the South African gold mining industries are contributing to the decline in production tonnes [18].

The increasing production costs are directly related to factors such as the South African electricity tariff and increasing labour costs [10]. Mine production can decrease by up to 2.02% due to a 1% increase in the electricity tariff [19].

Mines with tight margins for profit are concerned with the impact of increasing electricity costs on the future of operations [10]. Consequently, the mining sector in South Africa is decreasing in delivering competitive profits, with high electricity costs being one of the main contributors [20].

Electricity in the mining sector

The primary electricity supplier of South Africa is Eskom, supplying roughly 95% of the total electrical demand [21]. Some of the deepest mining operations are located in South Africa. These operations have high energy demands and consume up to 14% of the total energy generated in South Africa, as displayed in Figure 4 [21], [22].

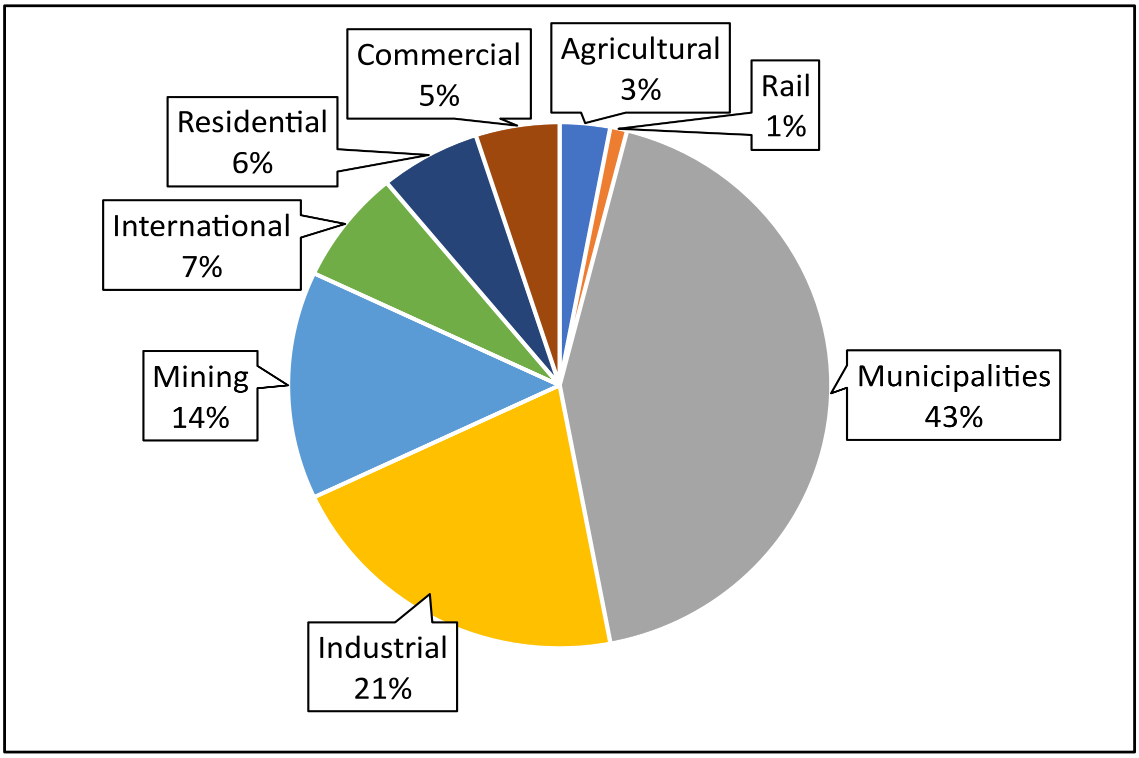


Figure 4: South African energy consumption by sector (Adapted from [21]).

These rising operating costs have the potential to shorten the life of mine, causing mines to reach the point of unfeasibility sooner [23], [24]. This indicates that high electricity costs contribute to the decline in competitiveness of the mining industry in South Africa [10]. The extraction of fossil fuels and the cost of electricity production is steadily increasing annually [25].

The projected increase in electricity costs provided by Eskom indicates that there is a reason for concern about further increasing operating costs for South African Mining industries [14], [22]. Displayed in Figure 5 is the 653% tariff increase in Eskom's' electricity compared to the 129% increase in inflation from 2007 to 2022 [26].

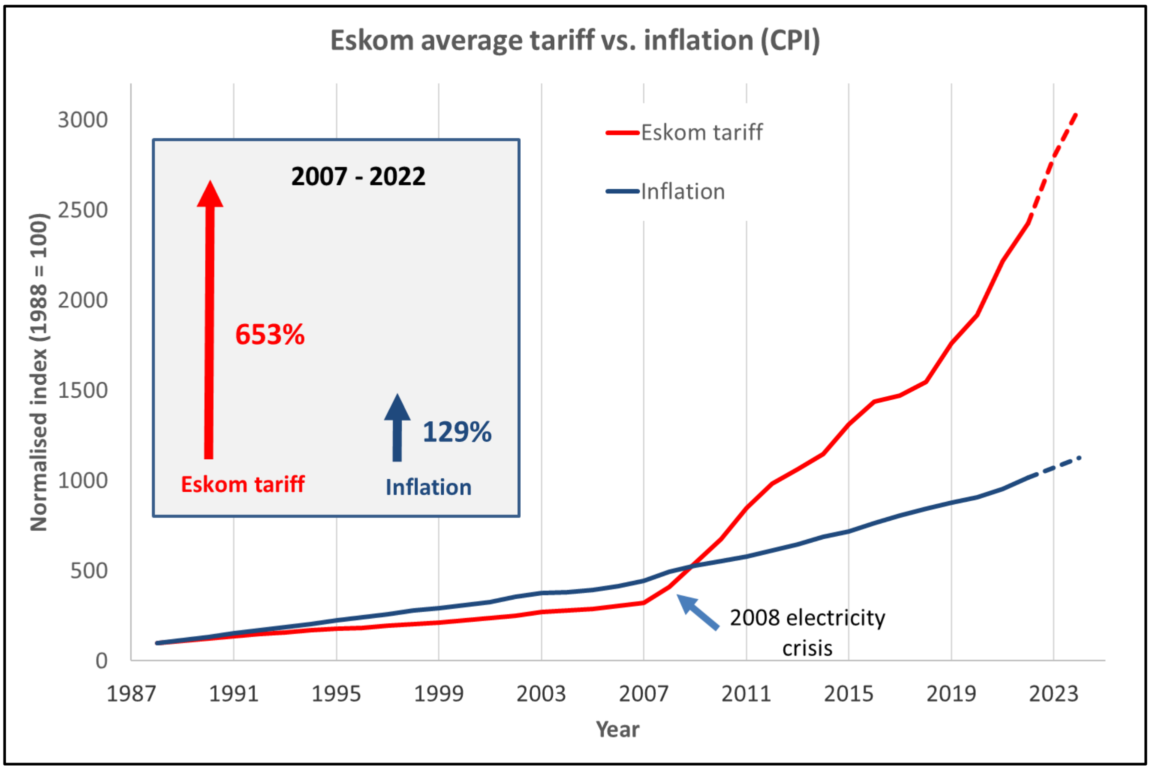


Figure 5: Comparison between the historical and projected Eskom electricity tariffs [26].

A significant portion of the monthly expenditure of a mine goes towards electricity. South African gold mines present difficulties that call for energy-intensive machinery due to the extreme depths of nearly 4 km below the surface [27]. Industrial ventilation fans, complex compressed air systems, pumping chambers, and cooling systems are needed to maintain production trends [17].

Sibanye Stillwater, one of South Africa's major mining industries, reported to have consumed 6.59 TWh of electricity during the 2021 financial year [14]. This is equivalent to an annual cost of over R16. 67 billion spent on electricity [22].

Figure 6 gives a representation of how energy usage is typically distributed in deep-level mines. It is shown that refrigeration and pumping make up 16% and 12%, respectively, of the total energy expenditure [19].

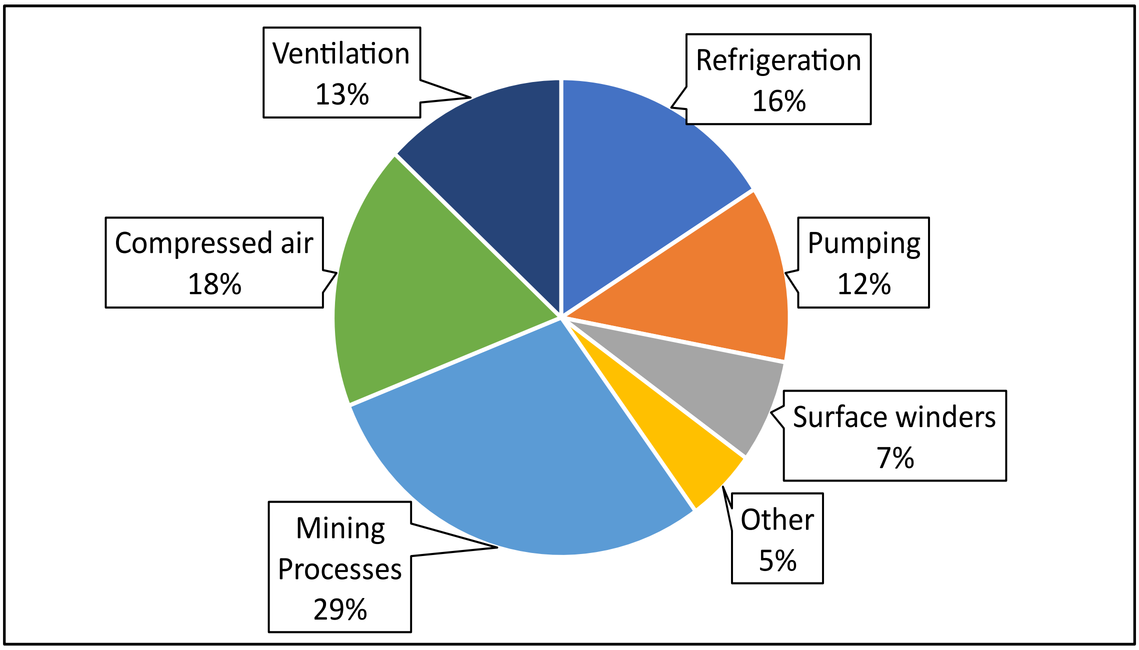


Figure 6: Mining electricity breakdown. (Adapted from [19]).

Figure 6 indicates that pumping and refrigeration make up more than a quarter of the total energy expenditure. Due to their high contribution to the electricity consumption, these systems will be investigated further in this study.

1.2. Chilled water in deep-level gold mines

Conventional mining consists of a cycle that follows a drilling period, blasting period, loading period and rock hauls. One of the resources needed to effectively complete this cycle is a reliable supply of chilled water [22].

Water is used in refrigeration systems for underground ventilation purposes and is also used for services such as drilling, suppression of dust, cleaning, drinking water and, in certain cases, for hydraulic uses [23].

The cold-water supply in deep-level mines is carried out through a complex water reticulation system. As displayed in Figure 7, this water supply can then be used for any of the following applications [28]:

- Dust suppression
- Working fluid of drilling and hydraulic equipment
- Cleaning and sweeping in working areas
- Cooling and ventilation

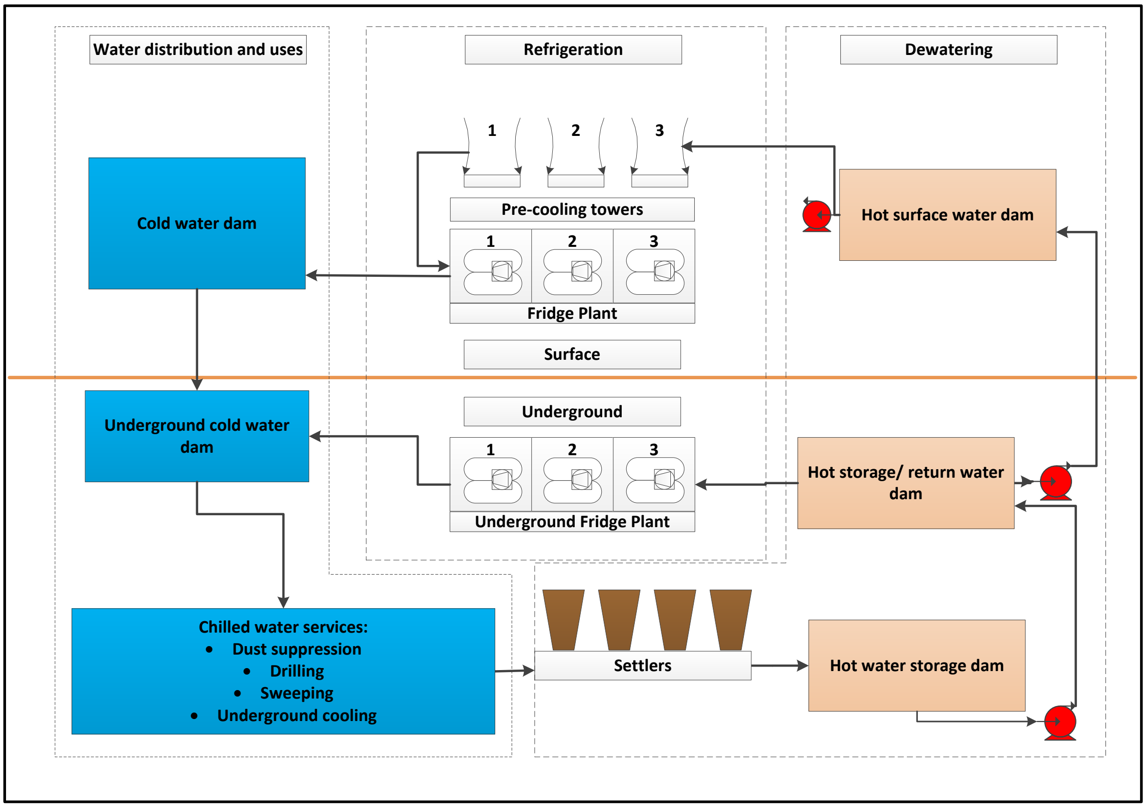


Figure 7: Mining water reticulation system (adapted from [29]).

The water reticulation system is an integral system made up of three essential sub-systems. These sub-systems are known as water distribution, refrigeration, and dewatering. The combination of these three sub-systems allows for water to be chilled on the surface and stored in chilled water dams.

The water is then distributed for various uses that are discussed in more depth below. The water undergoes a filtering process and is pumped to hot water storage dams before the cycle is repeated [29].

Water distribution

Before the water is distributed, the water passes through industrial refrigeration plants. The chilled water is stored on the surface in cold water storage dams after being refrigerated. South African gold mines can go as deep as 4 km below the surface, which assists gravity-fed water supply to underground working areas. Pressure builds up in gravity-fed systems and has to be reduced using cascade dams or pressure-reducing valves [29].

Cascading dam systems allow for gravity-fed water to be stored in a main receiving dam. Thereafter, the dam overflows into dams on lower levels and achieves the required pressure with the head difference between dams [30]. Cascading water supply is illustrated in Figure 8 and compared with the shaft column water supply.

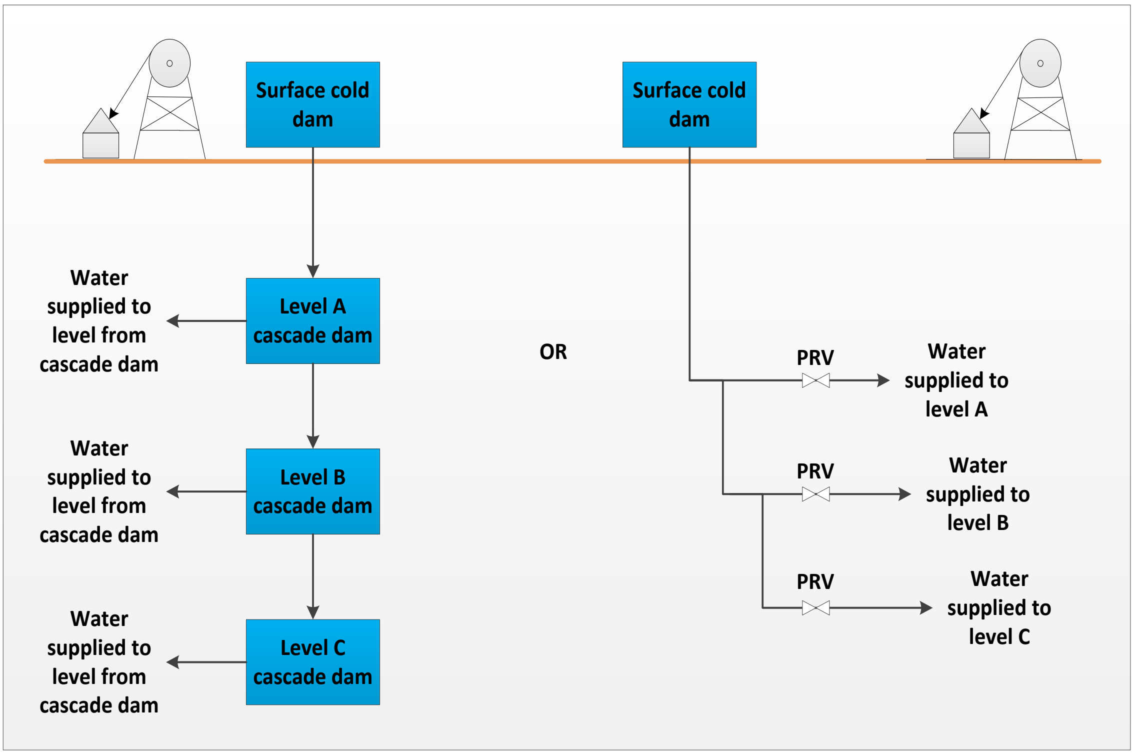


Figure 8: Cascading water supply vs shaft column supply (Adapted from [29]).

Pressure-reducing valves assist in the shaft column supply method to break the pressure on each level. Once the chilled water is distributed successfully underground, it can be used in services such as dust suppression, drilling, sweeping away rock, and for underground cooling.

Dust suppression

Dust accumulating in underground working areas pose a great threat to mine workers [31]. Silicosis is caused when high silica content dust is inhaled over long periods [32]. Dust is also known to cause obstructive pulmonary disease when inhaled [33].

Dust suppression plays an important role in providing safer underground working conditions [28]. Personal protective equipment is worn to further mitigate the risk, especially after the blasting period. Displayed in Figure 9 is a mine working using chilled water to cool down a working area and suppress the dust in the air.

Figure 9: Mine worker applying dust suppression with chilled water [34].

The working fluid in drilling

Holes are made into the face of the hard rock using drills. To break the rock for easier transportation to be crushed and processed, explosives are inserted into the holes and blasted [35].

Typically, pneumatic or hydraulic drills are used as they are efficient, durable and do not present much of a safety risk [36]. In addition to flushing out the debris from the drill holes, chilled water is used as a cooling fluid. The fluid assists with heat removal at the rock face and ensures the drill bit does not overheat. The water supply helps to suppress the dust for smoother drilling [18], [36].

Figure 10 illustrates how a mine worker operates a pneumatic drill to drill holes for blasting. The water around the miner's feet indicates the amount of water used in drilling operations [29].

Figure 10: Mineworker operating a drill [29].

Cleaning and sweeping in working areas

After the blasting period has passed and the area has been declared safe, the mineworkers collect the blasted ore pieces from the ground. Scraper winches are used to move the larger pieces, while smaller ore pieces are moved by using high-pressure water cannons. These cannons flush the particles into loading boxes as seen in Figure 11. The water cannons help to save time and make work more efficient [34].

Figure 11: Water cannon in operation [34].

Cooling and ventilation

Proper ventilation and cooling methods are required to ensure the mine does not exceed legal temperatures and is well ventilated underground. The temperature of the exposed rock face is known as the virgin rock temperature [17], [37].

The rock face can reach temperatures up to 60 °C when mining at depths of approximately 4 4 km underground [29], [38], [39]. Safe working conditions are required before any work can continue [40].

For mine workers to work in a safe underground environment, large, energy-intensive cooling systems are needed. As mines reach deeper depths, additional cooling and sufficient airflow are to ensure that heat is removed from warm areas [17]. Illustrated in Figure 17 are the different stages of cooling needed as mines develop and explore deeper. Primary, secondary and tertiary cooling methods are used to ensure work areas remain within legal and safe standards [17].

Primary cooling uses large bulk air coolers (BACs) to cool down large volumes of ambient air before transporting it underground [41], [42]. Ventilation fans on the surface are connected to the return airway (RAW) and remove the hot air from the underground working areas. This creates a negative pressure and circulates the cooled air [29].

Bulk air coolers can either be designed as vertical or horizontal forced draft coolers. It may either be an open or closed system with direct contact spray chambers or closed cooling coils as heat exchangers [41].

Primary cooling such as BACs is used on the surface, making use of direct spray chambers to remove heat from the ambient air in large volumes before sending it down the shaft as displayed in Figure 12.

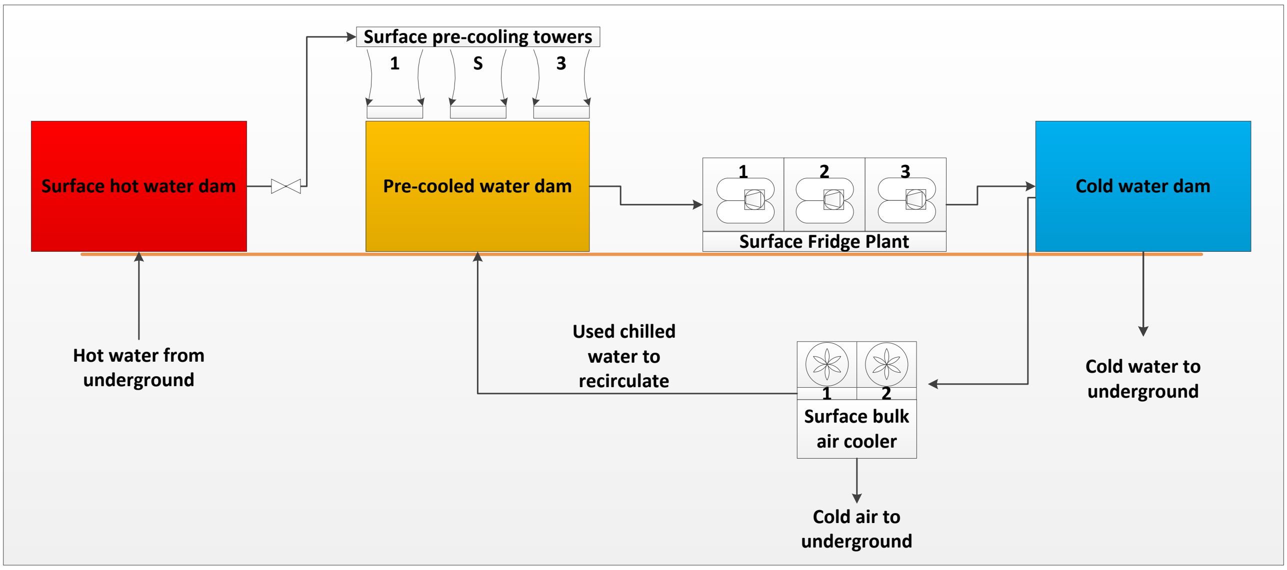


Figure 12: Primary cooling from surface using a BAC.

Typical secondary cooling systems consist of horizontal forced draft BACs as displayed in Figure 13. Cold water is transported through cooling coils and the uncooled air is forced over the coils for heat transfer to occur. The air is cooled and sent to the working areas [34].

Figure 13: Horizontal forced draft underground BAC with direct-contact heat exchange [28].

These BACs are preferred underground as they fit into existing haulages. However, the vertical forced draft BACs can achieve up to five times better cooling [29]. Figure 14 is an illustration of how the single-phase heat exchange takes place in a horizontal forced draft BAC underground.

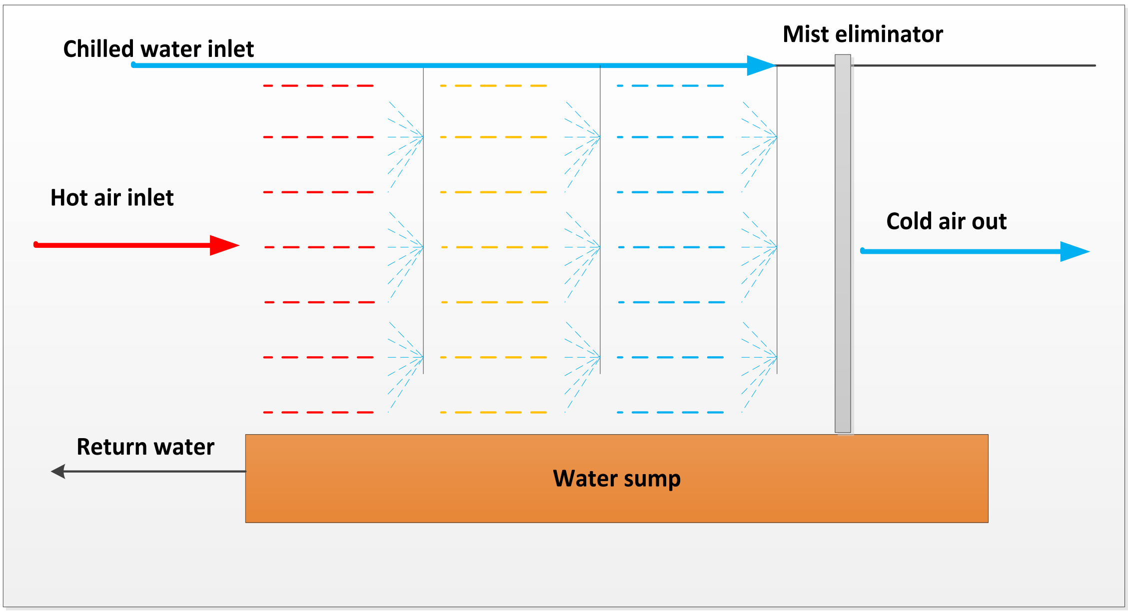


Figure 14: Underground horizontal spray chamber schematic (Adapted from [28]).

Cold water is sprayed through the nozzles and makes contact with incoming air. This allows for the heat to be removed from the air and transferred to the droplets. The warm water is collected in a sump at the bottom and pumped to refrigeration plants to be cooled and recirculated [41].

When primary and secondary cooling methods are no longer adequate to provide sufficient cooling, then tertiary cooling is needed. Typically, tertiary cooling is used when mining activities are too deep and far away from the primary or secondary cooling source [29], [41]. These systems are smaller and provide less cooling than larger systems.

Mobile cooling units known as cooling cars are installed in the main walkways or haulages and at the entrance of cross-cuts with high temperatures unsuitable for working conditions [17], [43]. These cooling cars consist of a radiator or cooling coils that have a steady supply of chilled water and a booster fan to create airflow [29].

The fan blows over the radiator, allowing for heat transfer to take place and remove heat from the air as depicted in Figure 15. The hot water is either pumped back to an underground refrigeration plant to chill and recirculate or dumped on the footwall [28].

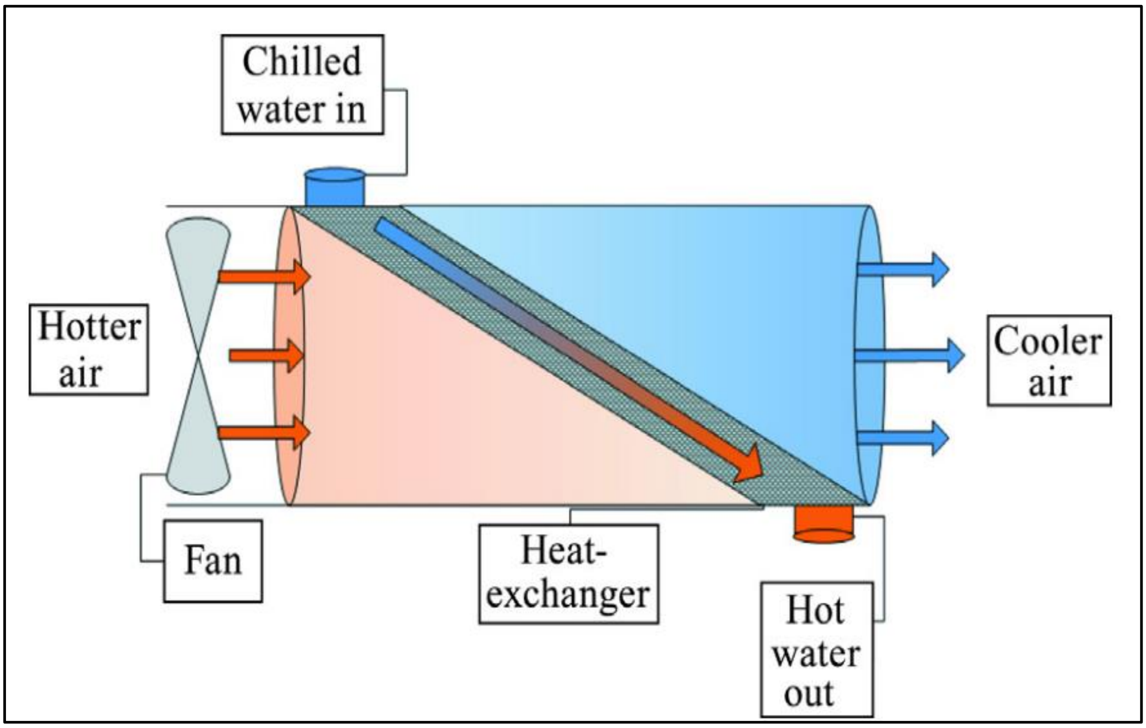


Figure 15: Heat transfer in a cooling car [17].

This is known as in-stope cooling and is crucial for safe working conditions when primary or secondary cooling is insufficient [17]. Figure 16 shows a cooling car on the surface before being taken underground and connected to the chilled water supply and booster fan.

Figure 16: Mobile cooling unit (cooling car) [28].

The combination of all three types of cooling allows for deep-level mines to continue developing up to 4 km underground and still be able to continue deepening within the health and safety regulations [29], [40]. Figure 17 displays a schematic containing all three phases of cooling and ventilation to ensure regulated temperatures and sufficient airflow.

Studies based on tertiary cooling systems have focused on the removal of cooling cars and the control of chilled water supply [17], [28], [41]. The findings from this research conclude that the tough underground environment and lack of maintenance contribute to the inefficient use of these systems. It was also found that inefficient tertiary cooling systems can negatively affect underground temperatures and increase operating costs [41].

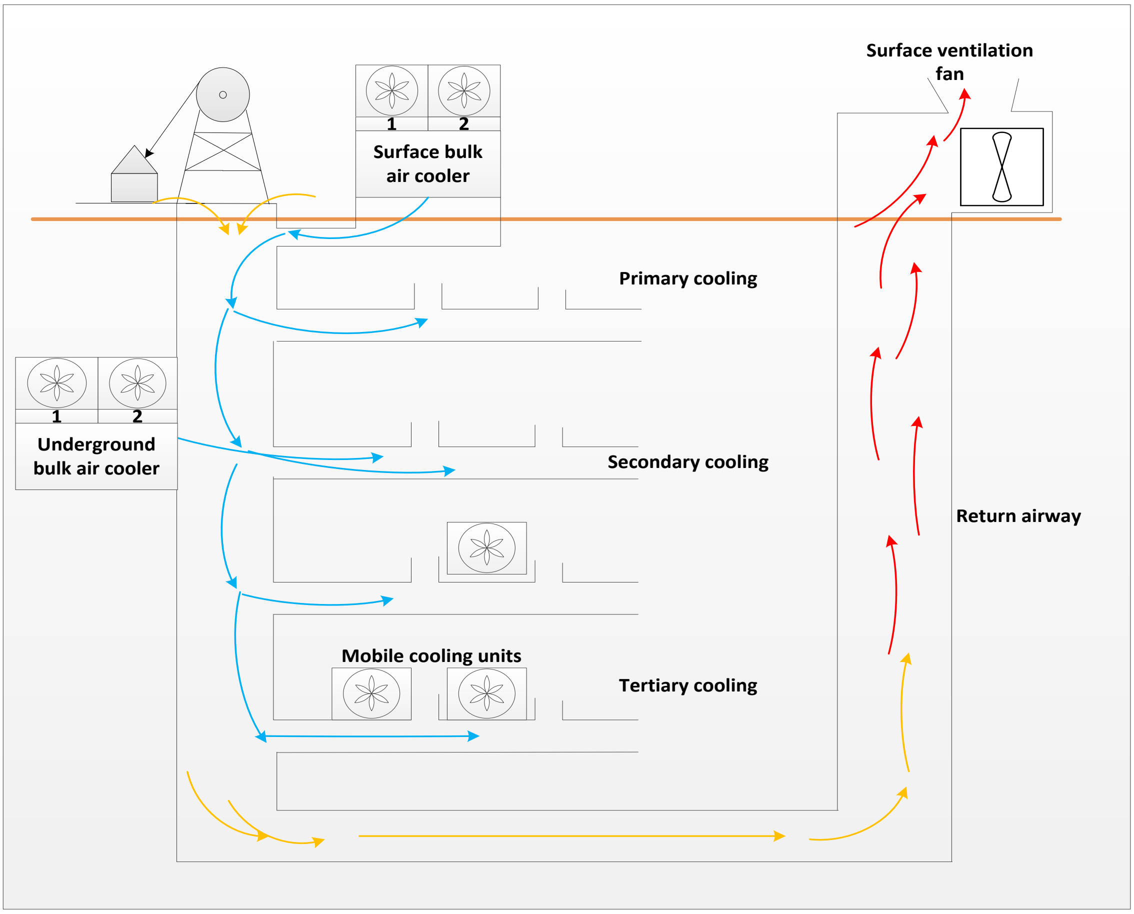


Figure 17: Different types of cooling combined in a deep-level mine (Adapted from [29]).

Refrigeration

Before the water can be supplied to perform numerous services, it has to be chilled or refrigerated. The refrigeration process consists of removing heat from warm circulated mine water on a large scale for reuse [17], [44]. Heat is removed from the water to be used for mining heat exchange of air for ventilation purposes and temperature regulation.

The refrigeration cycle consists of fridge plants (FPs), dams, pre-cooling towers, and various pipes and valves. BACs and cooling cars are considered as water consumers in this study and not as part of the refrigeration cycle as they heat water to cool down air [28]. Figure 18 displays a schematic of the refrigeration cycle in the water reticulation system.

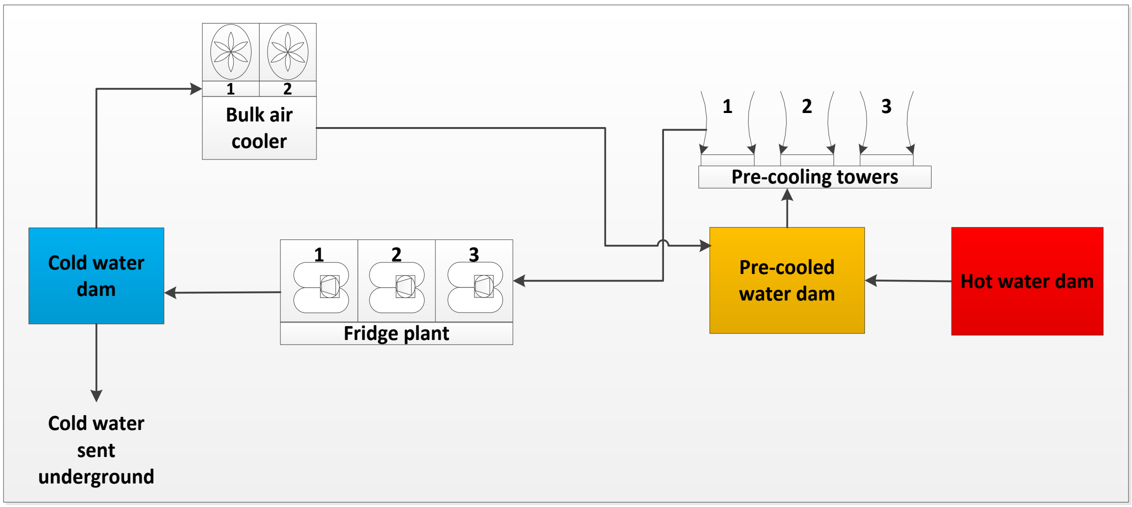


Figure 18: Refrigeration cycle of the water reticulation system [28].

Pre-cooling towers

After the water has been utilised and passed a filtration process, it is pumped into hot water storage dams on the surface. The water is stored in the hot surface dams at temperatures up to 30 °C. These temperatures need to be cooled to below 20 °C before the water can be refrigerated and stored in the cold dams [29]. The pre-cooling towers used to remove heat from the water prior to being chilled at the refrigeration plants can be seen in Figure 19 [45].

Figure 19: Example of pre-cooling towers [29].

Fridge plants

The water enters the fridge plants after first passing through the pre-cooling towers at around 20 °C. The water passes through the cycle and is chilled to around 3 °C. The fridge plants operate using the standard refrigeration vapour-compression cycle as displayed in Figure 20 [41], [46].

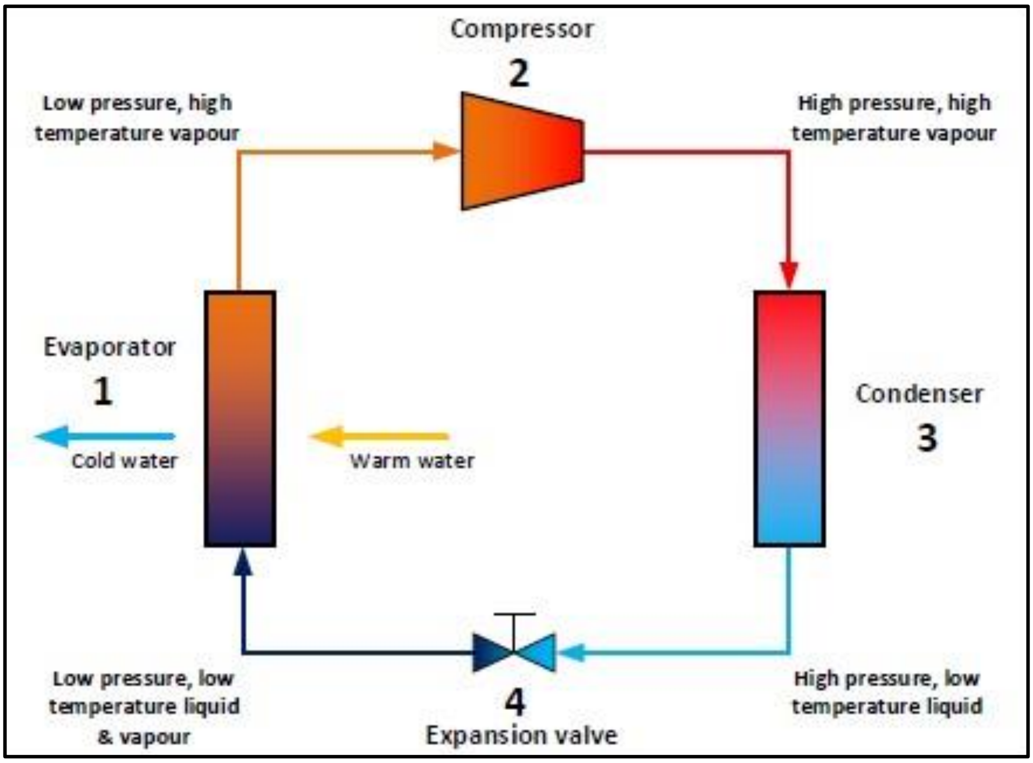


Figure 20: Vapour-compression refrigeration cycle [28].

The vapour-compression refrigeration cycle consists of the following four stages [47]:

- Evaporator (1): A refrigerant circulates inside the shell-and-tube type heat exchanger where hot water flows over the finned tubes. The heat transfers to the refrigerant to cool down the water.
- Compressor (2): The compressor does the mechanical work and can regulate the cooling duty of the system through variations in compressor speed. The compressor speed affects the flow rate of refrigerant and is controlled with the compressor guide vanes.

- Condenser (3): The condenser is where the refrigerant passes through after exiting the compressor. Heat is removed from the refrigerant by the shell-and-tube heat exchanger, known as the condenser.
- Expansion valve (4): After the refrigerant exits the condenser, it passes through the expansion valve which decreases the pressure of the fluid before entering the evaporator to repeat the cycle.

The water is transported to cold water storage dams with auxiliary pumps on the surface after it leaves the refrigeration plants. The chilled water is stored to be ready for the previously mentioned mining purposes when needed.

Dewatering

Water sent down for mining operations is combined with fissure water and can accumulate to volumes of over 40 million litres per day. After water has been used, it falls to the footwall and flows to settlers at the lowest level of the mine with gravitation. The mine is at risk when water accumulates underground and the water has to be removed to prevent flooding [30], [48], [49].

The dewatering system is the final phase in a functional water reticulation system. Warm water is removed from the underground storage dams with large industrial multi-stage pumps. The water is then supplied to the refrigeration cycle to be chilled and used for mining. Dewatering is essential in the prevention of flooding and to regulate underground storage dam levels [29], [50], [51].

The dewatering system starts at the bottom of the shaft where water gathers. The water is sent to settlers to remove mud and debris, thereafter dewatering pumps move the water in stages to the surface storage dams. Mud is removed from the water in the cleaning process to prevent cavitation and damage to water pumps [28], [52].

Displayed in Figure 21 is a schematic illustration of how water and mud are removed from the mine to complete the cycle of the water reticulation system.

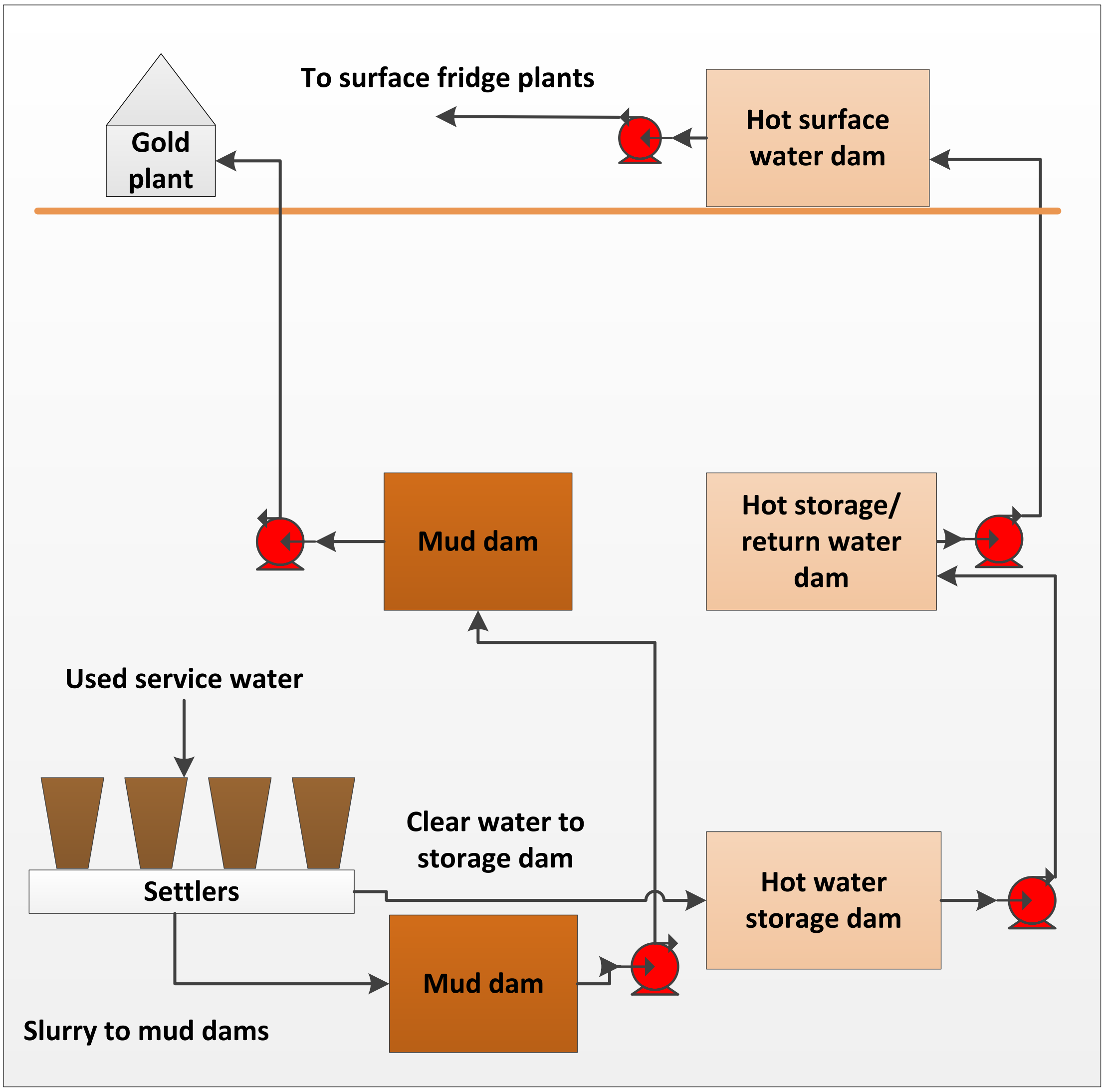


Figure 21: Mine dewatering system [29].

Multiple energy-saving initiatives have been researched and implemented to realise energy savings. Studies focused on the reduction of pumping costs usually include Demand Side Management (DSM) projects and initiatives.

Previous researchers put focus towards water demand reduction for daily activities to realise savings [28], [34], [41], [53]. Focus was placed on leak management or valve control. Valve control reduced the volumes of service water used by the shaft [34], [53]. The reduction of service water led to cooling services underground performing poorly with decreased cooling duties [41].

Reducing water consumption

Chilled water is used for mining activities and cooling down ventilated air and, as previously mentioned, the water consumption relates to the scale of mining operations and gold production [28]. The more water is consumed in mining activities, the more gold is supposed to be produced. Water used for cooling of ventilation air can be viewed as a baseload, as this water requirement is not dependent on specific working shifts.

Techniques to reduce water supply to underground have been implemented and effectively reduced the baseload consumption. Since certain mining activities require a sufficient water supply, it is not ideal to decrease the supply, but rather to control the demand [28].

The following section discusses techniques for demand-side management of water reticulation systems.

Water leakage management

Water inefficiencies due to leaks are one of the largest areas in need of improvement for deep-level mines. The water distribution network underground can span over 150 kilometres of water pipes.

These pipes are exposed to humid air and high pressures. Given enough time that the pipes are neglected, they rust and deteriorate [54]. Maintenance is neglected due to the warm and humid environments where maintenance-related labour is not prioritised, and resources are not available for regular inspection.

When leaks occur in the chilled water supply column, refrigeration efficiency decreases and leaks on the dewatering column may result in a decrease of the pumping efficiency [28]. Leakages occur in the form of open ends. When finished working, the miners may forget to close the chilled water supply [54]. An example of a leaking water pipe due to corrosion is displayed in Figure 22.

Figure 22: Water leak on steel pipe [28].

Currently the industry standard to identify leakages is through conducting inefficiency audits. Mining personnel and employees from an Energy Service Company (ESCO) need to physically walk every section of the mine to locate water inefficiencies and wastages [10], [28]. Reducing leaks on the water distribution system helps to supply sufficient chilled water to operations and not influence productivity.

The volume flow rate experienced through a water leak can be quantified using Bernoulli's theorem in Equation 1 [54]:

$$Q = \alpha A_t \sqrt{\frac{2(P_{inside} - P_{outside})}{\rho_{water}}} \quad (1)$$

where: Q = volumetric flow rate (m^2/s)

P_{inside} = pressure experienced inside the pipe (Pa)

$P_{outside}$ = pressure experienced outside the pipe (Pa)

A_t = Area of leak (m^2)

α = Fluid coefficient of flow (-)

ρ_{water} = Density of fluid (kg/m^3)

For example, the leakage flow rate through a pipe with a diameter of 25 mm, an inner water pressure of 3000 kPa, and an outer pressure of 110 kPa. The flow coefficient is included to account for friction and other losses. Typically calculated as the volume of water at a specific temperature through an opening with a pressure drop, thus requiring the flow rate. For this example, it is assumed as 0.7:

$$Q = (0.7)[\pi \times \left(\frac{0.025}{2}\right)^2] \sqrt{\frac{2(3\,000\,000 - 110\,000)}{1000}} \approx 26\,L/s \approx 2.25 \text{ ML per day}$$

From this example, an unattended water leak can waste up to 2.25 ML of water and it is beneficial to repair leaks in the underground water distribution system.

1.3. Previous studies on water reticulation systems

Literature reviews are important to lay the foundation for academic investigations. The following sections thoroughly investigates relevant studies to identify scope for further investigation based on systematic research [55].

Literature on refrigeration systems

Preamble

The shortage of electricity supply and extremely high energy costs have led to the research and implementation of energy management strategies to reduce energy consumption in mining activities.

Underground temperatures increase with depth as specified in research from preceding sections. These temperatures need to be regulated to maintain the productivity of mine workers and it is critical to comply to the health and safety regulations. The refrigeration system is integral to supply chilled water to complete the mining cycle.

Prior research completed on industrial refrigeration systems are found in the subsequent section. A review of each study is given briefly to identify available opportunities for further research.

Review of studies/strategies conducted on refrigeration systems

Study 1: Optimal use of mobile cooling units in a deep-level gold mine [17]

Van Staden *et al.* [17] opted for the use of existing mobile cooling units to improve on service delivery while reducing operating costs on a deep-level mine. The mobile cooling units were found to become inefficient due to the harsh working environments and negligence of maintenance. The chosen strategy for the case study mine involved removing 22 inefficient mobile cooling units.

By removing inefficient mobile cooling units, underground chilled water demand and temperatures at areas of interest were reduced. This study did not include improving chilled water distribution or increasing the efficiency of the mobile cooling units and did not consider the complications if the working areas were re-opened.

Study 1, however, would not be applicable to a case study mine that has an extensive heat rejection requirement where the majority of installed cooling units are efficient. Study 1 achieved a combined cost saving of R2.38 million in two months while improving the underground temperatures.

Study 2: Optimising the refrigeration and cooling system of a platinum mine [56]

Buys *et al.* [56] investigated the impact of applying variable speed drives (VSDs) to reduce energy consumption and improve cooling systems on mining operations. The installation of VSDs assisted to obtain energy savings by cutting back on the operational fan frequency during non-production periods.

Study 2 did not consider the feasibility implications associated with purchase and installation of the VSDs, even though savings of up to R12.5 million per annum were achieved. Section 1.1 of the current study revealed that the gold mining production trend is declining year-on-year. This entails that mines could be reluctant to consider the installation of VSDs if the return on investment does not fall well within the expected life of mine.

Study 3: Cooling pathways for deep Australian longwall coal mines of the future [57]

Belle and Biffi [57] evaluated the temperature profiles experienced on deep coal mines with toxic gasses. These mines tend to have the risk of spontaneous combustion, which adds risk to the initiative. The study reviewed the effect on the temperature profile related to chilled water sprayers and underground bulk air coolers. The positional placement of these bulk air coolers was investigated to enhance the efficiency of the cooling plants.

It was concluded that the refrigeration cycle plays an integral part in lowering underground temperatures to ensure safe working environments. In Section 1.2 of this study, it is discussed that BACs are installed in existing haulages. This means that positional placement would need to be considered with the planning of the mine infrastructure. Study 3 would not be applicable to a mine that has already installed cooling infrastructure, as it would be a difficult task to change the location of a bulk air cooler.

Study 4: Implementing a DIKW model on a deep mine cooling system [58]

Pretorius *et al.* [58] implemented the wisdom hierarchy model on a deep-level mine cooling system. The aim of the study was to improve the cooling system's performance while using existing infrastructure. By simply using existing infrastructure to measure the performance of cooling, inefficient cooling units were targeted using automatic reporting that extracts data from existing instrumentation.

These inefficient cooling units were then investigated to determine factors that could be improved on by taking action. Automatic reporting allowed managers to have knowledge of the performance of underground cooling units without the need for utilising manual labour for physical inspections.

Similar to Study 1 [17], the savings achieved within Study 4 [58] were made possible by the availability of inefficient cooling units. Should no inefficient cooling units be present in the case study, there would be no scope to identify these units and address for achieving savings. Measurement instrumentation was used to identify the inefficient cooling units through automatic reporting. This method to achieve energy savings would not be applicable to a case study that does not have the required measurement instrumentation installed.

Literature on dewatering systems

Preamble

As stated in preceding sections, the increasing electricity cost is a concerning factor in the mining industry and puts the mines at risk of early closure. The water reticulation system consists of refrigeration, water distribution, and dewatering to complete the cycle. Pumping is important to ensure the mine does not flood and that the water is recirculated to be used again for cooling and mining purposes.

Energy consumption of pumping systems can increase due to an increase of water supplied, mechanical factors such poor maintenance on pumping systems, and poor water quality [59]. There exists a need to cut pumping costs without reducing chilled water supply and neglecting underground conditions.

The reader will gain an understanding of the scope by reading the brief summary of the available research on dewatering systems in the following section.

Review of studies/strategies conducted on dewatering systems

Study 5: Reconfiguring mine water reticulation systems for cost savings [28]

Conradie [28] investigated the energy savings that could be achieved by the control of the water supply. The study determined whether the reconfiguration of the water reticulation system of a mine would result in a decrease of chilled water demand.

This involved removing inefficient mobile cooling units and replacing them with centralised bulk air coolers at the entrance to each active mining level. Simulations and calculations were used to verify data from the case study mine and resulted in a predicted saving of R31.8 million per annum.

This strategy planned to reduce the daily chilled water consumption. The overall decrease was calculated by using the designed flow rate of the mobile cooling units and multiplying it by the number of units removed.

Study 5 did not consider the cost implications of adding new infrastructure such as centralised bulk air cooling units. Section 1.2 of the study discussed how bulk air coolers are installed in existing haulages for cooling and ventilation. The installation of a new centralised bulk air cooler would entail additional infrastructure and be an extensive project.

Study 6: Optimising the demand of a mine water reticulation system to reduce electricity consumption [54]

Botha [54] considered to reduce the wastage of water and minimise water consumption during periods of low demand, such as blasting. Methods implemented were stope isolation, regulation of the supply pressure, and leak management. Leak management resulted in the highest water reduction and showed promising cost savings of R500 000 and R5.6 million per annum respectively on his two case studies.

Study 6 considered the improvement of water supply through means of reducing water inefficiencies. This entailed routine leak audits accompanied by mining personnel and ESCO employees. This method was effective but relied on manual labour to identify inefficiencies. Study 6 did not consider a method to assist with the location of these inefficiencies and extensive manual leak audits were conducted, which are time consuming and labour intensive.

Study 7: Optimising energy recovery in mine dewatering systems [60]

Van der Wateren [60] considered the use of energy recovery devices to reduce energy consumption. The study found that previous research did not consider the difficulties associated with the operation of these systems and that some energy recovery devices had outdated technology.

To optimise energy recovery, the study proposed the integration of the dewatering system with energy recovery devices. The case study mine used in Study 7 had multiple three-chamber-pumping energy recovery systems that utilised a u-tube system to overcome head and reduce pumping costs with up to R1.7 million per annum.

The strategy had constraints on water supply that affected performance of the mining operations. This study is only applicable to a mine that was designed with additional infrastructure such as existing three-chamber-pumping energy recovery systems.

Study 8: Optimum water distribution between pumping stations of multiple mine shafts [61]

Schoeman *et al.* [61] investigated water management initiatives that can be implemented on deep-level mines. It was found that scenarios exist where less water is needed and that shifting loads on pumping operations are possible.

Energy savings were achieved by implementing load demand shifting. Additional cost savings were achieved by shifting loads according to the time-of-use electricity tariff low-demand periods with lower electricity tariffs. A combined saving of R39 million per annum was achieved over four case study mines.

Study 8 is only applicable if the case study mine is not constrained by low dam capacity. As discussed in Section 1.2, dewatering has a primary objective of eliminating the risk of flooding the mine. The failure of dewatering pumps, which introduce the risk of flooding, should also be considered.

Study 9: Optimization of the Water Reticulation System at Bulawayo Mining Company (BMC), Zimbabwe [30]

Ngoroyemoto *et al.* [30] reviewed the impact of poor water management and the design requirements to obtain optimal dewatering efficiency. Simulation software was used to optimise the water reticulation system.

It was found that the selection of pipe sizes influences the delivery flow rates of dewatering pumps. When installed pipes are larger than needed, the laminar flow restricts the velocity of the water.

The simulation software and algorithm assisted to reduce stoppages due to low water supply, but could not resolve the bottlenecks associated with dewatering large quantities of water. Due to the financial cost of upgrading an entire water reticulation system, this initiative could not be implemented.

As discussed in the preceding sections, the water distribution system spans across multiple kilometres of pipelines. The application of Study 9 to a case study mine would entail replacing these pipelines with the correct design requirements.

Literature on water-use efficiency improvement techniques

Previous studies conducted on the improvement of the distribution system has led to promising energy savings, but did not consider the tedious and time consuming physical underground audits performed to locate the water inefficiencies. There exists a need to assist with locating underground water inefficiencies without using constrained labour resources to regularly audit for water inefficiencies on the water distribution system.

The following section gives a review of literature and studies conducted to assist in locating inefficiencies on water distribution systems with a brief description for the reader to better understand where a need exists.

Study 10: An optimization approach to leak detection in pipe networks using simulated annealing [62]

Huang [62] investigated the use of leak detection simulated annealing (LDSA) to use the parameters of transient flow simulations and simulated annealing for detecting leaks in a pipe network. Simulated annealing is an algorithm based numerical approach used to solve bound-constrained optimisation problems. Experiments performed in previous literature on a single pipeline was used to verify the capabilities of using LDSA for the identification of leaks.

Different scenarios were created in a simulated environment to evaluate the performance of LDSA, and it was found that the accuracy increased when multiple observation points were used in a simulated environment.

However, Study 10 did not consider the large and complex water distribution networks of the deep-level mining environment and was not fully implemented in practice to identify other water-use inefficiencies.

Study 11: Data-driven and model-based framework for smart water grid anomaly detection and localization [63]

Wu [63] opted to use available instrumentation to develop a novel analysis of data. This was coupled with hydraulic modelling to improve the quality and efficiency of distributed water services.

He highlighted the importance of detecting and locating anomalies in the real-time data which may be due to burst pipes, water leaks and illegal use of water. A data-driven model was developed to assist with anomaly detection and the localization of these occurrences using the calibration of the hydraulic model.

The aim of Study 11 was to develop a method for anomaly detection and the needed steps to classify and locate the occurrence before taking action.

The model was developed and tested on a case study water distribution system of an urban area and not on the water reticulation system of the deep-level mining environment. The harsh underground environment presents different challenges with internal water column pressures of up to 20 MPa.

Study 12: Localization techniques for water pipeline leakages: A review [64]

Lah [64] focused on the efficiency in the water distribution network and laid emphasis on how water leaks are a prominent issue in these networks. The study clarified that the first step would be to detect if a leak has occurred, followed by a localization strategy. A review of leak localization strategies was conducted to determine which strategies would be suited based on available infrastructure and instrumentation.

The review highlighted the constraints and challenges faced when implementing each technique and the proposed method was a localization technique using vibration sensors to pick up disturbances in the system.

Study 12 was not implemented in the deep-level mining environment and did not consider the implications of water systems similar to the water reticulation system of a deep-level mine. The study also did not consider the electricity saving benefits from implementing such techniques.

Study 13: Long-Term Monitoring for Leaks in Water Distribution Networks Using Association Rules Mining [65]

Harmouche [65] investigated the benefits of early detection of leaks in water distribution pipelines. This allowed for proactive maintenance and timely actions to take place, allowing for the mitigation of water loss and improving the longevity of the distribution network. The study discussed the use of acquiring long-term data from monitoring programs when dealing with large volumes of water.

He encountered challenges with the monitoring systems that would occasionally suffer from noise interference and be interpreted as leak-induced anomalies. The noise in the acquired data was addressed by using available data to characterise the operating conditions.

The data-driven approach allowed for association rules to be applied for the indication of anomalies that are associated with leaks. The model showed promising results in the indication of leaks by the distribution model and could associate anomalies with relatively small leaks.

It did, however, not consider other water-use inefficiencies or the localisation thereof. The strategy was not implemented on water systems found in in deep-level gold mine water distribution networks.

Study 14: Component analysis for optimal leakage management in Madaba, Jordan [66]

Aboelnga [66] provided a structured analysis to quantify the volume of leakages and the contributing factors of a water distribution network. Recommendations are made to reduce water losses through a framework that includes the utilisation of existing infrastructure, economic awareness, repair, and pressure profiles.

The aim of the study was to address the expenditure of costs for urban non-revenue water security in Jordan. Pressure management and leakage detection surveys were applied to improve the response time of leak management and reduce water losses.

By implementing the water management strategies based on pressure management and the improvement of response time on corrective maintenance, the study revealed scope for the improvement of the water distribution network, which could lead to cost savings.

Study 14, however, was not fully implemented and did not consider the implications of the deep-level mining environment where leaks can occur up to 4 km below surface in an area that can reach 10 km in length and width [27], [38]. Personnel can take up to two hours to reach the problem area on the complex water distribution system. The investigation by Aboelnga did not contribute in the identification of water-use inefficiencies or anomaly detection.

Study 15: Study on Pipe Burst Detection Frame Based on Water Distribution Model and Monitoring System [67]

Cheng [67] considered the feasibility of the detection of bursts, the burst detection algorithm, and the design of the monitoring infrastructure. These considerations combined made it possible for detecting water bursts in a water distribution network.

Noise was experienced in the monitored data and identified through statistical analysis. The ability to distinguish between noise and accurate data allowed for an effective burst detection algorithm on existing infrastructure without additional costs.

Study 15 hypothesized that a minimum pipe diameter is associated with the accuracy of the burst detection, and that there exists a limit on the pipe diameter to where burst detection is possible. The investigation required a minimum of two sensors close to the event of a burst for detection errors to be reduced.

The possibility of leak localisation on water distribution systems was not implemented on a large-scale complex water reticulation system. Study 15 also did not consider the cost saving involved by locating and repairing water leaks on similar water reticulation systems as found in deep-level mines.

Study 16: Real-time burst detection in water distribution systems using a Bayesian demand forecasting methodology [68]

Hutton [68] utilised a demand forecast approach to forecast problematic future events under normal operating conditions. The aim of the study was to reduce non-revenue water losses on the water distribution system through timely identification of leaks and irregular conditions. The method was tested and implemented under experimentally controlled conditions to quantify the probability of future leak occurrences.

The synthetic environment enabled the investigation to evaluate the detection bursts in the system under real-time demand controls. Improved efficiency of the water distribution network was not the aim of Study 16. This study was not implemented in an environment with similar conditions to deep-level mining water reticulation systems. The possibility of cost savings was also not considered.

Study 17: A Review of Vibration Detection Methods Using Accelerometer Sensors for Water Pipeline Leakage [69]

Ismail [69] reviewed techniques applied for leakage detection on pipelines distributing water to cities. The techniques were categorised according to the use of software, hardware, or conventional methods. Conventional methods require experienced personnel to manually audit pipelines and conduct a manual inspection. Unusual patterns are identified based on sounds and smells that occur due to leaks. Hardware-based methods were highlighted after an evaluation of advantages and disadvantages of each category. Previous research was discussed and the specifications of testbenches to experimentally represent pipelines were reviewed.

The aim of the study was to distinguish what the instrumentational requirements are of the different techniques. The instrumentation used, the cost, and the accuracy were evaluated, with the conclusion that vibration sensors delivered promising results in the detection of leaks on the theoretical pipelines. The study successfully reviewed different leak detection techniques in an experimental environment.

Study 17 did not consider the complications of a vibration-based leak detection model on pipelines distributing similar volumes of water through the system such as the distribution networks found in deep-level gold mines. The benefits of successfully identifying and locating leaks were also not investigated. [70]

Study 18: Leak localization in a real water distribution network based on search-space reduction [71]

Sophocleous [71] presented a model-based framework for the detection and localisation of leaks in water distribution networks. The two-stage method involved search space reduction to assist with leakage detection, followed by localisation. Search space reduction reduced the number of variables involved for an optimised solution and leak detection localisation determined the size and area of the leak.

Simulation software was used to strategically place nodes on the simulated distribution network and leaks were simulated to calibrate the model for minimal difference in pressure head and flow compared with results observed in the field. The solution was generated through a genetic algorithm that was implemented on two case studies. One case study involved a real large-scale water distribution network with theoretically generated data to determine the limits of the method. The other case study was implemented fully on a large-scale water distribution system and successfully detected a leak that occurred in practice.

It was found that the method could contribute to faster anomaly detection and localisation of leakages, but was not implemented on a system with similar pressure and flow requirements to that of a deep-level mine’s water reticulation system.

Study 19: A review of data-driven approaches for burst detection in water distribution systems [70]

Wu [70] focused on burst detection by using data-driven approaches. Different classification methods, prediction methods and statistical approaches were evaluated. The different data-driven approaches were assessed based on performance, and uncertainties were analysed.

The investigation revealed that reliability of data required pre-processing to ensure accurate results. Data-driven approaches were, however, recommended due to the promising detection of bursts in real time while limiting false alarms due to unreliable data.

Study 19 briefly discussed the impact of leak size on the performance of leak detection models and using clustering analysis to further improve the accuracy of detection. The objective of the study was to evaluate the use of data-driven approaches and highlight the key factors of accurate models, but the full-scale implementation of data-driven approaches on complex deep-level mining water-reticulation systems was not investigated.

Summary

Mines are continuously deepening to greater depths, resulting in the need for improved cooling to supply safe working environments. The electricity tariff that increases annually makes the implementation and maintenance of energy efficient equipment essential and the reduction of energy consumption a key initiative. Initiatives for energy management, such as regulating the supply of service water, have been put in place to reduce energy consumption. The reduction in chilled water affects the cooling performance of the system.

Initiatives have been implemented to pump during certain time-of-use periods to reduce the cost of pumping. Unfortunately, this initiative requires sufficient dam storage capacity and does not mitigate the risk of pump unavailability or power failure after the time-of-use period. This creates an elevated risk of flooding.

Leak management initiatives that require external parties to audit entire underground pipelines and report on leaks have been implemented. This is a tedious, time consuming and physical activity as the water distribution networks can span up to 20 km in warm underground environments.

Without an indication of whether water inefficiencies are present in the system, these audits are generally performed blindly until water-use inefficiencies are located.

Furthermore, various leak- and water-use anomaly identification models have been developed and tested on water distribution systems. None of the studies reviewed covered the use of models on the water reticulation systems of deep-level underground mines or in experimental setups with similar conditions.

Displayed in Table 1 is a summary of the state-of-the-art matrix, containing the relevant keywords. The state-of-the-art matrix is used as a research mining technique to divide information gained into parts of critical information. Dividing literature into sections using keywords obtained from articles and summarising the relevance to the study.[72] The orange blocks represent keywords not included in the relevant study and the green blocks indicate keywords included in the study.

Table 1 highlights the need for the study as deep-level mines have implemented various cost saving initiatives not within the scope of this study. Previous literature shows that there is a need to focus on leak identification and location. The implementation of a model-based method for the localisation of water-use inefficiencies would be beneficial.

Table 1: State-of-the-art matrix.

Source	Deep-level mine	Water reticulation system			Model-based	Leak identification	Leak Localization
		Refrigeration	Distribution network	Pumping			
[17]							
[56]							
[57]							
[58]							
[28]							
[54]							
[60]							
[61]							
[30]							
[62]							
[63]							
[64]							
[65]							
[66]							
[67]							
[68]							
[69]							
[71]							
[70]							

	Not within scope of references
	Included in the scope of the references

1.4. Problem statement and research aim

Problem statement

Water inefficiencies in deep-level mines contribute to additional pumping and refrigeration costs. The current methods to identify these inefficiencies include inefficiency audits of underground pipelines to report on found leaks and poor water management. This process is a physical, labour-intensive activity that can be time consuming in the warm underground environments. Existing methods require capital expenditure and typically influence the cooling and ventilation performance of the mine.

Previous studies identified that a model-based method to locate water-use inefficiencies would assist to reduce unnecessary cost related to wastage. The implementation of a model-based method would reduce the need for routine inefficiency audits. The literature review indicates that there is no model related to the localisation of water-use inefficiencies in deep-level mines. The pumping and refrigeration systems can both benefit from focus on the water distribution system.

A model-based approach would reduce the need for labour-intensive underground audits to identify water-use inefficiencies. It is expected that the implementation of a model-based approach would reduce operational costs in the water distribution system. Therefore, a need exists for a method that uses a model to assist in locating water-use inefficiencies in deep-level mines.

Research aim

This study aims to develop a method which assists with the detection of water-use inefficiencies in the water distribution network and then use the available data to locate these anomalies to specific areas. To this end this study has the following objectives:

1. Develop a method to assist with the identification and localisation of water-use inefficiencies in a deep-level gold mine.
2. Validate the accuracy and financial impact of the method through implementation on a deep-level gold mine.

1.5. Dissertation layout

Chapter 1

The combination of declining gold production and increasing operational cost leads to unprofitability and the possible early closure of deep-level gold mines. Chapter 1 identified the water reticulation system as one of the largest contributors to electricity usage on mines. The three systems within the water reticulation system were included for background, followed by a literature review with focus on the components within the system and initiatives to improve efficiency.

One of the key components that presented a potential for potential savings is the water distribution system. A need exists for a method to identify and locate water-use inefficiencies on the water distribution system.

Chapter 2

Chapter 2 elaborates on the development of a method that can be implemented for the model-based localisation of water-use inefficiencies in deep-level gold mines. The method involves the case study evaluation, which is followed by the procedure of data extraction and data noise filtering. The process for outlier detection, anomaly classification and inefficiency localisation, is discussed.

Finally the implementation of the method is explained before the integration and verification process. This method is developed to be generic for deep-level gold mines that comply with the case study evaluation process.

Chapter 3

The identified case study mine for the developed method is located in South Africa. The relevant information regarding the case study background is provided. The results obtained prove that applying the developed method could assist with the localisation of water-use inefficiencies. Where action could be taken, the obtained savings are presented, whereafter the method is validated.

Chapter 4

The final chapter serves as a research study summary. The achievements of the study are described along with shortcomings and recommendations for future work.

Summary

The dissertation follows the research and design method as recommended by previous literature. The need for the study was identified through preliminary research. The need for the study is followed by a research aim and objectives.

Thereafter, a literature review was conducted to compile a state-of-the-art matrix. The research and design methodology was applied to achieve the set aim and objectives.

With the intention to validate the method, it is used in a case study. The results are then analysed and validated with literature before the research study is concluded with recommendations for future work. An overview of the dissertation layout with the relation to the research method can be seen in Figure 23.

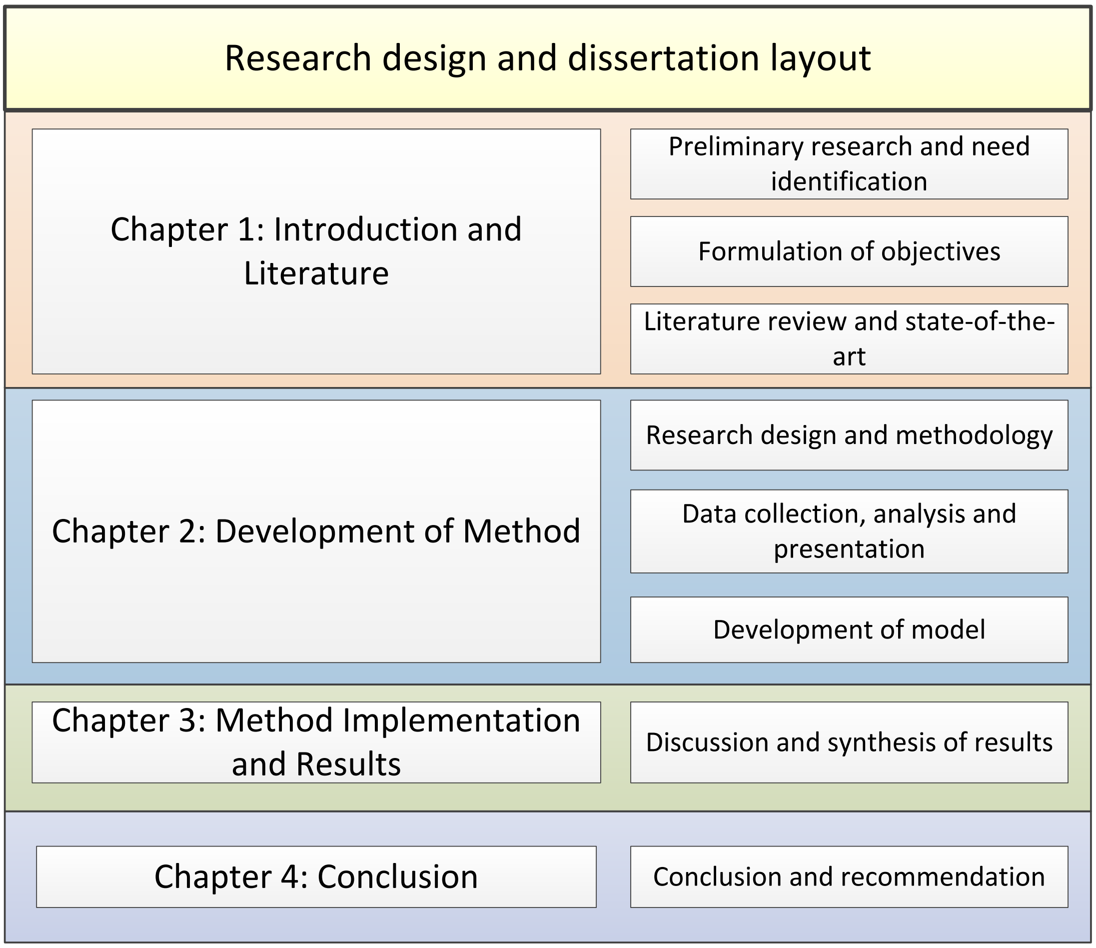


Figure 23: Dissertation layout [73].

Chapter 2: Development of Method

Figure 24: Mobile cooling unit operating underground[2].

[2] JM van Coller, Personal photograph, Westonaria, 2023

2. DEVELOPMENT OF METHOD

2.1. Preamble

Chapter 1 revealed that there is a need to assist with locating water-use inefficiencies to reduce the operational cost of mines. Using a model-based localisation method allows the user to reduce the need for labour-intensive audits while eliminating the need for capital expenditure to reduce electricity costs.

Various studies have been considered and integrated to successfully solve the problem identified in this study. The methodology overview gives background on the research method for the reader to better understand the reasoning behind the chosen method. The steps included in the method have been determined to achieve the set research goals and objectives stated in Section 1.4.

Five different steps are included in the method to develop and implement model-based localisation of water-use inefficiencies in deep-level mines. These steps are: system requirements investigation, data procurement and processing, development of a data-driven model, implementation, and integration and verification. Each step is discussed in the subsequent sections.

2.2. Overview of the research methodology

Multiple methods are presented in literature that can be used for conducting research. To ensure key research objectives were addressed, this research method used quantitative methods [73], [74]. After evaluation, it was viewed as beneficial to apply the case study method to the research study.

This method is typically used for the validation of the developed method and is ideal when it is impossible to regulate behavioural occurrences [73]. The sections that follow are based on the case study method where an evaluation process is followed to determine whether the case study meets the requirements for the method before the developed method is applied.

An integrated method has been developed from previous studies. A combination of previous research in anomaly detection and deep-level mining is considered in the method. The method proceeds in five steps to assist with its successful implementation.

- **Step 1:** Identify a suitable case study, as the study is dependent on the availability of infrastructure and design specifications to obtain data and be implemented [21], [73].

- **Step 2:** After the case study has been evaluated and the available measurement instruments have been identified, the data procurement and processing are required. This assists with setting up the model for anomaly detection [63].
- **Step 3:** Following the successful procurement of available data, the generic model is set up. The generic model is used for outlier detection and to identify water-use anomalies [63], [70].
- **Step 4:** The generic model assists with the identification of water-use inefficiencies. These inefficiencies can only be addressed once located and reported. This step considers the process of implementing the anomaly detection model on a deep-level mine [75]. Implementation consists of user notification, classification of the anomaly and localisation [76].
- **Step 5:** Successfully achieving the aims of the research study is dependent on the integration of the model and the user [77]. The model-based localisation method is measured by model accuracy and reduction in operational costs.

2.3. Step 1: System requirements investigation

Case study evaluation

To be able to achieve the set aim and objectives from Section 1.4, the chosen case study mine needs to be evaluated for suitable system requirements [73]. The successful implementation of model-based localisation for water-use inefficiencies requires an intensive evaluation of the mine.

This section will elaborate on the system requirements involved with the chosen case study and briefly discuss the findings.

After completion of the investigation the following should be known:

- Design and configuration of the water reticulation system
- Available data and instrumentation
- Location of measurement instrumentation
- Whether the case study is applicable for the developed method for water-use inefficiency localisation

Figure 25 is an example of the Supervisory Control And Data Acquisition (SCADA) interface seen when monitoring the chosen case study mine. An overview of the water reticulation system is present with various available live data measurement points. These available data measurement points are evaluated before determining a suitable area for the study.

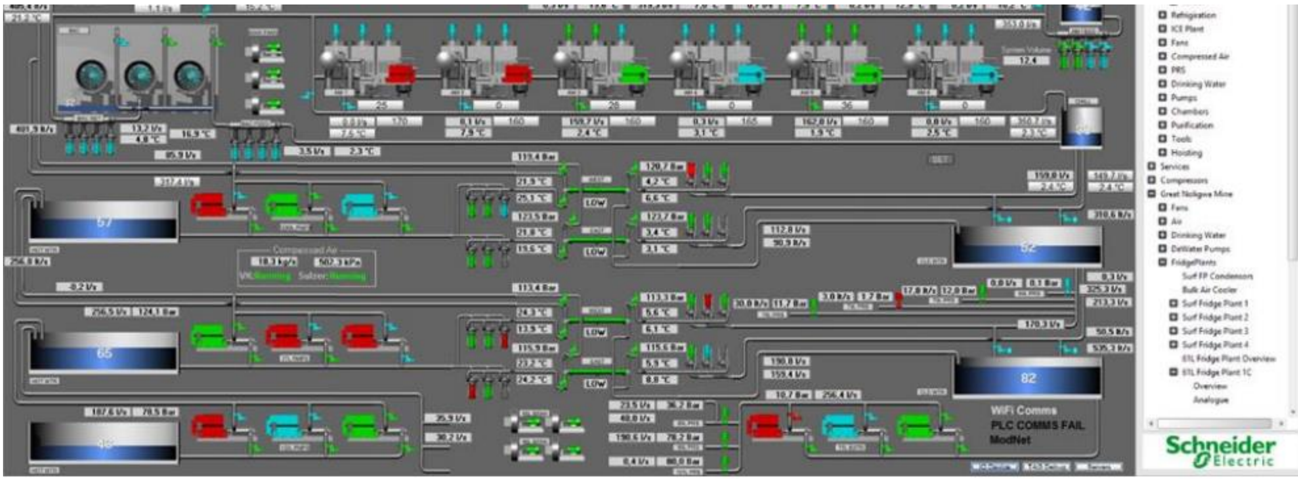


Figure 25: Example of a SCADA interface [78].

After the availability of data has been established, it is important to understand where this data are transmitting from as the field device responsible for capturing live data can be up to 4 km underground and 20 km in horizontal distance from the supervisory computers and server [66].

Figure 26 displays the top-view of a deep-level mine level, it illustrates the distances that water is distributed to be used for mining operations. These layouts can be obtained from mining personnel to assist with understanding the configuration of the water reticulation system [77].

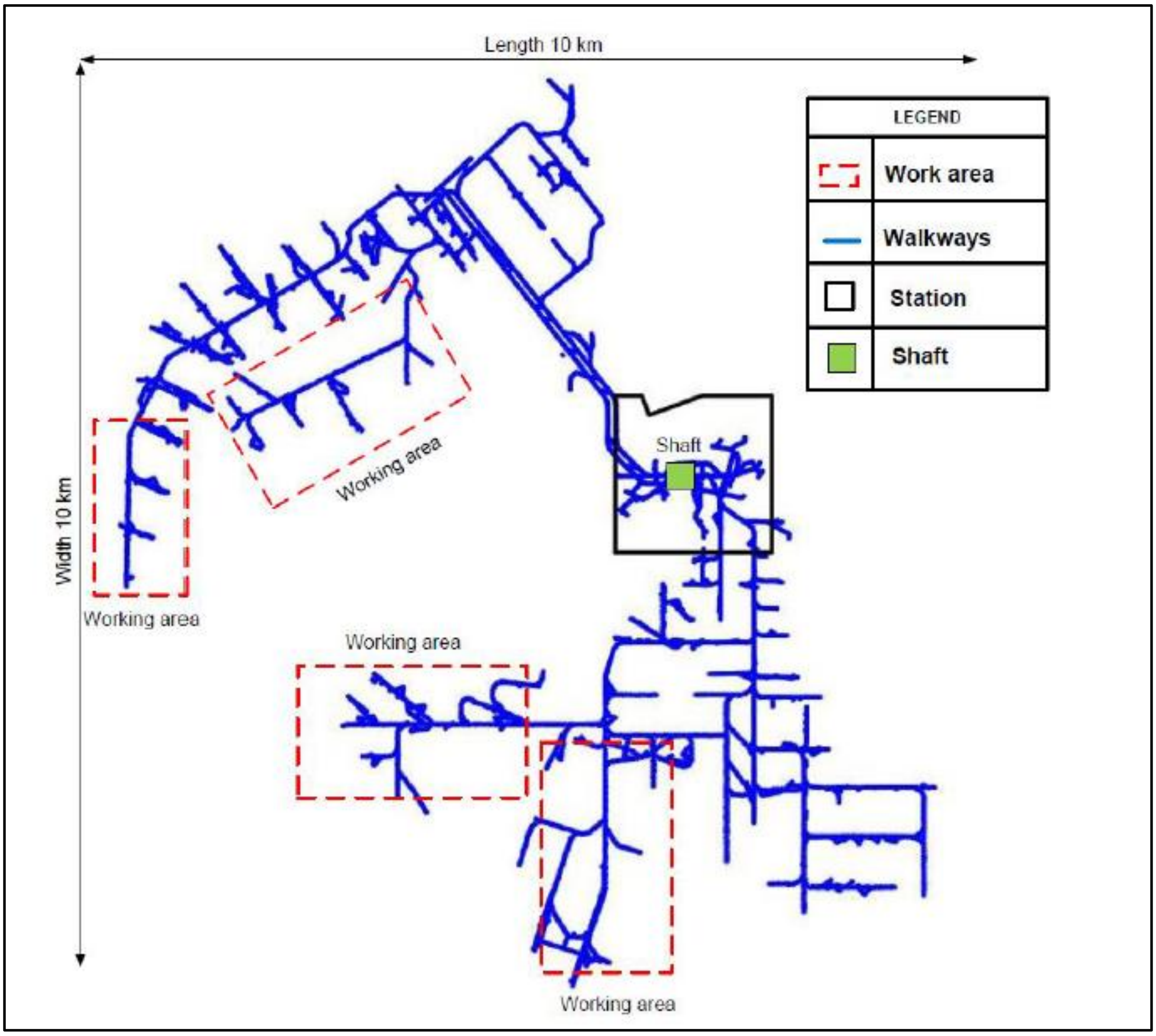


Figure 26: Top-view layout of a deep-level mining level [10].

The physical location of the measurement instruments are required to assist with the localisation of the detected water-use anomalies [71]. After the available measurement instruments have been identified, the data procurement process follows to obtain the captured data from the system.

Data acquisition theory

The supervisory control and data acquisition (SCADA) system is typically used in systems to monitor real-time operations underground [76]. Illustrated in Figure 27 is the typical SCADA configuration used for deep-level mines.

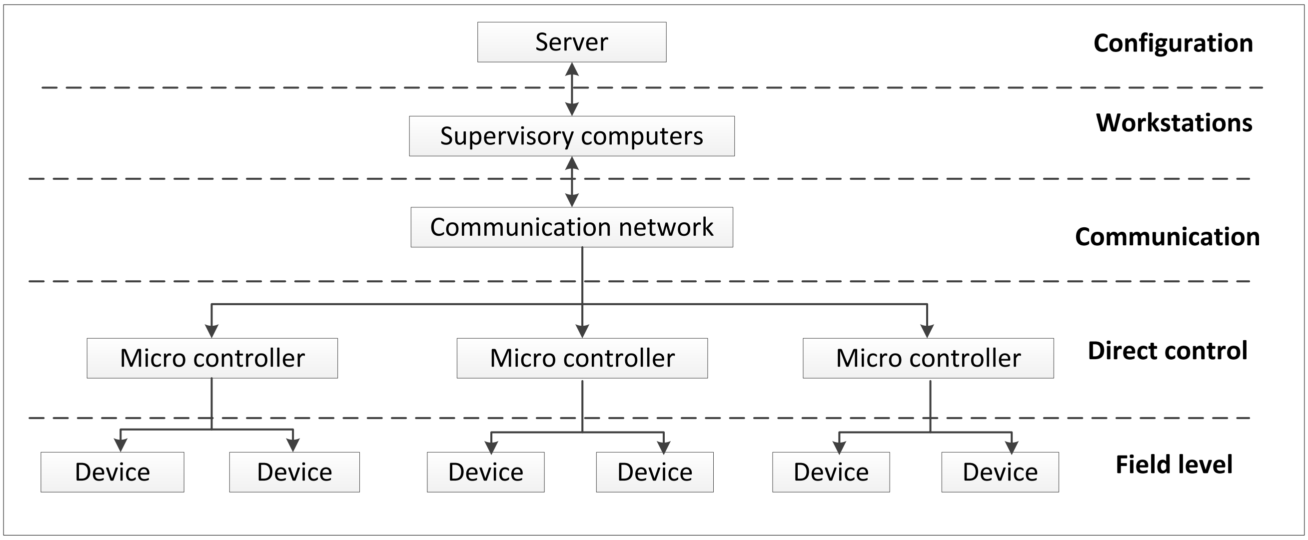


Figure 27: Typical SCADA design (Adapted from [79]).

Each sub-level is described as follows [76], [79]:

- **Configuration:** Computers and the primary data server used to set up and maintain the SCADA software.
- **Workstations:** Human interface with micro controllers. Contains the visual screen to present the graphics used during operation. Also known as HMI, or human machine interface.
- **Communication:** This enables communication between the user interface workstations and the remote devices.
- **Direct control:** Micro controllers such as programmable logic controllers (PLCs).
- **Field level:** Contains the lowest level of infrastructure such as the sensors, signal transmitters and additional hardware needed to capture data.

For the success of this study, the case study mine would need to have an available SCADA system or a similar system that has monitoring and data capturing capabilities [75]. This is needed for real-time monitoring and plays an integral role in the identification and locating of water-use inefficiencies, which will be discussed later [68], [71].

2.4. Step 2: Data procurement and processing

To successfully develop a model-based method for the localisation of water-use inefficiencies in deep-level mines, reliable data are needed. For the development of the generic model, historical data are used [70]. Real-time data are used for operation of the system to identify anomalies and notify the user. The steps taken to ensure usable data are available for the model development are discussed in this section.

Data extraction methods

Reliable data are necessary for the proposed model-based localisation system [79]. Displayed in Figure 28 is an illustration of the how real-time data are collected from underground operations. This is done through PLCs installed underground, which processes the data of the field instruments. The SCADA system then stores data on the historian. No human interaction is needed for the data to be stored to the historian. The HMIs are used to override control and change operations if needed [77], [79].

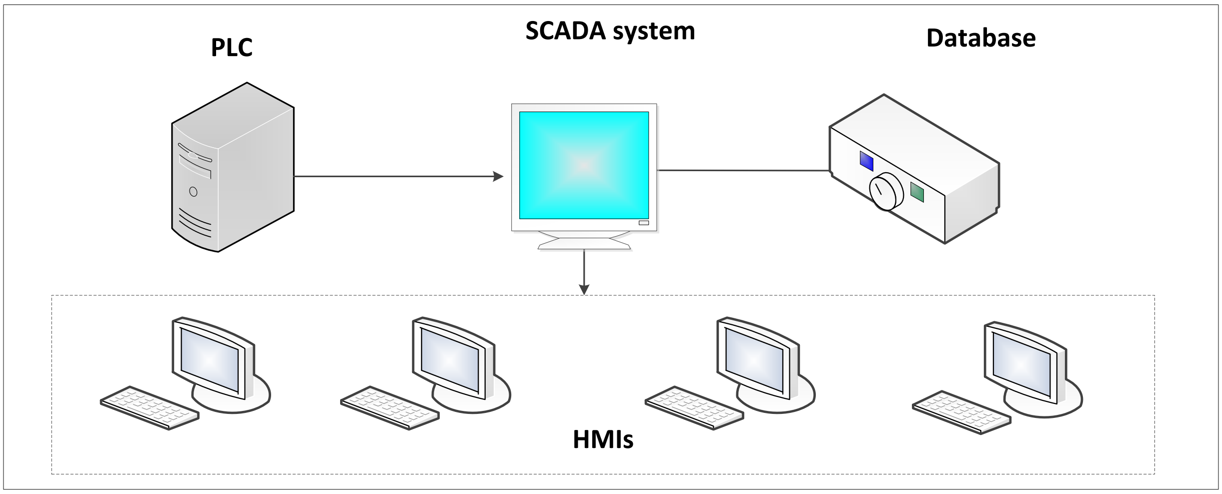


Figure 28: Data acquisition process [80].

Instantaneous information is logged to the SCADA system directly from the underground communication devices. Direct connection through the SCADA system to the PLCs is the best way to extract data. This could lead to problems with incompatibility, depending on the drivers used by the client, due to the protocols involved with SCADA communication networks [80]. To ensure incompatibility is included in the method, a universal solution is implemented.

The solution involves extraction directly from the historian. This ensures incompatibility does not interfere with the data extraction. However, data transfer delays may be introduced between the capturing and storage of data. The use of Structured Query Language (SQL) assists with the continuous extraction of data at specified intervals [80].

Data transmission

Data transmission is important to ensure a continuous stream of reliable data outside of the secure mine network. Data are transmitted from the remote server. To ensure that data are continuously transmitted, file transfer protocols (FTPs) can be used. However, accessing the remote server to obtain data during transmission is often required to make use of a virtual private network (VPN) [80].

Interruption in the continuous stream of data can result in downtime and loss of data. The mail server can be used as a data transmission method as illustrated in Figure 29. The client and the data historian are not linked. The secure mine network can be utilised to set up the data extraction software, without the requirement of a VPN connection.

The client is then sent an email with the extracted data, which is then saved in the client's database. With this approach, lost data is less likely to happen, if the historian gets damaged, the data are not lost. This can be automated to simplify the process.

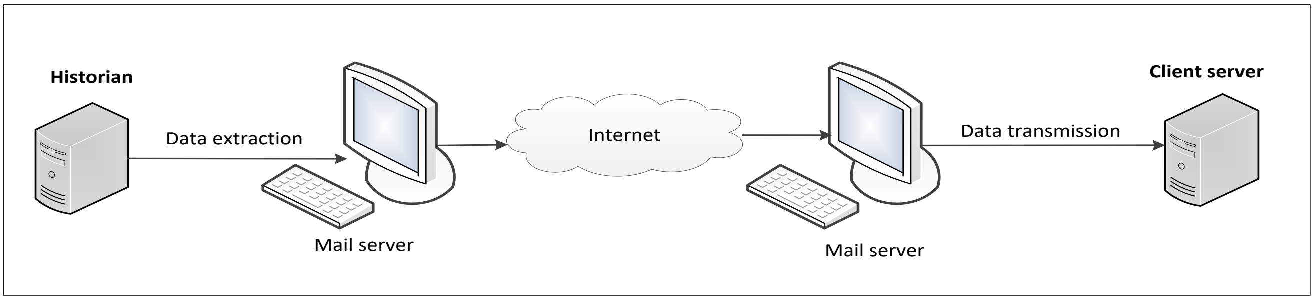


Figure 29: Mail server data transmission [81].

Data noise filtering

The captured data needs to be filtered to ensure good quality datasets have been allocated to the study. For this study, raw data are defined as data that has been extracted directly from the historian and not changed in any way. The data quality is evaluated to ensure that there are no faults present in the dataset. This contributes to the accuracy of the model. The method used to evaluate the data quality is illustrated in Figure 30.

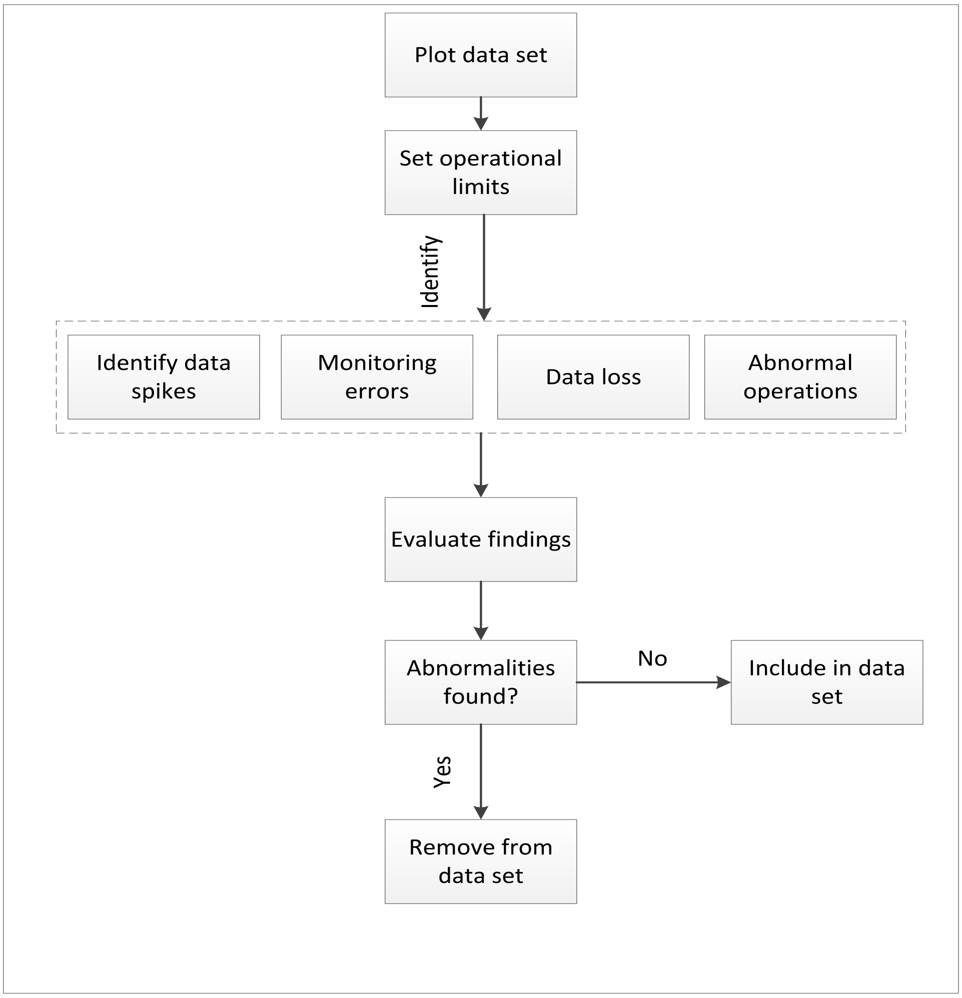


Figure 30: Data quality evaluation method [78].

The first step is to plot the raw data set. Previous studies indicated that the preferred method for non-programmers to plot raw data is by using tools such as Microsoft Excel [78], [82]. Illustrated in Figure 31 is an example of plotted data for the application of the data quality evaluation method.

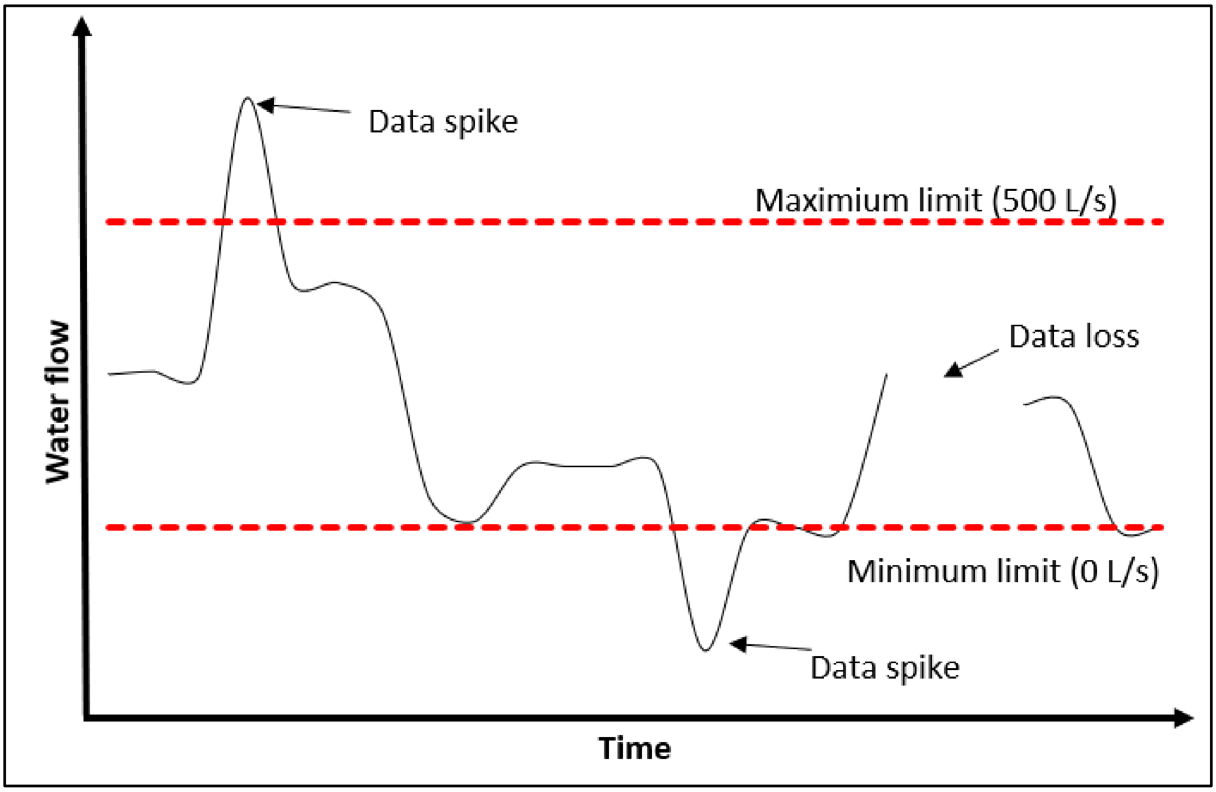


Figure 31: Process for dataset quality (Adapted from [82]).

Processing the data includes the identification of operational limits specific to the system [82] and defining these limits by considering the values generated through normal operations. These limits can be defined through examination of the design specifications or theoretical operating conditions of the applicable system [78].

The example illustrated in Figure 31 is for the set point of a water flow meter. The water flow rate could have a theoretical maximum flow rate that is constrained by the specific pipe as a maximum value.

The minimum flow rate is set at zero due to unidirectional flow caused by one-way valves installed on the system [82]. Any recorded data outside of the limits can be viewed as irregular data spikes or noise, as displayed in Figure 31.

Other contributing factors to consider for quality data include data loss, faulty or malfunctioning measuring instruments, and irregular operations, as depicted in Figure 30. A previous study discovered that malfunctioning measuring equipment occurs frequently in mines [60]. Inaccurate data are captured because of malfunctioning measuring instrumentation. An example is illustrated in Figure 31.

Non-routine mining activities also result in abnormal measurements if the activities are not expected during specific times. These non-routine activities can be neglected if they are not essential to the study [82].

After the majority of the data has been analysed, further steps can be taken to ensure the data set is of high quality and accurate. This ensures that the validation process is implemented accurately for the developed method. The following applicable quality checks can be implemented [78]:

1. **Units**: It is beneficial for stored data to have the same units throughout the data gathering phase. It is also recommended to convert all units to Système Internationale (SI) units.
2. **Constant value**: Captured data that display constant values for extended periods of time can be considered as malfunctioning measurement instruments and must be excluded from the data set.
3. **Redundancy**: Measuring instruments with certificates of verified measurements are preferred. When this is not an option, additional measuring instrumentation can help to compare two data points. Data that indicate a discrepancy between data captures using similar measurement instruments must not be considered in the data set.
4. **Correlation**: Measuring instruments that are measuring on the same system should have a correlation with one another. Data that do not correlate with the majority of the system should be excluded from the data set.

After the above-mentioned processes have been applied for data quality assurance, the data set can further be used for the development of the model. The accuracy of the model is dependent on the thorough quality assurance.

2.5. Step 3: Development of a data-driven model

The generic model to assist with the localisation of water-use inefficiencies in deep-level mines contains three stages for functionality. The three stages are importing data, processing data, and data export [76].

Data are imported from the client database where it is stored periodically, as discussed in Section 2.4. The imported data are then processed to ensure the data set is suitable to be used as an input in the model for the remaining steps illustrated in Figure 32.

Data export is the final stage and involves the prepared data being used as input in the model, which evaluates the data set and alerts the user by means of an alarm if the data set has breached the model parameters [63], [76].

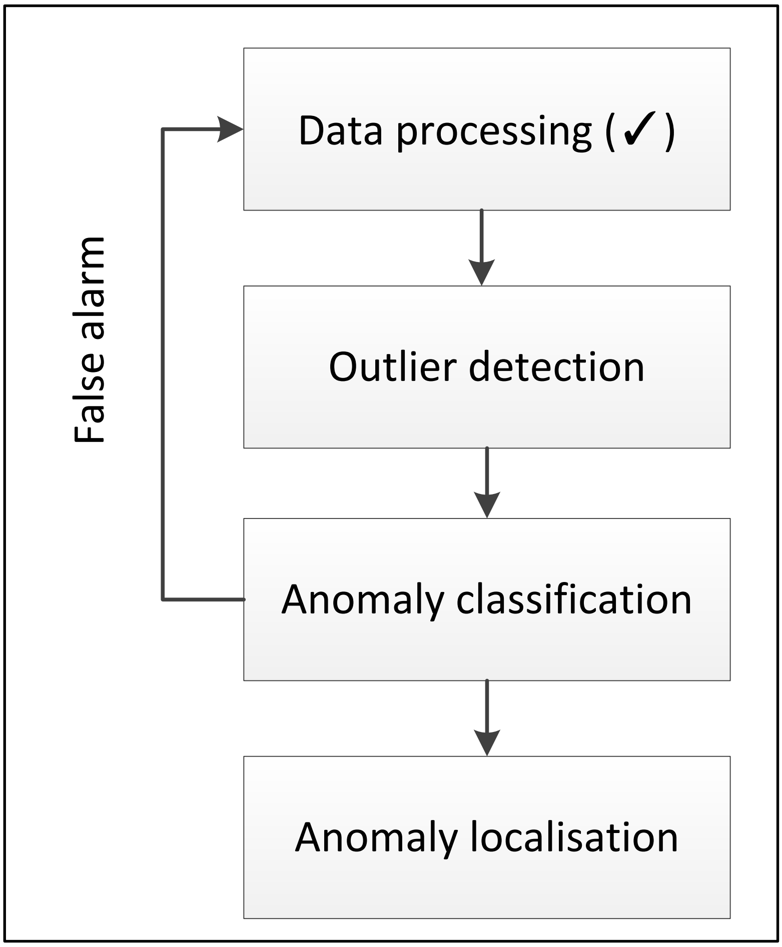


Figure 32: Development of model (Adapted from [63]).

Outlier detection

After the data analysis has been completed and noise has been removed from the data set, the flows and pressures can be used for outlier detection. Detecting outliers assists in identifying anomalies occurring in the system. Multiple statistical methods can be applied to assist with outlier detection. The method used is determined by the available information and compatibility to the case study [70].

X-bar: The X-bar ($\bar{x}$) chart is a statistical process control (SPC) method used to monitor attributes of variables. The method assumes adequate modelling by normally distributed random variables [70]. The upper control limit (UCL) and lower control limit (LCL) are the two control limits that are used. [63].

$$UCL = \bar{x} + 3 \frac{\sigma}{\sqrt{N}} \quad (2)$$

$$LCL = \bar{x} - 3 \frac{\sigma}{\sqrt{N}} \quad (3)$$

where the symbols consist of the following definitions:

$\bar{x}$	-	the average reading in the sample.
N	-	is the sample size.
σ	-	the estimated standard deviation of the individual values.

CUSUM: The cumulative sum chart method is used as a sequential analysis technique. CUSUM is typically applied for smaller shifts in sample data. When the cumulative sum value exceeds a set limit, an anomaly is identified. High-side and low-side cumulative sums can be calculated with the following definitions [63].

$$SH(0) = \mathrm{SL}(0) = 0 \quad (4)$$

$$SH(i) = \mathrm{Max}\,[0, \mathrm{SH(i-1)} + X_i - \mu - 0.5\sigma] \quad (5)$$

$$SL(i) = \mathrm{Min}\,[0, \mathrm{SL(i-1)} + X_i - \mu + 0.5\sigma] \quad (6)$$

Where the symbols consist of the following definitions:

$SH(i)$	-	The high CUSUM value for positive anomaly detection of the i^{th} point.
$SL(i)$	-	The low CUSUM value for negative anomaly detection of the i^{th} point.
X_i	-	The result for the i^{th} data point.
μ	-	The target value.
σ	-	The allowable standard deviation.

Mass balance: The sum of all mass flows entering the specific system should be equivalent to the sum of all mass flows exiting the system. A previously conducted study assigned a 5% deviation to measurement instrumentation for accuracy deviations [83].

Notification design

The notification system allows the user to be notified whenever an anomaly has been identified by the model-based water-use inefficiency localisation system. Three main components are defined to set up the notification system.

The components are as follows [76]:

1. The anomaly description provided in the notification
2. The reference repository
3. The relevant captured date

The description of the notification contains the name given to the alarm, associated with the mining system, or working area. The value is associated with the notification which was identified as an outlier. Each notification individually describes the anomaly that has occurred along with the date and time at which the anomaly has occurred.

User interface

The user interface is usually rooted on an existing energy management platform. An embedded ESCO platform is preferred for the development of the model.

This platform assists users with implementation of the model-based system. The user interface's data flow structure from the data transmission step can be seen in Figure 33.

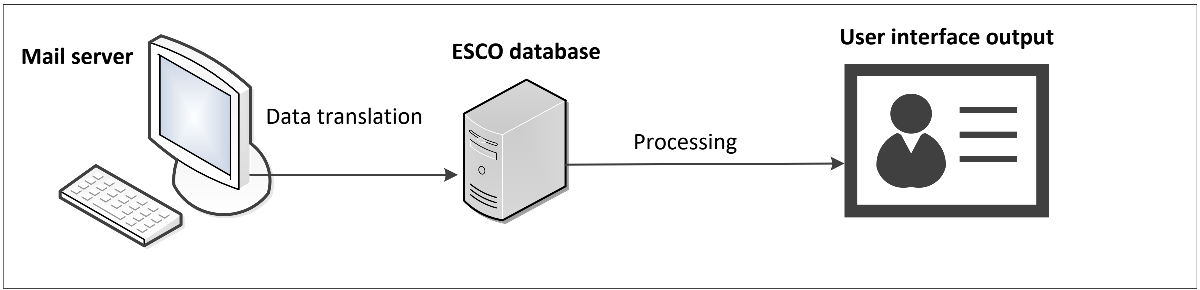


Figure 33: Data flow for user interface.

To set up the user interface, the processing step illustrated in Figure 33 contains additional steps before the output can be presented to the user. Various systems can be linked to represent the main mining systems that are relevant to the model. It is recommended to focus on pressure and water flow rate profiles. These parameters are considered to be the most relevant for the implementation of a model-based localisation of water-use inefficiencies [64], [70].

The initial step includes linking available data tags that have been identified during the system requirements investigation of the mining system. Thereafter, the limit profiles are linked for a visual comparison of resource usage. The interface updates periodically as new data are received by the historian, as discussed in Section 2.4.

The design of a user-friendly interface follows practices recommended in [76]. Visual design and simplifying the available SCADA interface assist with user interface satisfaction. Previous research has shown that SCADA has the tendency to overload the user with information [76], [79]. This can be resolved by implementing a simplified user interface. This user interface is used to evaluate the significance of the anomaly and influence the action to be taken as discussed in 2.5.

2.6. Step 4: Implementation

The implementation of the model-based localisation for water-use inefficiencies in deep-level mines incorporates the combination of the following. The system notifications, an accessible user interface, and the localisation of water-use inefficiencies are implemented to meet all the set objectives and requirements in Section 1.4.

Alarm notification

Once an anomaly has been identified, it is necessary to classify the occurrence as an inefficiency before it can be located and action can be taken.

The preferred method to locate water-use inefficiencies is by performing an underground inefficiency audit [29]. These audits involve available mining personnel and/or an external energy service company (ESCO) to physically walk the water reticulation system underground and check each section for inefficiencies [29], [54].

The following procedure has been adapted from previous research to assist with the localisation of water-use inefficiencies after classification [54], [63], [71].

1. Identify working level
2. Identify working areas
3. Plan according to working areas
4. Conduct an underground visit to verify exact location

The required information mentioned above has already been included in the design of the system notification. It is assumed that the average flows used are accurate, therefore non-working areas are assumed to give readings of 0 L/s in this methodology. The information provided by the notification should indicate which areas are responsible for the anomaly before further information can then be gathered for anomaly classification.

System anomaly classification

In the event of an anomaly occurring in the data set, the event must be classified as a water-use inefficiency for further action to be taken. As discussed in Section 1.2, various mining activities use water to successfully extract ore from the reef.

These activities are typically repeated on 24 hour cycles with the exception of non-mining days and Sundays [19]. The typical mining shifts in correspondence with cooperation from the mining management team is used to determine under which categories of water-use the anomaly falls. The following variables have been identified to associate with any water-use inefficiencies captured in mining operations [75]:

- **Metering errors**: As discussed in Section 2.4, metering errors tend to occur and require additional noise filtering to ensure they are not included in the data set. It remains important to consider the possibility of metering errors when classifying the anomaly identified by the model [78].
- **Excess usage**: From a previous study it was frequently found that mine workers sometimes leave the cold-water hoses open after their shift has ended. This results in an increased wastage of chilled water [29].
- **Increased production**: According to previous research, the deep-level gold mining industry in South Africa needs about 2 500 litres of water to extract one ton of rock [53], [54]. When deadlines for production targets are set, they cause an increase in the chilled water consumption. These activities typically occur when nearing the end of the target date and the production target has not been met. They involve additional shifts to ensure the tonnes hoisted increase to meet the required target for profitability [82].
- **Non-routine activities**: These occur when the water consumption increases while there is no shift scheduled to be at an area during a certain time. This anomaly is subject to behavioural events [73], [82].
- **Modelling errors**: Errors that occur due to modelling discrepancies are typically associated with dimensionality increases [75].

- **Leakages**: Water distribution pipelines are exposed to harsh and humid environments in deep-level underground gold mines. Leaks are identified as a non-behavioural water-use inefficiency and should be repaired as soon as possible [29], [54].
- **Scheduled water usage**: Scheduled water usage can result in higher water consumption rates. If this scheduled activity is not included in the model, an anomaly is detected unnecessarily. This can be resolved by continuous involvement in planned operations from the consumer and involving it in the classification process [63], [75].

These categories for anomaly classification should be considered when classifying a water-use inefficiency anomaly identified by the model. Figure 34 illustrates a flow diagram representing the different categories to be considered.

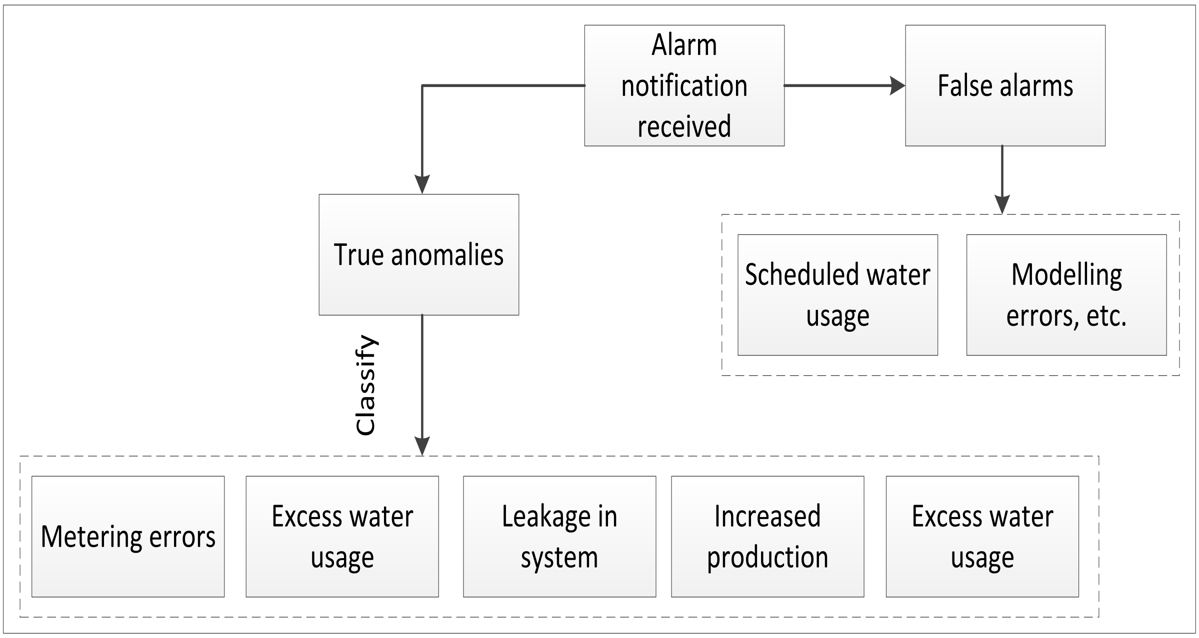


Figure 34: Alarm classification (Adapted from [75]).

After the anomaly has been classified, action can be taken to mitigate the effects of the water-use inefficiency. Table 2 is used to consider other possibilities behind why the water consumption could exceed the defined upper control limit.

Table 2: Anomaly category classification checklist.

Possibilities to consider	Evaluation process	True inefficiency? (Yes/No)
Metering errors	Plot data to exclude unreliable data from the data set and if needed report to instrumentation department for repairs.	
Increased production	Enquire with the mining manager whether more production shifts are planned (for outlier detection adjustment).	
Non-routine activities	Enquire with the mining manager whether shifts were planned during the timeframe the alarms were received.	
Scheduled water usage	Enquire with the mining manager about scheduled water use which is not included in the original planning.	
Excess usage	Could only be determined by conducting a physical audit.	
Leakages	Could only be determined by conducting a physical audit.	
Modelling errors	Repetitive false alarms need remodelling.	

If the Table 2 suggests excess usage or leaks, an underground audit is scheduled for localisation of the water-use inefficiencies. In the section that follows, the localisation method will be briefly discussed with a more detail discussion of the model's implementation.

Localisation

The notification contains the working level and working area to the closest available water flow meters. This information allows the user to plan an underground visit to the closest working area related to the anomaly.

Visual inspection of the water columns have been identified as the simplest method to locate water leaks [54]. The mining industry has various sections that are appointed to responsible personnel. Each person in charge makes sure that their designated section is maintained and that the water distribution columns are in good shape.

The section supervisor may not always consider fixing water leaks to be of the utmost importance. This results in some leaks being unattended for weeks before they are identified and repaired [54]. Inefficiencies that have been identified should be reported to the responsible section supervisors and management for repairs to be arranged.

To simplify the process of managing reported water-use inefficiencies, the following information is required [54]:

1. The shaft name and working level on which it has been identified.
2. The section within the level.
3. The type of inefficiency (damaged valve, leaking gasket, unattended open hose, etc.).
4. Photographic evidence of the inefficiency to serve as motivation for management to arrange for the repairs.

The inefficiency report is then distributed to the responsible person, and a feedback session is recommended to determine if the water-use inefficiency has been attended to. Once confirmation has been received that the inefficiency has been mitigated, the data can be re-evaluated to determine the effect of the repair on the water consumption.

The reduction of water consumption can then be converted to an estimated cost saving to be discussed in Section 2.7.

2.7. Step 5: Integration and verification

System integration

An integrated system between the data-driven model and the implementation thereof allows for the proposed system to function with the desired ease of use. The entire system is displayed in Figure 35 as a flow diagram to show the process for the entire method from the data extraction process in the mine data base to the ESCO-based system with a more user-friendly interface.

For continuous operation, the data extraction process is performed with calculated intervals. The data are then transmitted via email to the external database, usually provided by an

ESCO, as discussed in Section 2.4. By implementing a notification system on the remote site, latency in the data transmitted via email is reduced to ensure that notifications are received as soon as an anomaly is detected [76].

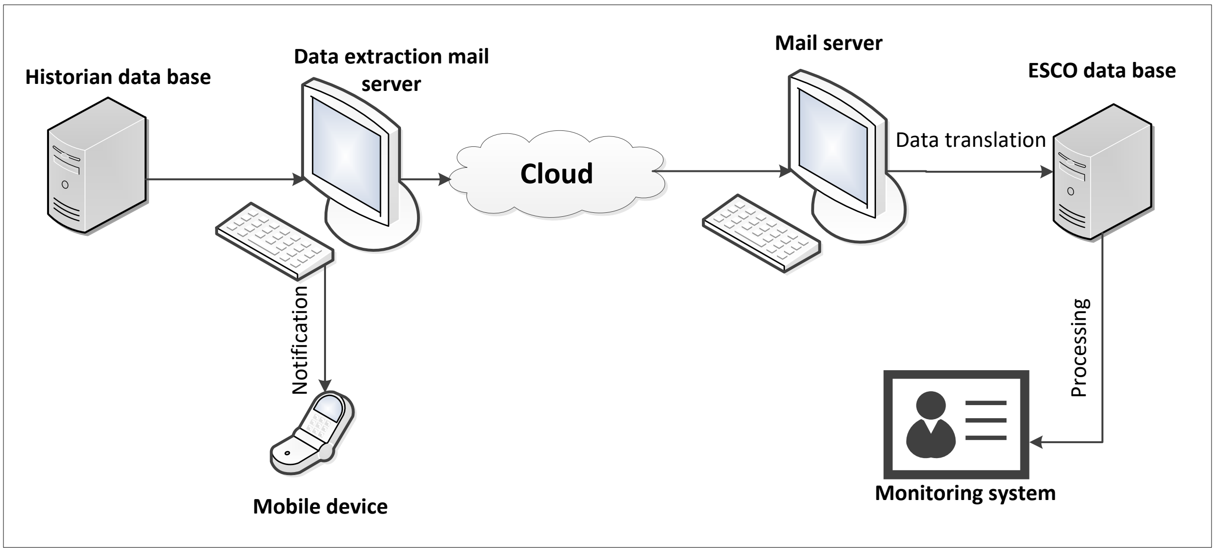


Figure 35: Full system integration schematic.

The limit profiles used for the outlier detection as discussed in Section 2.5 can be adjusted according to the current operations. These limits are stored in the ESCO database to use in the processing of the user-interface output and the notification system as indicated in Figure 35.

Method verification

The verification of the model-based localisation of water-use inefficiencies in deep-level mines is completed by evaluating the design requirements stated in Section 1.4.

- Develop a method to assist the identification and localisation of water-use inefficiencies in the deep-level gold mining environment.
- Validate the accuracy and financial impact of the method for model-based localisation of water-use inefficiencies in deep-level gold mines.

Calculating the model accuracy

The model performance is evaluated according to different strategical proposed key metrics such as the true positive rate (TPR) or identification rate, which measures the precision of the model [63], [84].

$$TPR = \frac{TP}{TP+FP} \qquad (7)$$

where the equation consists of the following definitions and units:

TPR	-	True positive rate
TP	-	Total correctly detected system anomaly events
FP	-	Total number of false system anomaly events

A precision score of at least 70% and above is considered reasonably high when at least 95% of reported events are included in the data set [63], [85].

Calculating the power reduction due to reduced water wastage with energy intensity

The two systems affected by water-use inefficiencies on the water distribution system are mainly the pumping and refrigeration systems. The holistic approach to quantify energy saved due to a reduction of flow is based on energy intensity or specific energy [59], [86], [87]. The following strategy is used to determine the energy intensity of the system:

1. Quantify the total energy consumption of the specific pumping or refrigeration system in kWh.
2. Convert the energy consumption to power using Equation 8.

$$P_{feed} = \frac{Energy\ (kWh)}{24 \times 1000 \times Number\ of\ days\ in\ the\ specific\ month} \qquad (8)$$

3. Calculate the average water flow rate delivered by the specific system for the month.
4. Calculate the energy intensity (EI) for the system using Equation 9:

$$EI = \frac{P_{feed}}{Average\ flow\ rate} = MW_{eq}/L/s \qquad (9)$$

This process can be used to determine reduced power consumption related to the pumping and refrigeration systems from an average reduction in water flow rates.

$$Power\ (MW) = Average\ flow\ rate\ \times EI \tag{10}$$

Calculating the theoretical power reduction due to reduced water wastage

Due to the mine not having power metering on feeders to equipment, Equation 11 can be used to calculate the ideal hydraulic power, based on the necessary head requirement [34], [54].

$$P_{ph} = \frac{Q\rho gh}{3.6 \times 10^6} \tag{11}$$

where the equation consists of the following definitions and units:

$P_{ph}\ (kW)$	-	Hydraulic power
$Q\ \ (m3/h)$	-	Pump volumetric supply flow rate
$\rho\ \ (kg/m^3)$	-	Density of water (assumed constant)
$g\ \ (m/s^3)$	-	Gravitational acceleration constant
$h\ \ (m)$	-	Pump head requirement

Equation 11 is used to determine the ideal hydraulic power needed to cause a volumetric flow rate of the fluid over a particular pressure head. The energy imparted by the pump impeller on the fluid is presented as the calculated hydraulic power. This results in the specific flow rate. In this method, the specific flow rate is represented by the average water reduction achieved from attending to the reported water-use inefficiencies. The calculated hydraulic power thus represents the power no longer required to pump the reduced flow rate in the dewatering system.

The number of pumps and pumping system operating conditions, such as the combination of pumps and the lengths of time each pump is in operation, are not factors in Equation 11. Regardless of operational conditions, Equation 11 accounts for the required power of an entire pump station. This benefits the study as it eliminates the effects of irregular pumping operations such as breakdowns and scheduled maintenance.

After the hydraulic power has been determined, the required electrical power needs to be determined to be able to calculate the energy reduction from water-loss inefficiencies reduction. An efficiency factor is used to determine the electrical power requirement. This calculation is shown in Equation 12 [85], [88].

$$P_P = \frac{Pph}{n_{eff}} \tag{12}$$

The motor energy (P_P) that is required to drive the impeller is represented in Equation 12. Mechanical and electrical motor losses are both accounted for by n_{eff} [89]. This efficiency can be calibrated from available data on the dewatering system to ensure the pumping conditions are accurately reflected.

The energy consumption can be calibrated by using historical data. The energy consumption is calculated using Equation 13 [88].

$$E_p = t_{running} \times P_p = t_{running} \times (P_{ph}/n_{eff}) \tag{13}$$

Where Equation 13 requires the total number of hours ($t_{running}$) that all the dewatering pumps must run in a month. The efficiency factor is calculated to produce a monthly energy consumption equal to that of the dewatering system.

Refrigeration plants have an energy consumption based mainly on the flow rate of the water that must be cooled and the parameters involving the working fluid. Heat transfer takes place when the compressors assist the refrigerant at the required flow rate to cool down the water as it is pumped through the plant, as briefly discussed in Section 1.2.

The energy consumption of the fridge plant is thus determined by the flow rate of the water that needs to be cooled down. If less water is required to be cooled down, the plant requires less energy. Equation 14 is used to determine the energy consumption during operation of the fridge plant [46], [90].

$$P_F = \frac{\dot{m}_w C_{p,w} \Delta T}{COP} \tag{14}$$

where the equation consists of the following definitions and units:

P_F (kW)	-	Power consumption of fridge plant
$\dot{m}_w$ (kg/s)	-	Water mass flow of fluid being cooled
$C_{p,w}$ $(kJ/kg \cdot K)$	-	Specific heat constant of water
ΔT (K)	-	Change in temperature of fluid being cooled
COP	-	Coefficient of performance

Equation 14 is applicable to specific fridge plants. To be able to apply the equation to multiple plants or an entire refrigeration system, the system would need to consist of multiple plants with the same temperature and flow operational properties.

The COP must be determined under normal operational conditions. Where data on the power consumption of the fridge plant is available, this is possible. It ensures accuracy in the calculation of plant efficiency, accounting for unpredictable operational behaviours.

Similarly to Equation 13, the refrigeration power consumption is calculated. Like the pumping system, based on the plant's operating hours, electricity consumption can be calculated. The effect of reduced flow can now be used to determine the reduction in energy consumption.

The reduced power consumption related to the pumping and refrigeration systems can now be calculated from an average reduction in water flow rates. This reduction of energy consumption can be converted to a monetary value, which is discussed in the following section.

Result visualisation and monetary impact

Detected anomalies are represented to visualise the flow increase when it occurs and to illustrate the reduction in flow when the water-use inefficiency has been addressed. Previous literature indicated that the impact of actions should be included to assist with determining the financial benefit and motivate future actions [54], [76].

The personnel directly involved in the corrective actions are often not aware of the results of their actions. Since SCADA shows real-time monitored data, the operators can not create a comparison of what the operations looked like before and after the action has been taken. Therefore, it is recommended to illustrate the data through various graphs to better display the occurrence of the anomaly and the result of addressing it as discussed in Section 2.6.

To illustrate the impact of the detected inefficiencies, the average flow reduction is calculated. This is determined by using the available water flow meters and the average flow rate. Literature emphasises the importance of equivalent data being used when determining the impact of implementation [91].

The period when the anomaly has been detected is used as the baseline and compared with the average water flow rate after the inefficiency has been attended to.

Calculating the monetary cost of energy reductions

Energy costs are determined by Eskom, the national energy supplier of South Africa. Tariffs are charged at time-of-use (TOU) rates, which differ depending on the time of the day. Different tarrifs are used for winter and summer seasons due to increased energy demands during the months of winter (June, July and August).

The time-of-use tariffs are related to the nation-wide electricity demands. Periods of the day with the highest demand rates are known as peak hours, while the low-demand periods are known as off-peak hours. Different time-of-use tariff structures are used for weekdays, Saturdays, and Sundays, respectively. The time-of-use rates for the MEGAFLEX tariff in 2022/2023 are given in Table 3 [22].

Table 3: Time-of-use rates for the MEGAFLEX tariff in 2022/2023 [22].

Demand season	Off-peak [c/kWh]	Standard [c/kWh]	Peak [c/kWh]
Low (summer)	64.14	101.1	146.87
High (winter)	74.09	136.41	450.29

The correct amount of hours in each section of the tariff structure is required to accurately determine the respective energy cost. The running hours of refrigeration plants and dewatering pumps are calibrated with historical operational data during normal operation.

The data includes the running time of the machines during the determined tariff period. Thus, the operating hours of refrigeration plants and dewatering pumps are required for this method of cost calculation.

The average hours of operation per tariff period can now be determined. This only requires the average hours that the refrigeration plants and dewatering pumps are operational daily. The daily average can be used for several months to account for all possible tariff changes.

The power consumption related to pumping and refrigeration are then included to result in a daily cost. The two separate seasonal demand daily costs need to be calculated for high-demand and low-demand season.

Described in Equation 15 is the calculation to determine the daily cost of power according to the above-mentioned tariff structure [22], [88].

$$E_{daily\ cost} = \left[\frac{t_s}{100} \times t_{peak} \times \left(P_p + P_F\right)\right] + \left[\frac{t_s}{100} \times t_{std} \times \left(P_p + P_F\right)\right] + \left[\frac{t_s}{100} \times t_{off} \times \left(P_p + P_F\right)\right] \tag{15}$$

where the equation consists of the following definitions and units:

$E_{daily\ cost}\ (R)$	-	Reduced pumping or refrigeration costs per day during the corresponding demand seasons
$t_s\ (c/kWh)$	-	The tariff based on the time-of-use and demand season
$t_{peak}\ (hrs)$	-	The average time the machine was operational in the peak tariff period
$t_{std}\ (hrs)$	-	The average time the machine was operational in the standard tariff period

t_{off} (hrs) - The average time the machine was operational in the off-peak tariff period

P_P (kWh) - The reduced power consumption due to less pumping

P_F (kWh) - The reduced power consumption due to less chilled water supplied

Equation 16 gives the average cost expected per day, including weekdays, Saturdays and Sundays. Appendix D, Table 17 gives a more detailed view of how the tariff structure changes depending on the type of day.

$$E_{daily\ average} = \frac{(E_{weekday} \times 5) + E_{Satuday} + E_{Sunday}}{7} \quad (16)$$

where the equation consists of the following definitions and units:

$E_{daily\ average}$ (R) - Average reduced pumping or refrigeration costs per day, incorporating weekdays, Saturdays, and Sundays

$E_{weekday}$ (R) - Average reduced pumping or refrigeration costs per weekdays during the corresponding demand seasons

$E_{Satuday}$ (R) - Average reduced pumping or refrigeration costs per Saturday during the corresponding demand seasons

E_{Sunday} (R) - Average reduced pumping or refrigeration costs per Sunday during the corresponding demand seasons

Equation 16 results in the average daily costs and can be used to determine the daily cost savings achieved related to energy consumption. This can be extrapolated to determine the long-term cost saving, excluding public holidays.

Total annual cost savings

To successfully extrapolate the performance of the model, the operational days are required. Operational costs, calculated daily, factor in the hours that each system was operating during the relevant tariffs. The monthly saving is calculated by multiplying the daily performance by the number of days in the relevant month. Equation 16 is used to calculate the annual financial savings [88]:

$$Cost_{annual} = E_{daily\ summer\ cost} \times [(5 \times 31) + (3 \times 30) + 28] + E_{daily\ winter\ cost} \times [(2 \times 31) + 30] \quad (17)$$

$$\therefore Cost_{annual} = E_{daily\ summer\ cost} \times 273 + E_{daily\ winter\ cost} \times 92$$

where the equation consists of the following definitions and units:

$Cost_{annual}$ (R)	-	Reduced pumping or refrigeration costs per annum, during the corresponding demand seasons
$E_{daily\ summer\ cost}$ (R)	-	The average daily cost saving during summer demand season
$E_{daily\ winter\ cost}(R)$	-	The average daily cost saving during winter demand season

The calculated annual cost saving will assist with the reduction of the mine's overall operation cost.

2.8. Conclusion

This section presented the research methodology that was created based on pertinent findings from prior studies. The process starts with the investigation of system requirements, where the research problem is identified. Thereafter, the case study is evaluated to determine whether the required parameters are available to apply the method.

The process for data acquisition is discussed as this is needed for the model to be successful. Data acquisition is followed by the data noise filtering process as high-quality data are needed for the model to be successful.

The method is followed by the development of the data-driven model. This requires a generic model, obtained from previous research and studies relevant to the topic. Derived from previous research is different methods for detecting outliers in the data. Outlier detection is discussed along with an anomaly classification and localisation strategy.

The implementation of the model is discussed, from the notification design, followed by background on the user interface system and the method for locating the water-use inefficiencies. The last step of the method involves the integration of the model with the user-friendly interface and the process for verifying the model by quantifying the energy cost saving due to a reduction in water-use inefficiencies.

Displayed in Figure 36 is an illustration of the research method used to successfully complete this study as adapted from previous research [21], [73].

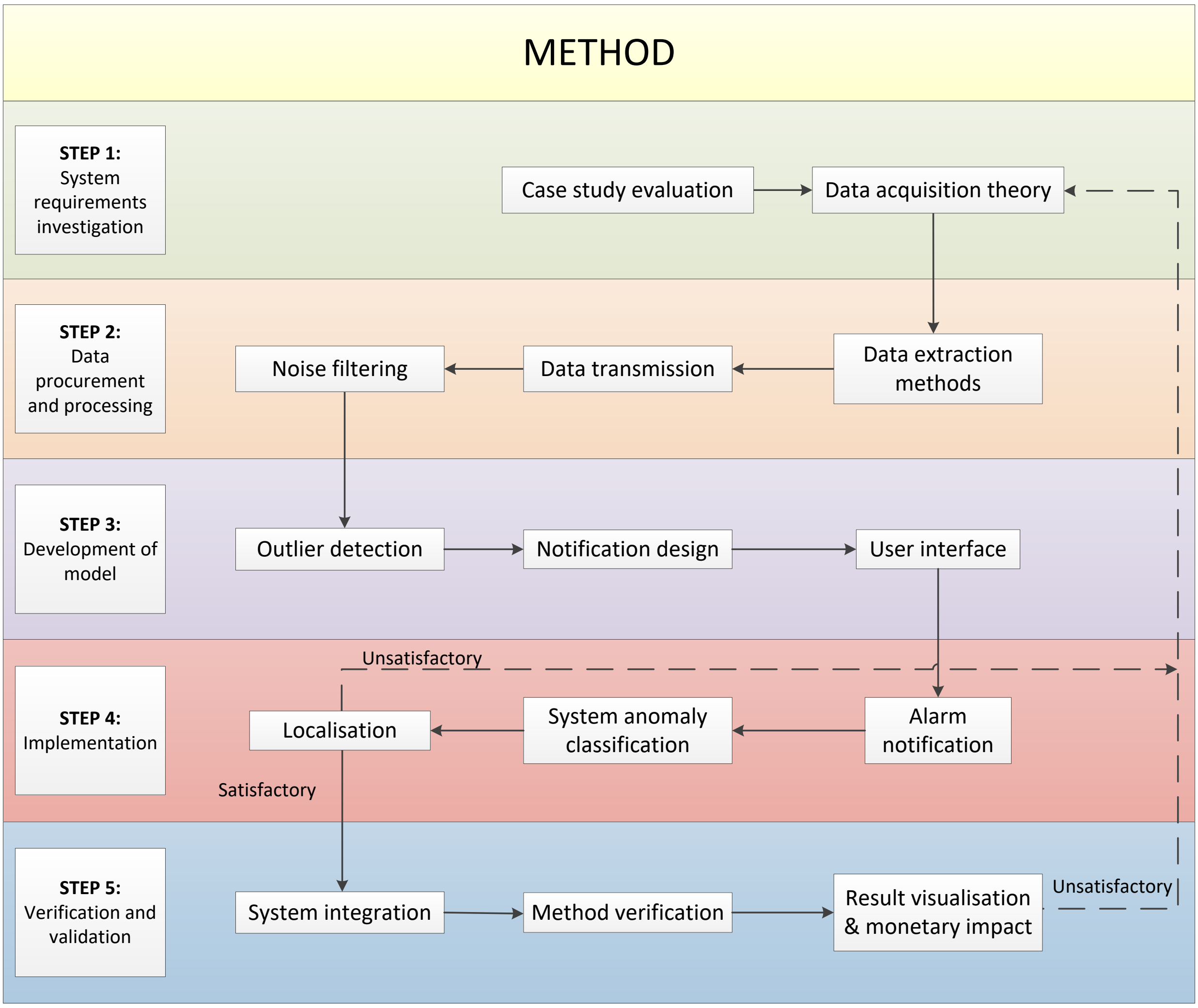


Figure 36: Developed method for a model-based localisation of water-use inefficiencies in deep-level mines.

Chapter 3: Results and Discussion

Figure 37: Chilled water distribution columns[3]

[3] JM van Coller, Personal photograph, Westonaria, 2023

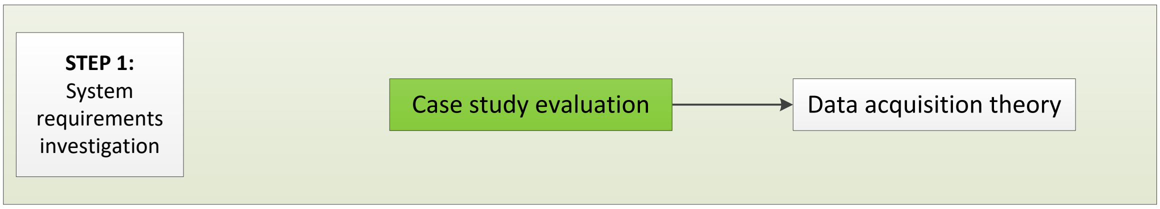
3. METHOD IMPLEMENTATION AND RESULTS

3.1. Preamble

The developed method was applied to a case study mine operating in South Africa. Background is given for the reader to understand the met requirements and why this case study is applicable to validate the developed method. The data procurement process was applied as discussed in the development of the method.

The data-driven model was developed, and the implementation of the model is presented with comparisons made to illustrate the user interface and localisation results. The results obtained during each section are discussed and the method was validated by comparing the achieved results to previous research studies.

3.2. Step 1: System requirements investigation



The flow diagram above will not be referred to, it is purely to give the reader an indication to which step of the developed method is being discussed in line with the obtained results.

The case study was considered in correspondence with the first step discussed in the research methodology. Mine A was identified to apply the developed method described in Chapter 2. The identified case study gold mine is a South African mine, reaching depths of up to 3.7 km below datum on the deepest level.

The water reticulation system found on Mine A is suitable for the developed method as the availability of measurement instrumentation can assist to identify water-use anomalies. These anomalies can be classified as water-use inefficiencies upon the application of the developed model. Figure 38 illustrates the water reticulation system of Mine A and displays the water distribution system as it is used to distribute chilled water for mining purposes.

It uses a complex water reticulation system with refrigeration plants to supply chilled water for mining operations underground. There is a total of fifteen working levels with the inclusion of two half-levels, although, there are only five active mining levels in operation on Mine A.

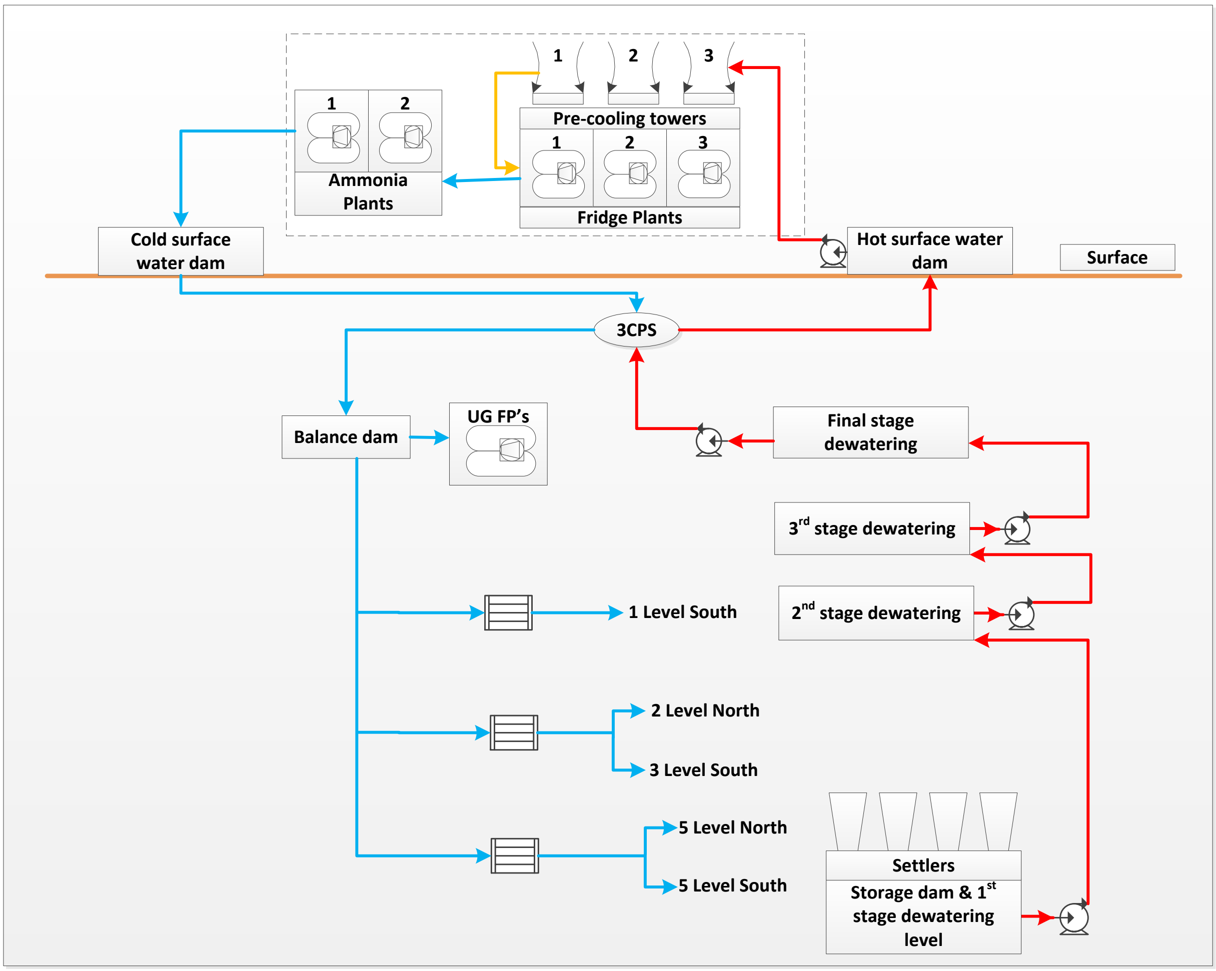
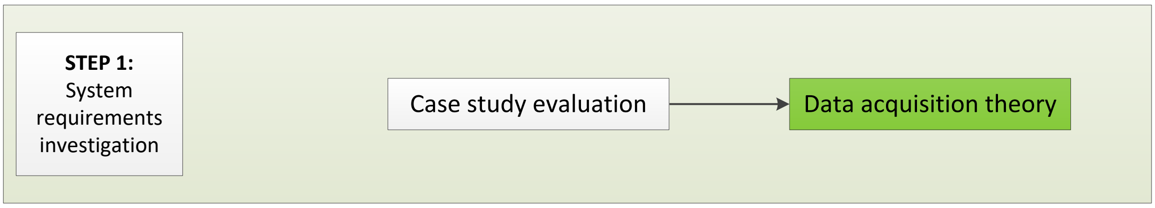


Figure 38: Water reticulation system of Mine A.

For this study, the developed method was implemented on the five active mining levels of Mine A. These levels use a high-pressure water-distribution system to transport chilled water for mining purposes. The water then travels towards drainage holes and is pumped back to the surface by settlers.



Mine A has a SCADA system to monitor water flow rates and pressure profiles of water sent to the five identified working levels underground for mining purposes. The SCADA overview used by Mine A to monitor water flow rates, pressure profiles, dam levels and other critical parameters throughout the water reticulation system is displayed in Figure 39.

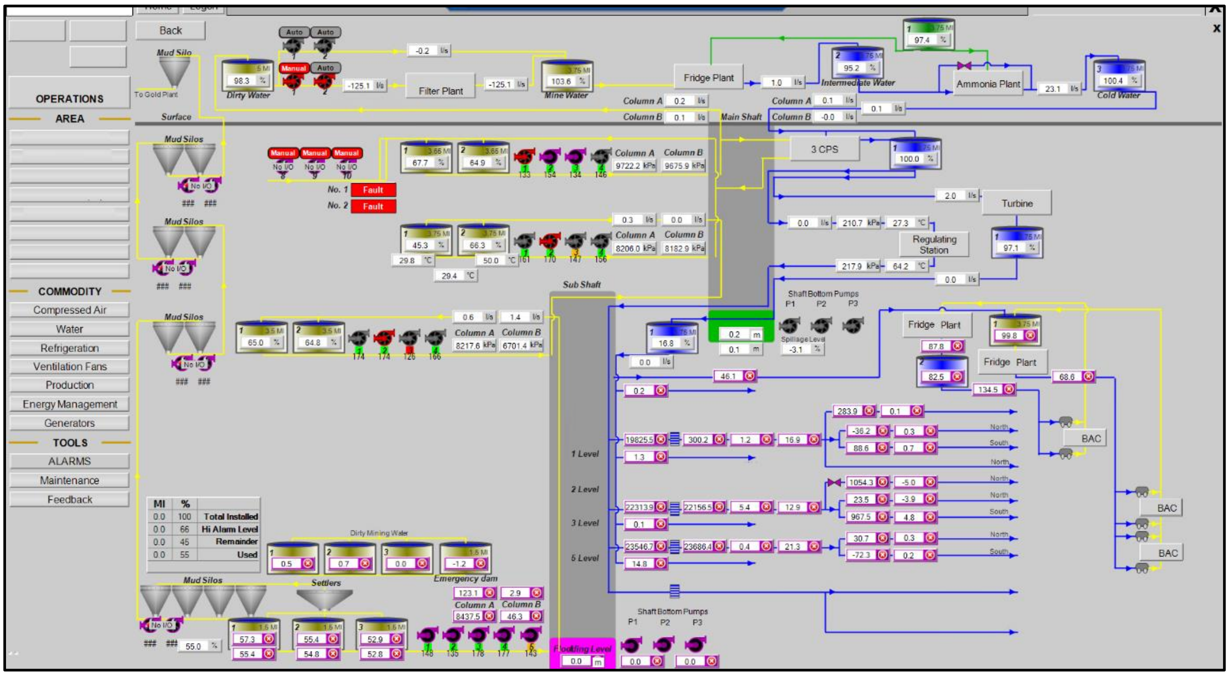


Figure 39: SCADA water overview of Mine A.

As discussed in Section 2.3, real-time monitoring is needed to assist with the identification of the water-use anomalies. Thus, Mine A was suitable to apply the developed method due to the availability of a SCADA system to monitor parameters of the water reticulation system.

The physical location of these water flow meters is required to assist with localisation of identified anomalies. Manual audits were conducted to identify the exact locations of these water flow meters.

Illustrated in Figure 40 is an example of a top-view layout of an underground working level located on Mine A. Water flow meters were found on the working level on the 200NB main supply column at the station and about 1.8 km further at the half-level split.

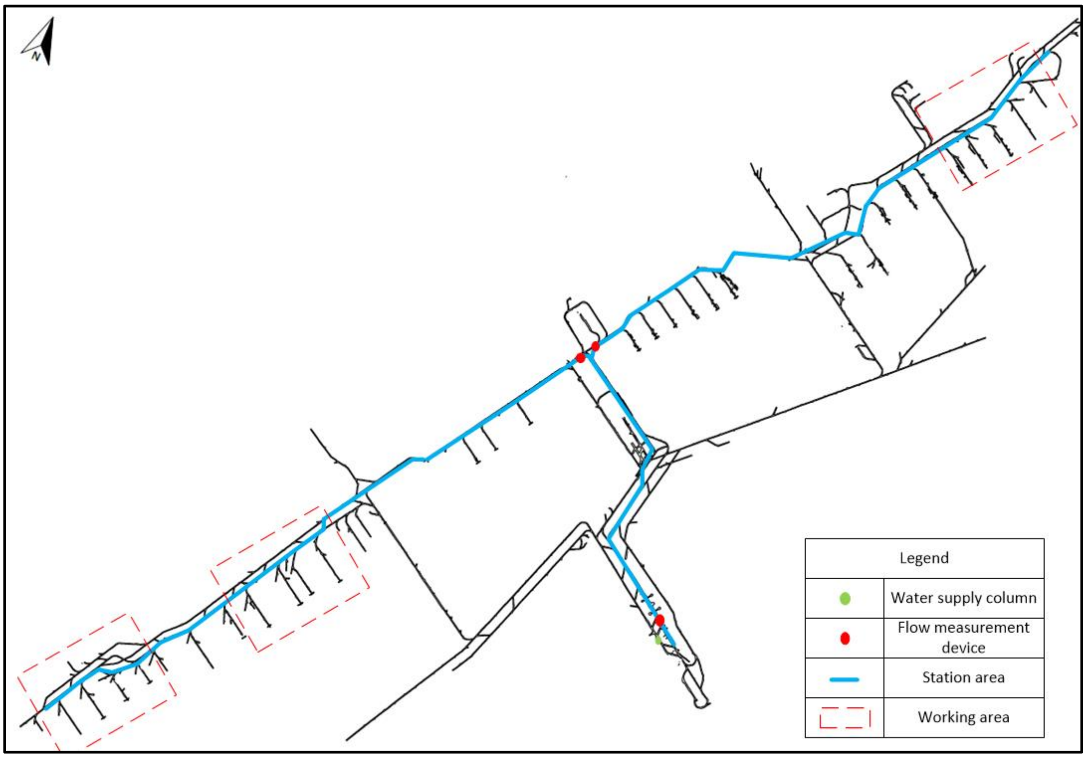


Figure 40: Location of identified instrumentation.

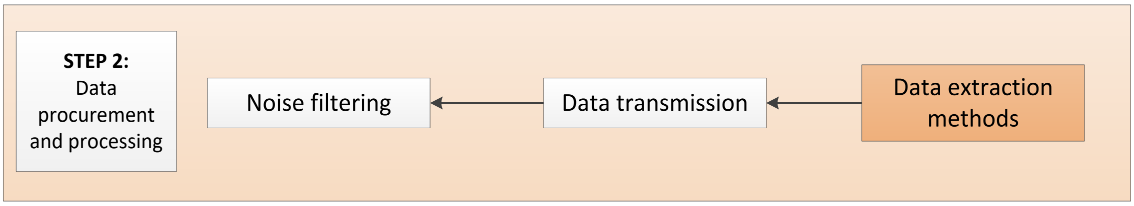
This allows monitoring of water usage found on a specific working level as well as half-level water usage. This is essential for localisation purposes as audits are currently conducted by manual labour in all working areas based on the availability of personnel. The rest of the layouts obtained to implement the study can be found in Appendix A.

The system-requirement investigation concluded that Mine A was suitable for the developed method based on the criteria set in Section 2.3 that has been met:

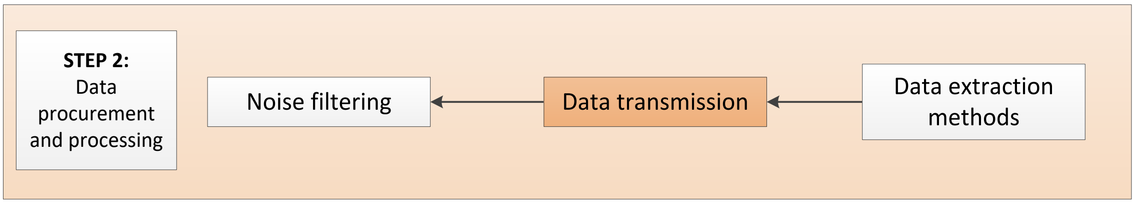
- ✓ Design and configuration of the water reticulation system
- ✓ Available data and instrumentation
- ✓ Location of measurement instrumentation
- ✓ Whether the case study is applicable for the developed method for water-use inefficiency localisation

After the system requirements investigation, Mine A was deemed suitable to apply the developed method from Chapter 2. The following sections provide the results obtained by applying the developed method to Mine A.

3.3. Step 2: Data procurement and processing

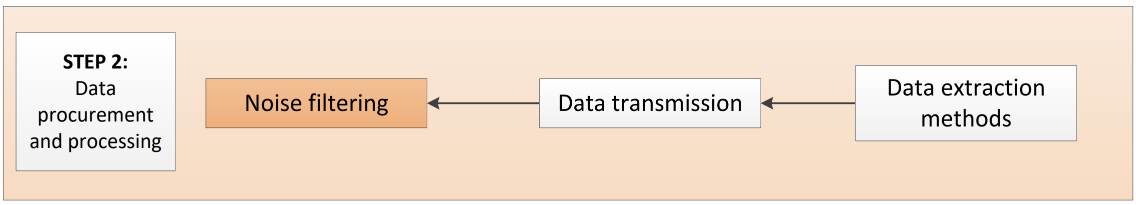


Data extraction methods were set up as discussed in Section 2.4. This allowed historical data to be analysed and used in the development of the data-driven model. Client access was required to access the historian that contains all relevant site data captured through SCADA.



The data transmission was set up by obtaining access to the server of Mine A. Accessibility was obtained by following the site-specific procedure, which involved proper motivation and head of department (HOD) approval.

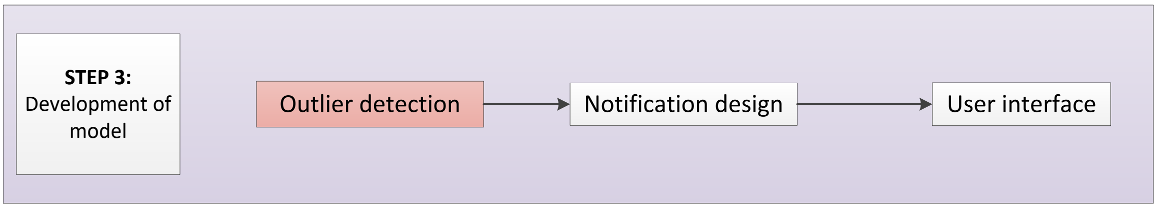
Setting up VPN access was also obtained through the IT-department, which allowed for SCADA access even if the user was not connected to the internet connection provided by the mine. For half-hourly extraction, the measured data from Mine A was extracted from the client historian and transmitted to the ESCO database for further analysis.



The data noise filtering process was used to eliminate uncertainties in the obtained datasets, an example is available in Appendix C. Gathered data was plotted to implement the data quality and the data validation method as provided in Section 2.4 was implemented. This allowed reliable data to be available on the ESCO database to be used for development of the model. This data could later be used for data visualisation and accessed when an anomaly occurred.

3.4. Step 3: Development of data-driven model

To determine the upper control limit, historical data dating back to January 2021 was initially considered. It was found to be more advantageous to only take data from the previous month into account because of the unpredictable nature of mining operations. This allowed for control limits based on the current operations.

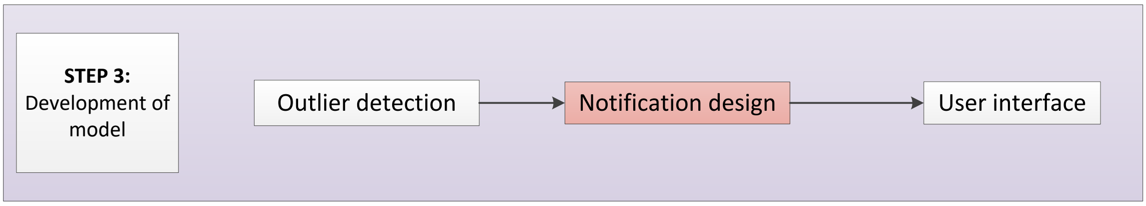


The daily average water consumption for the previous month was considered to set up an upper control limit based on the average consumption over a 24-hour period. Using Equation 2, Section 2.5, the following upper control limits (UCLs) were obtained for the active mining levels on Mine A. The active mine levels known as 1 Level South, 2 Level North, 3 Level South, 5 Level North and 5 Level South were considered. The results for a sample size of 30 days are presented in Table 4. The data used to calculate these limits can be found in Appendix C.

Table 4: Upper control limit for outlier detection.

Variable (L/s)	**1 Level South**	**2 Level North**	**3 Level South**	**5 Level North**	**5 Level South**
$\bar{x}$	19	11	36	29	37
σ	4	3	9	9	11
UCL	22	12	41	34	43

The data from 3 Level South on Mine A resulted in an upper control limit of 41 L/s. Thus, the outlier detection model should trigger an alarm whenever the average water consumption over the 24-hour period exceeds 41 L/s.



The notification design process was followed as discussed in Section 2.5. The critical information needed to determine the location and priority of the anomaly was provided in the notification. The notifications were distributed through the ESCO database to a mobile device that had been granted access. Figure 41 illustrates the received notifications for Mine A over a set period.

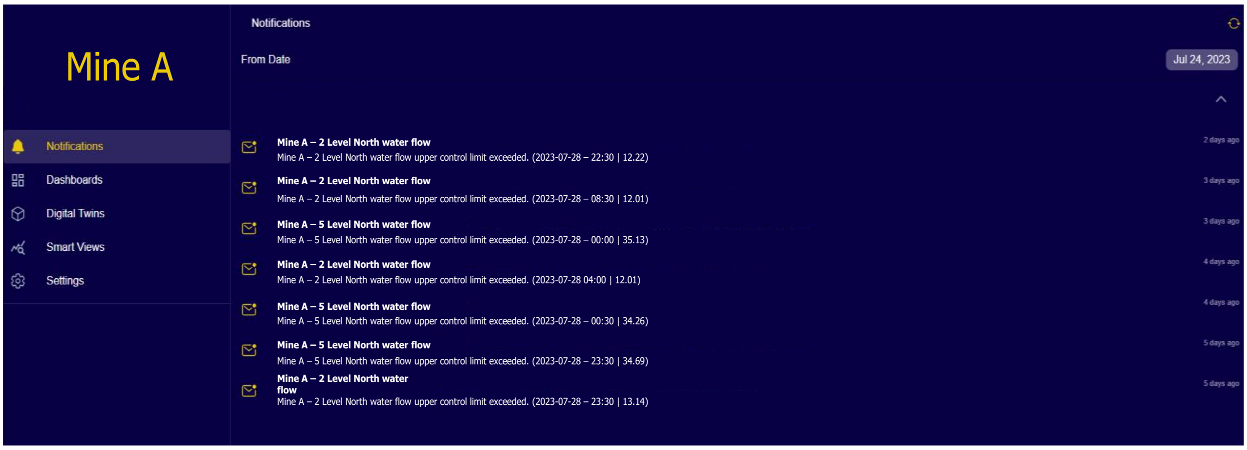
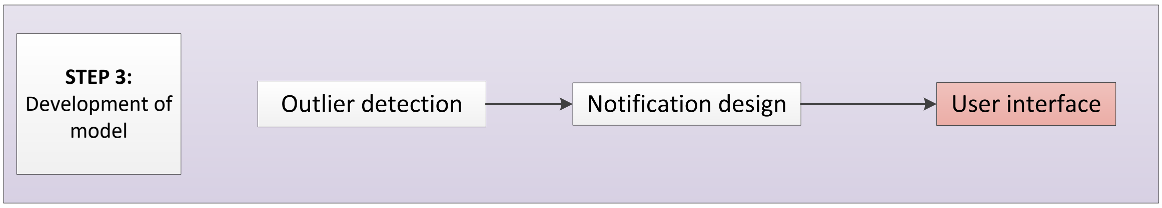


Figure 41: Alarm notifications for Mine A

After the notification was received, the user could analyse the captured data through the user-friendly user interface to visually determine the timeframe in which the water flow exceeded the upper control limit.



To mitigate the possibility of overloading the user with information, the simplified overview of water consumption per flow meter was used. This allowed the user to analyse the water consumption over the 24-hour interval after an outlier had been detected.

Displayed in Figure 42 is the flow profile for 3 Level South in hourly intervals. This interface displays the average flow rate captured as 49.58 L/s. This overview was used to determine whether the flow increase occurred during a specific working shift.

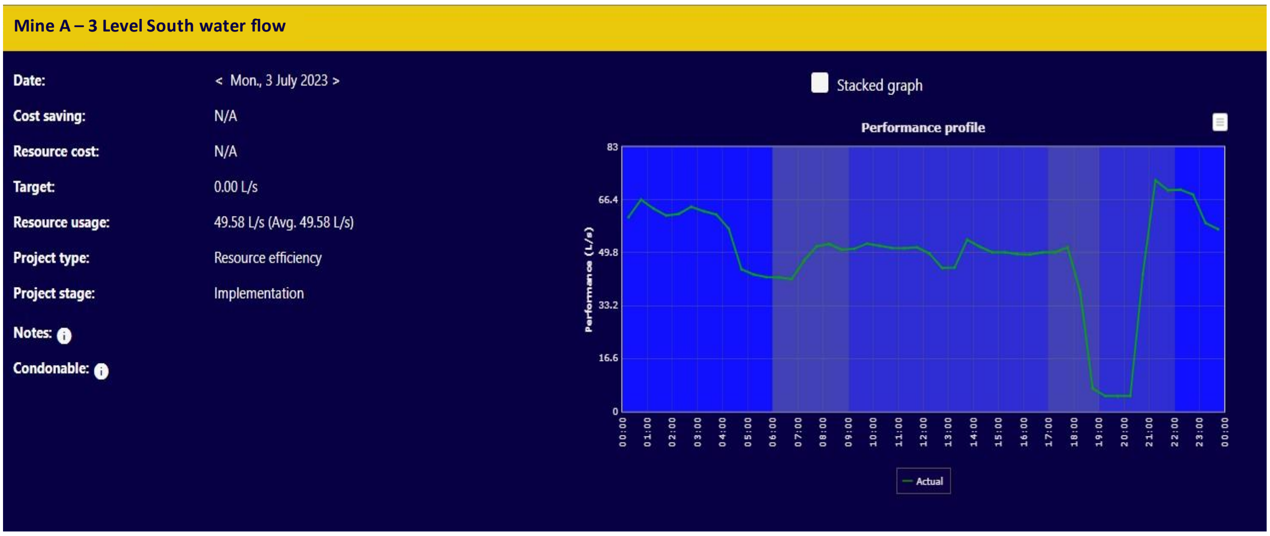


Figure 42: 3 Level South hourly water flow profile.

A notification was received when the water consumption for the day had exceeded the upper control limit considered over a 24-hour period. The 24-hour average water flow rate was used to assist with the unpredictability of mining demand and to reduce the possibility of false alarms.

This user interface assists to evaluate the significance of the anomaly and influences the action to be taken as discussed in Section 2.5. The daily impact can be seen in Figure 43.

It can be seen how the daily average water flow rate increased when an anomaly occurred and returned to below the upper control limit when it had been attended to.

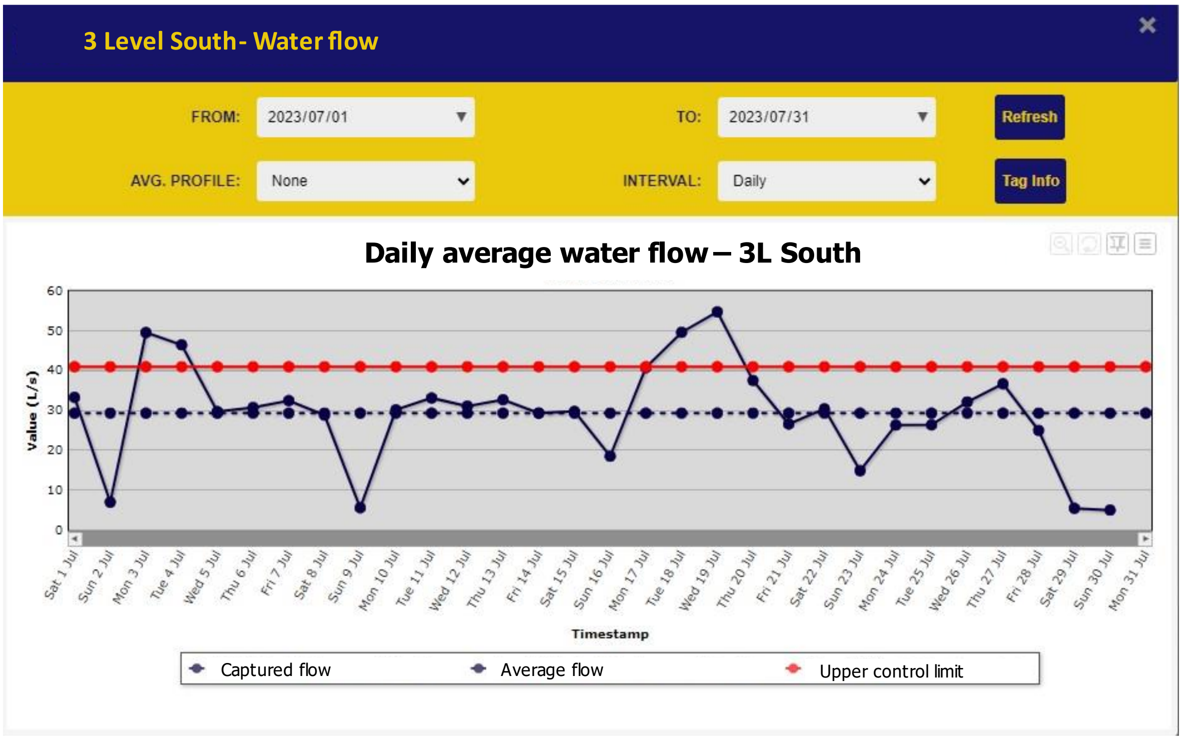


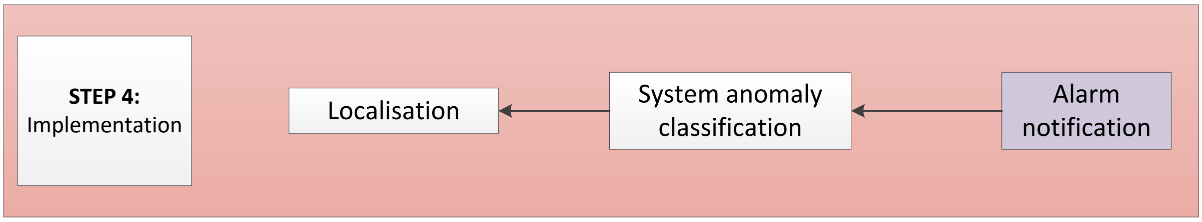
Figure 43: 3 Level South daily water flow profile.

The anomaly displayed in Figure 43 exceeded the upper control limit on the 3rd of July and was located the following day as a leak and fixed after it was reported. As can be seen from the trend, the average water flow rate decreased after the anomalies were located and action was taken. A separate occurrence was captured over the period of the 18th to the 19th of July. The following section discusses the location and magnitude of a single occurrence.

3.5. Step 4: Implementation

The implementation step integrated the developed model with the data procurement and processing steps to assist with locating water-use inefficiencies. The upper control limits calculated in Section 3.4 were applied to alarm the user when the limit was breached. A single occurrence is discussed, followed by the summary of all detected anomalies and their outcomes.

The single occurrence mentioned previously on the 3rd of July, was of an anomaly that triggered an alarm due to the captured flow rate being higher than the upper control limit determined in Table 4.



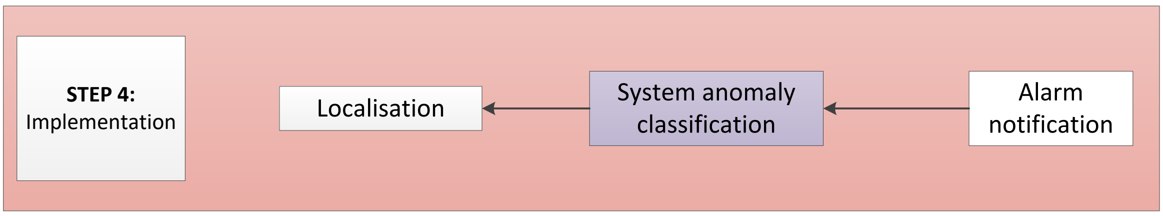
The flow meter located near the working area referred to as 3 Level South, triggered the alarm with high flow rates. Figure 44 illustrates the received notification due to the flow exceeding the upper control limit.

Figure 44: Notification as received from breach upper control limit.

Valuable information given from the notification were as discussed in Section 2.6:

1. Working level: 3 Level
2. Working areas: 3 Level South.
3. The average flow rate that exceeded the upper control limit: 42.11 L/s
4. Time the limit was breached: 16:30

From the given information, it was now known when and closest to which flow meter the anomaly occurred. The notification described the captured flow rate at 41.11 L/s, which exceeded the set upper control limit.



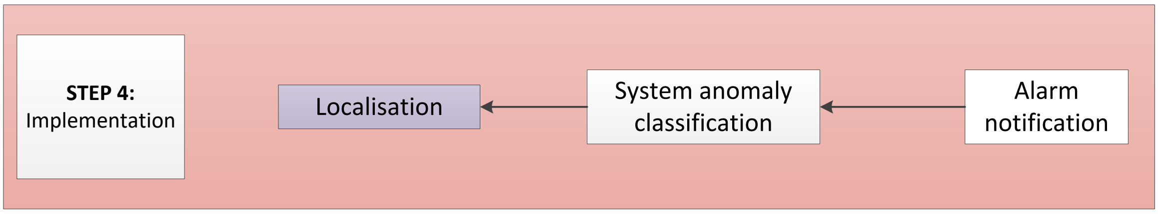
The classification process was followed to determine the possible reason why the water-usage exceeded the upper control limit. Table 5 was used to determine possible reasons for the increased consumption. The classification process used the data's visual representation to help with decision-making. The graph displayed in Figure 42 displays hourly datapoints that can be associated with scheduled shifts and communication with the mine to determine whether the water usage corresponds with their demands.

The anomaly classification process used is displayed in Figure 34. This ensured that all possible reasons for an increase in water consumption was considered before classifying the anomaly as a water-use inefficiency. During the implementation phase, the upper control limit and the classification method were applied. The following results were obtained.

Table 5: Completed anomaly category classification checklist.

Possibilities to consider	**Evaluation process**	**True inefficiency? (Yes/No)**
Metering errors	Plot data to exclude unreliable data from the data set and if needed report to instrumentation department for repairs.	No
Increased production	Enquire with the mining manager for outlier detection adjustment whether more production shifts were planned.	No
Non-routine activities	Enquire with the mining manager whether shifts were planned during the timeframe the alarms were received.	No
Scheduled water usage	Enquire with the mining manager about scheduled water use which was not included in the original planning.	No
Excess usage	Could only be determined by conducting a physical audit.	No
Leakages	Could only be determined by conducting a physical audit.	Possible yes
Modelling errors	Repetitive false alarms need remodelling.	No

From Table 5 it can be seen that there were no additional water consumers planned. The anomaly could now be classified as a water-use inefficiency and the localisation method was implemented as the next step.



Localisation requires the physical inspection of the water distribution column. However, the process has been simplified by utilising the available water flow meter to narrow down the possible inefficiency to a certain area.

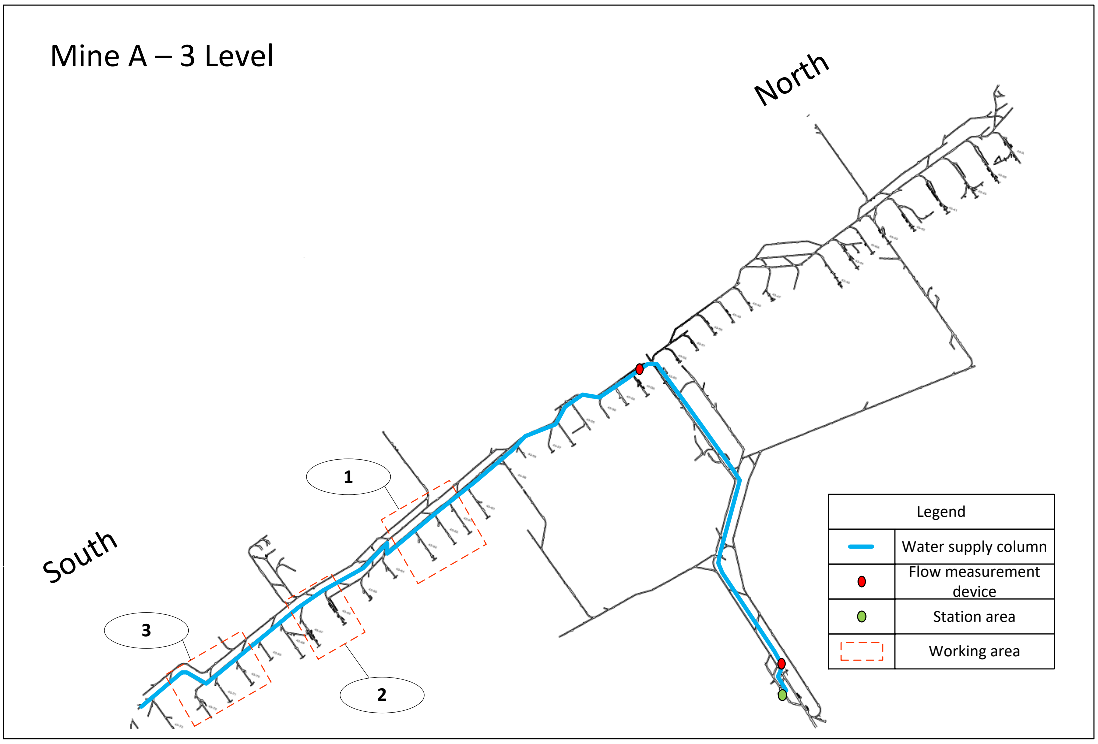


Figure 45: Top-view of underground working areas with possible water-use inefficiency.

The localisation method discussed in Step 4 of the developed method was implemented and a physical audit was conducted. The audit resulted in locating a leaking pipe connection at Working area 3, indicated on Figure 45. Other examples of top-view layouts relevant to the case study mine can be found in Appendix A.

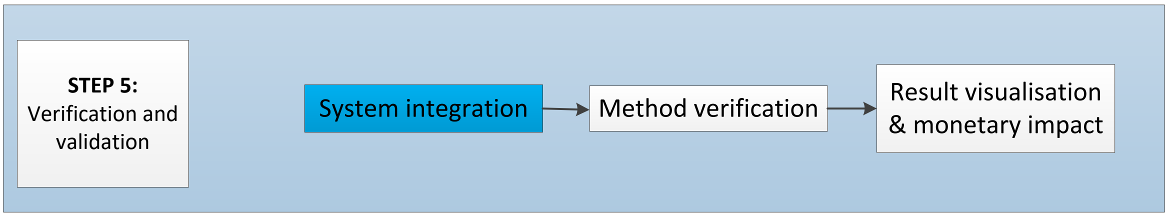
Displayed in Figure 46 is a photograph of the leaking pipe connection that was located using the developed method from Chapter 2. The leak was reported to the responsible personnel and arrangements were made for repairs. Examples of other water-use inefficiencies are available in Appendix B.

Figure 46: Identified water-use inefficiency.

The photograph displayed in Figure 46 captures the severity of pipe leaks in the underground deep-level mining environment, with the internal working pressure of this column at 19 MPa. The visualisation of taking action and repairing the leak is discussed in the next section.

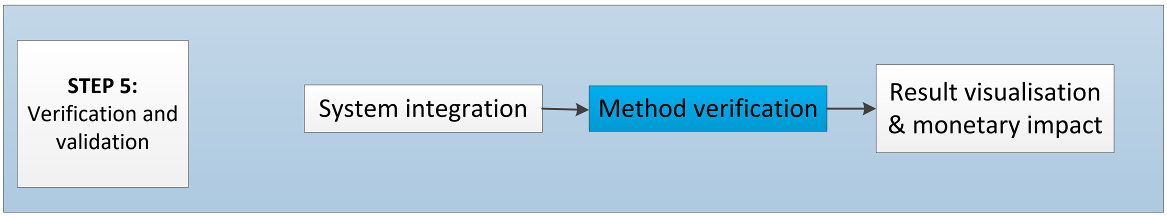
3.6. Step 5: Integration and verification

The impact of the model can only be determined by integrating the developed model with the imbedded user interface for application as a combined system.



Thus, the system integration process involved proving to the mine that this model is beneficial for implementation and reflecting on the importance of maintenance and repairs on the water distribution system. This persuation took multiple meetings and trial periods where the entire system was demonstrated to the repsonsible foreman.

Method verification was used to determine whether the developed method met the requirements set by the research aim and objectives.



The impact of the anomaly was reflected in the captured data. Verifying water flow reduction after repairs were made is important for the calculation of cost savings and to support the model's performance.

Table 6 displays the classification of all anomalies that were identified using the method developed in Chapter 2. Majority of the anomaly classificaiton was personally determined by the author, with help from mining personnel when visiting specific areas was not possible. The possibilities considered were based on the classification process described to determine whether the occurred event was due to regular mining activities that would not normally have been scheduled, non-routine activities or possibile water-use inefficiencies.

Table 6: Anomaly classification precision summary.

Possibilities considered	1 Level South	2 Level North	3 Level South	5 Level North	5 Level South	Total
Metering errors	0	1	0	0	0	1
Increased production	1	0	0	0	0	1
Non-routine activities	0	13	1	2	0	16
Scheduled water usage	1	0	0	0	0	1
Excess usage	0	0	1	3	0	4
Leakages	10	0	8	5	18	41
Modelling errors	0	0	0	0	0	0
Total true alarms	11	12	10	12	18	63
Total false alarms	3	1	0	1	0	5

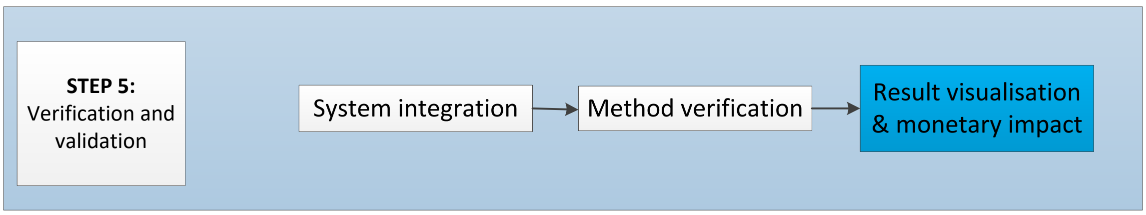
From Table 6 it can be seen that there were a total of 63 correctly detected anomaly events and 5 false system anomaly events. Using Equation 7 to determine the model's precision, the following results were attained:

$$TPR = \frac{TP}{TP + FP}$$

$$TPR = \frac{63}{63 + 5}$$

$$TPR = 0.93$$

The model was capable of accurately identifying anomalous behavior in the water distribution system. A high precision score of 93% was obtained, while ensuring at least 95% of detected events were included in the data set as correctly detected.



The result visualisation of the single event discussed in Section 3.5 can be seen in Figure 47, where the water flow rate increased after the leaking pipe was repaired. The localisation audit was initiated by the received notification and the leak was identified.

Thereafter, the inefficiency was reported and repaired in the next possible shift. The impact of this leak over a 24-hour average was measured at 15 L/s. This is equivalent to 1.3 ML of water over a 24-hour period.

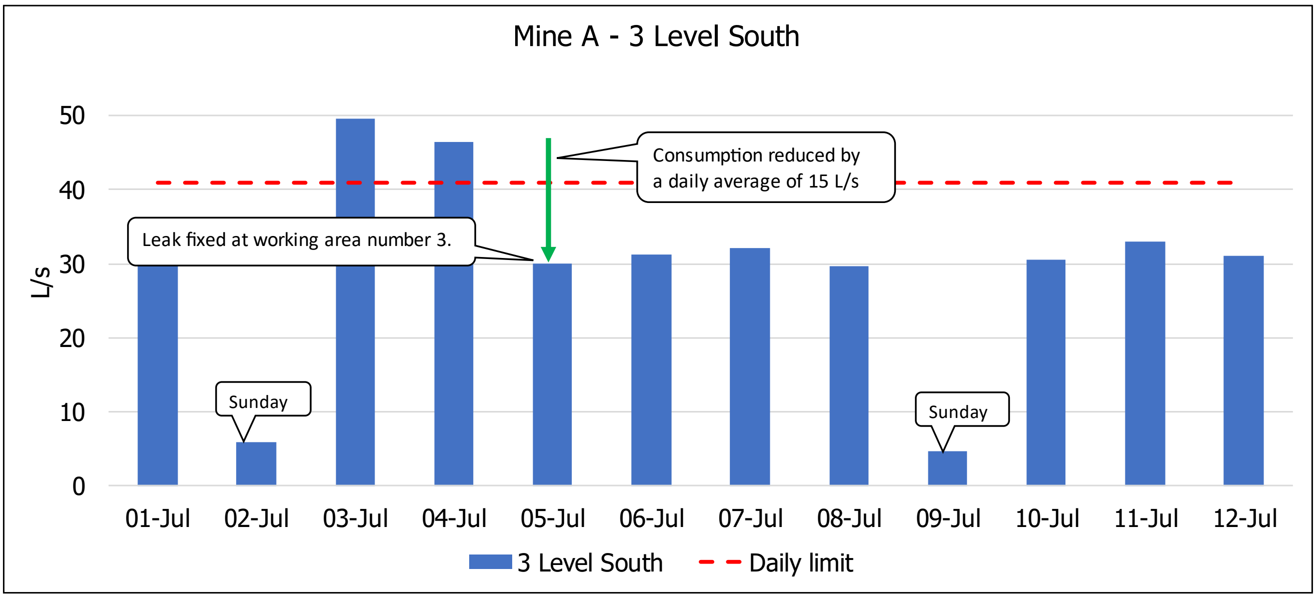


Figure 47: Result visualisation of reported water-use inefficiency.

To determine the monetary impact of the single occurrence discussed in the previous sections, Equations 8 – 10 were used as recommended in Section 2.7 to determine the power requirement, and Equations 15 & 16 were used to calculate the cost equivalent.

The power required to process the flow reduction through the refrigeration cycle for mining purposes and pump out to complete the water reticulation cycle is calculated in Table 7. The available pumping power data for Mine A during May 2023 was used.

Table 7: Pumping and refrigeration power usage on Mine A.

System	Energy (MWh)	P_{feed} (MW)
Pumping	6 310	8.5
Refrigeration	7 545	10.1

The energy intensity could be calculated using Equation 9. The respective energy intensities for the pumping and refrigeration systems were calculated using the average delivery flow rate for May 2022 and are displayed in Table 8.

Table 8: Energy intensity calculation.

System	P_{feed} (MW)	Average water flow rate (L/s)	Energy intensity $(\mathbf{MW/L}/s)$
Pumping	8.5	259	0.033
Refrigeration	10.1	233	0.043

The power reduction on the pumping and refrigeration systems can be seen in Table 9. This power reduction was calculated using the water flow reduction of 15 L/s displayed in Figure 47 and calculated using Equation 10.

Table 9: Power reduction due to reduced water flow rate.

System	Energy intensity (MW/L/s)	Power reduction (MW)
Pumping	0.033	0.5
Refrigeration	0.043	0.7
Total	0.076	1.1

The monetary impact of the event described in Section 3.5 was determined by assuming the inefficiency would not have been detected for an additional 7 days. This assumption was made based on the availability of personnel and the fact that Mine A excecutes routine leak audits on a weekly basis, dependent on the breakdown schedule.

The average monetary impact of the power reduction due to the localisation of the 15 L/s leak discussed in Section 3.5 was then calculated using Equations 15 & 16. The daily cost reduction displayed in Table 10 was calculated using the winter tariff as the leaks were identified during July.

Table 10: Cost savings due to reduced water flow rate.

System	Energy $(\mathbf{M}Wh)$	Daily cost reduction (ZAR)
Pumping	82	20 000
Refrigeration	110	27 000
Total	192	47 000

To determine the monetary impact of the developed method, the inefficiencies displayed in Table 6 were used to determine the average flow increase per detected anomaly.

The average flow increase was then used to determine the average power increase as a result of an exceeded upper control limit and converted to an average cost saving per anomaly.

Table 11 summarises the average daily cost benefit of the developed method. The calculations used to determine the annual cost benefit are available in Appendix D.

Table 11: Average cost benefit of developed method.

Parameter	Value	Unit
True alarms	63	-
Average flow increases per alarm	11	L/s
Power increase per alarm	0.81	MW
Daily cost per alarm (Winter)	R33k	ZAR
Daily cost per alarm (Summer)	R21k	ZAR

Based on the cost saving calculated in Table 11, the average daily cost saving was calculated at approximately R27 000 per detected anomaly. When extrapolated, the full implementation of this model has a potential cost benefit of around R8.6 million per annum.

3.7. Summary

During the implementation period on Mine A, the developed model identified 63 anomalies. The average reduction in pumping and refrigeration costs can be determined based on the assuption that the chilled water would leak out on to the footwall before it can be used for mining. This water would flow into the storage dams where it is filtered and pumped out to be cooled, ready to be used for mining.

An average power reduction of 808 kW was determined based on the average flow increase experienced per located water-use inefficiency of 11 L/s. Thus, the implementation of the developed method resulted in the localisation of water-use inefficiencies in the deep-level mining industry.

The increase experienced per water-use inefficiency could be mitigated by locating the anomaly and arrange for repairs. The continuous implementation of the model can lead to a potential cost saving of R8.6 million per annum, should the average water flow increase per alarm be maintaned.

The developed method, as discussed in Chapter 2, consists of 5 steps. These steps contributed to the research study by addressing the set objectives of Section 1.4. These objectives were addressed by the various steps. Table 12 illustrates which step contributed to achieving the specific objective. The descriptions of the objectives are given in the list below:

- **Objective 1**: Develop a method to assist the identification and localisation of water-use inefficiencies in the deep-level gold mines.
- **Objective 2**: Validate the accuracy and financial impact of the method for model-based localisation of water-use inefficiencies in deep-level gold mines.

Table 12: Validation of developed method.

Steps		**1**	**2**	**3**	**4**	**5**
Objectives	**1**	X	X	X	X	X
	2				X	X

Table 12 indicates that all set objectives were met through the developed method. The model was validated by addressing all set objectives. The validation parameters were in line with the results of previous studies mentioned and measurables from literature.

The following chapter provides a critique of the study, as well as its flaws, and suggestions for future research are given.

Chapter 4: Conclusion

Figure 48: Underground pump chamber[4]

[4] Photo by "Resource Erectors". [Accessed: 28-Feb-2022]. [Online]. Available: https://resource-erectors.com/career-blog/pumping-underground-mining-will-always-be-a-challenge/.

4. CONCLUSION

4.1. Preamble

This chapter gives an overview of the study's background and problem statement. The solution that was derived and the obtained results from implementation of the developed method are discussed. The set objectives are discussed, accompanied by the results and successes in addressing the objectives.

The shortcomings, where the study revealed areas that can be improved, are presented. Future research recommendations that might be pertinent to this study are discussed.

4.2. Summary

Water-use inefficiencies are prone to occur in the harsh deep-level mining environment. The distribution of chilled water is important for mining operations to reach targets and mine effectively.

The study focused on the localisation of water-use inefficiencies to reduce wastage on the water reticulation system without the need for capital expenditure or additional work on the existing infrastructure.

Using historical data to calculate upper control limits for the respective water flow meters, anomalies were identified, and the developed method was applied to classify and locate these occurrences. A total of 63 true anomalies were detected by implementation of the developed method on Mine A.

An estimated cost benefit of R27 000 per anomaly can be achieved when the model identifies an anomaly classified as a water-use inefficiency. The average flow reduction of 11 L/s when a water-inefficiency is identified and repaired is equivalent to a cost saving of around R8.6 million when extrapolated over a 12-month period. The developed method assists management to act when a notification is received, reducing the need for routine leak audits that occasionally have no benefit or positive outcome.

4.3. Study overview

Continuous increase of operational costs in deep-level gold mining industries, combined with declining production trends, are leading to profitability challenges. Literature identified that typical deep-level mines use a water reticulation system that combines refrigeration, pumping and water distribution. Based on additional research, the refrigeration and pumping systems can account for up to 28% of the total energy used in a deep-level mine.

Research of previous studies identified that energy efficiency can contribute to the overall reduction of operating cost and possibly lead to improved profits. This has potential to extend the lifespan of mining operations.

Focused on refrigeration, pumping and the water distribution system, a critical evaluation of literature was conducted. Literature revealed numerous studies on improvement of the water reticulation system. Most studies required capital expenditure or had not been fully implemented in the deep-level mining environment.

The literature review indicated that a need exists to develop a model to assist with the localisation of water-use inefficiencies in deep-level mines based on existing infrastructure.

The following objectives were derived after identifying the need for the study:

1. Develop a method to assist the identification and localisation of water-use inefficiencies in the deep-level gold mines.
2. Validate the accuracy and financial impact of the method for model-based localisation of water-use inefficiencies in deep-level gold mines.

The case study methodology was identified from previous literature for developing a model to be applied in a case study in the industry. A method was developed to identify anomalies with flow-meters, classify the type of anomaly, and follow the procedure to locate these anomalies. The guidelines and procedures to effectively locate water inefficiencies were incorporated in the developed method.

Mine A was evaluated according to the developed method and deemed applicable. The implementation of the developed method led to the detection of 63 anomalies. These anomalies were put through the classification process with a total of five unclassified anomalies or false alarms. The model had a precision rate of 93% and the anomalies where action was taken had an average flow reduction of approximately 11 L/s.

This flow reduction could be maintained through the continuous implementation of the model and the available personnel at the case study mine could be utilised when a notification was received. The average flow reduction of 11 L/s when extrapolated over a 12-month period has a potential cost benefit of around R8.6 million per annum.

The study was measured through the ability to achieve set objectives and these objectives were addressed throughout the various steps of the developed method and summarised in Table 12.

4.4. Shortcomings and recommendations

Observations made from the conducted study are intended to provide practical guidance for researchers considering a similar study. After concluding this study, it is recommended to take the following points into consideration for future research:

- Only one case study mine was used to test the developed method. More case studies that are suitable for the method can be used to improve the model's precision.
- The model identified anomalies based on the water flow rate that exceeded the upper control limit. The delayed response time to attend to these increases led to multiple notifications being received for a single anomaly.
- The average flow rate reduction of 11 L/s was determined over a two-month period, where the water-use inefficiency could be resolved. This could be improved by implementation over a longer test period.
- The study identified multiple occurrences of non-routine activities. However, these occurrences could not be responded to due to the daily aggregation used in the model.
- The availability of water flow meters limited the localisation process. The notification could only identify the working level and the working areas within a section.

- The study was highly dependent on an external data base such as an ESCO data base to analyse historical data and set up an anomaly detection model. It is recommended that built in SCADA alarms be investigated. This will allow for faster response time and eliminate the need for an external data base.
- Investigate methods to lower the overall water usage by improving the baseline used to determine the upper control limit. This will ensure that continuous wastage of water is not included in the daily average captured to calculate the upper control limit.

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APPENDICES

Appendix A: Mine A top-view layouts

The top-view layout for the various working levels is presented in Appendix A. Captured anomalies that were classified as water-use inefficiencies with corrective actions taken are numbered on these layouts. This will help the reader understand how far apart certain events were from one another. Presented in Figure 49 is the top-view layout of 1 Level. The chilled water distribution is illustrated by the blue line on the schematic. As can be seen, there is only one working area to the south side of the working level.

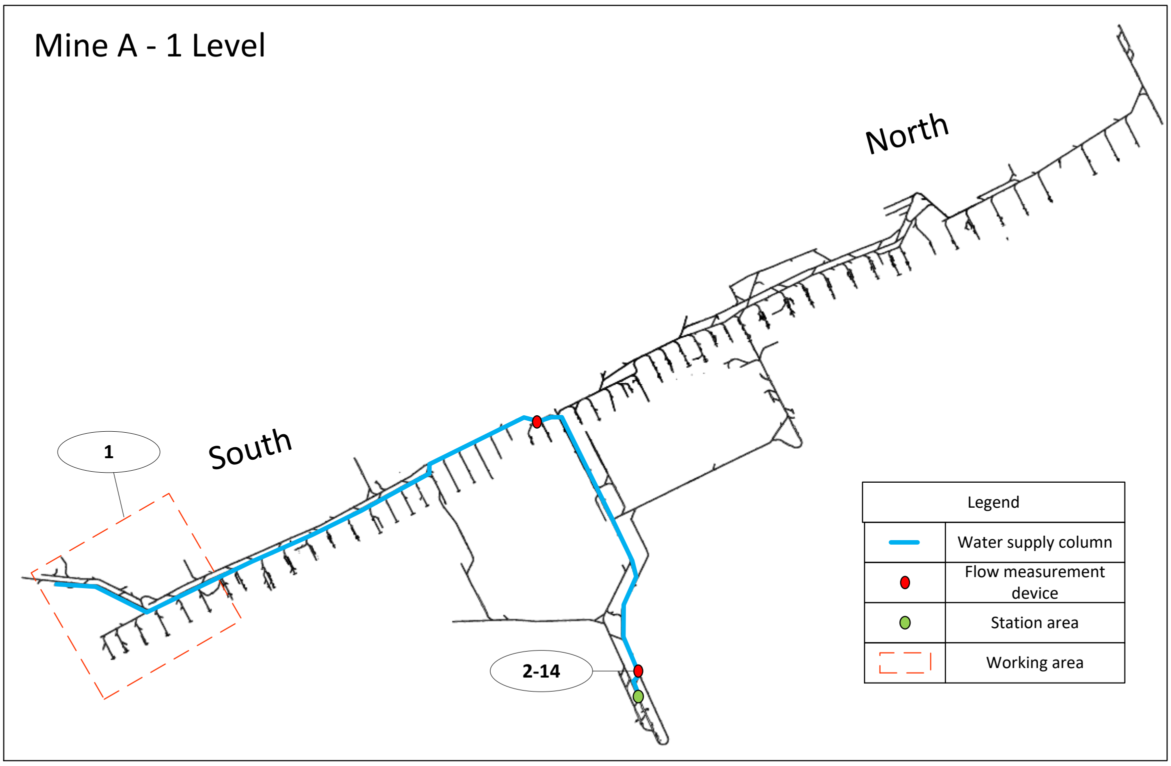

Figure 49: Top-view of 1 Level.

The top-view layout of 3 Level is illustrated in Figure 50. The blue line on the schematic indicates the chilled water distribution column and the red dot represents the water flow meter. As can be seen, there are three working areas to the south side of the working level.

The numbers on the schematic represent the distribution of occurrences categorised as water flow anomalies that were identified and where corrective action was taken.

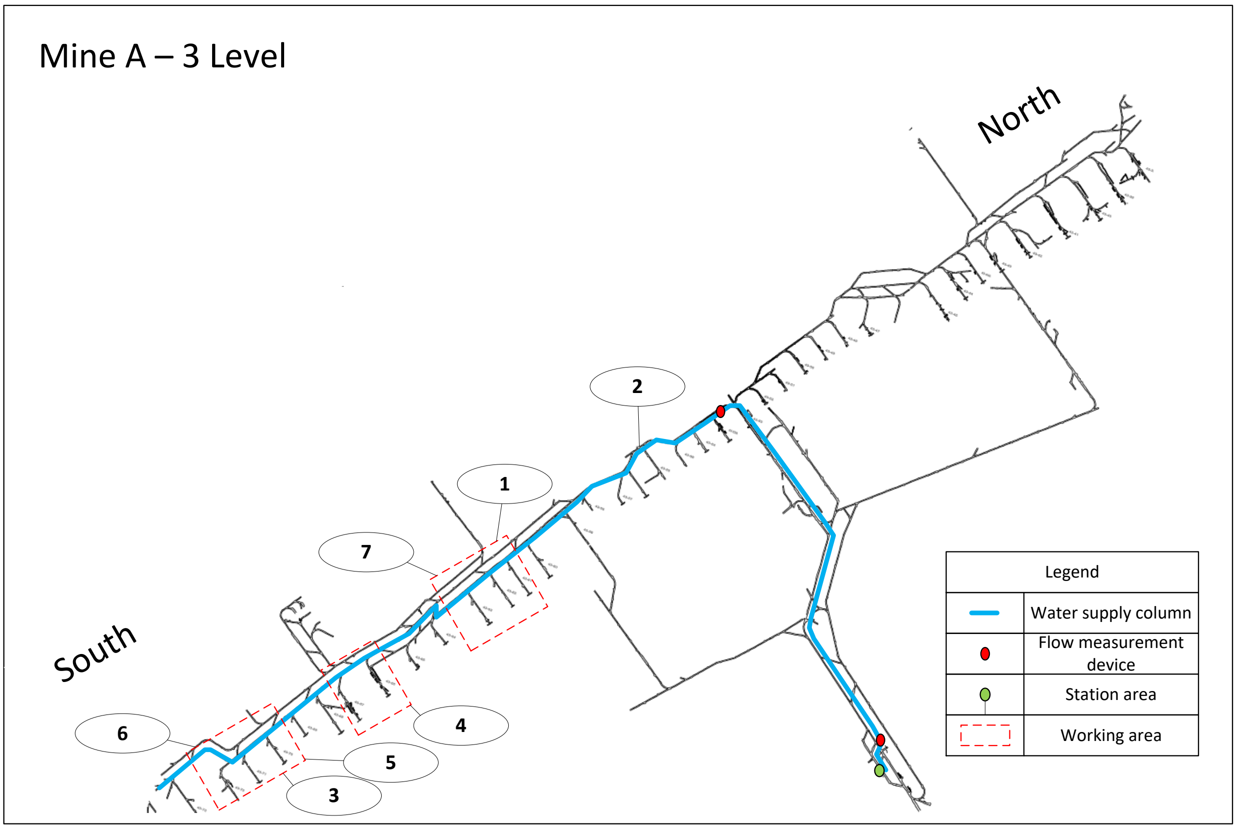

Figure 50: Top-view of 3 Level.

Figure 51 displays the top-view layout of 5 Level. As can be seen there are two working areas to the south side of the working level and one working area to the north side. The chilled water distribution column is represented by the blue line on the schematic. The numbers on the schematic represent the distribution occurrences of water flow anomalies that were identified and where corrective action was taken.

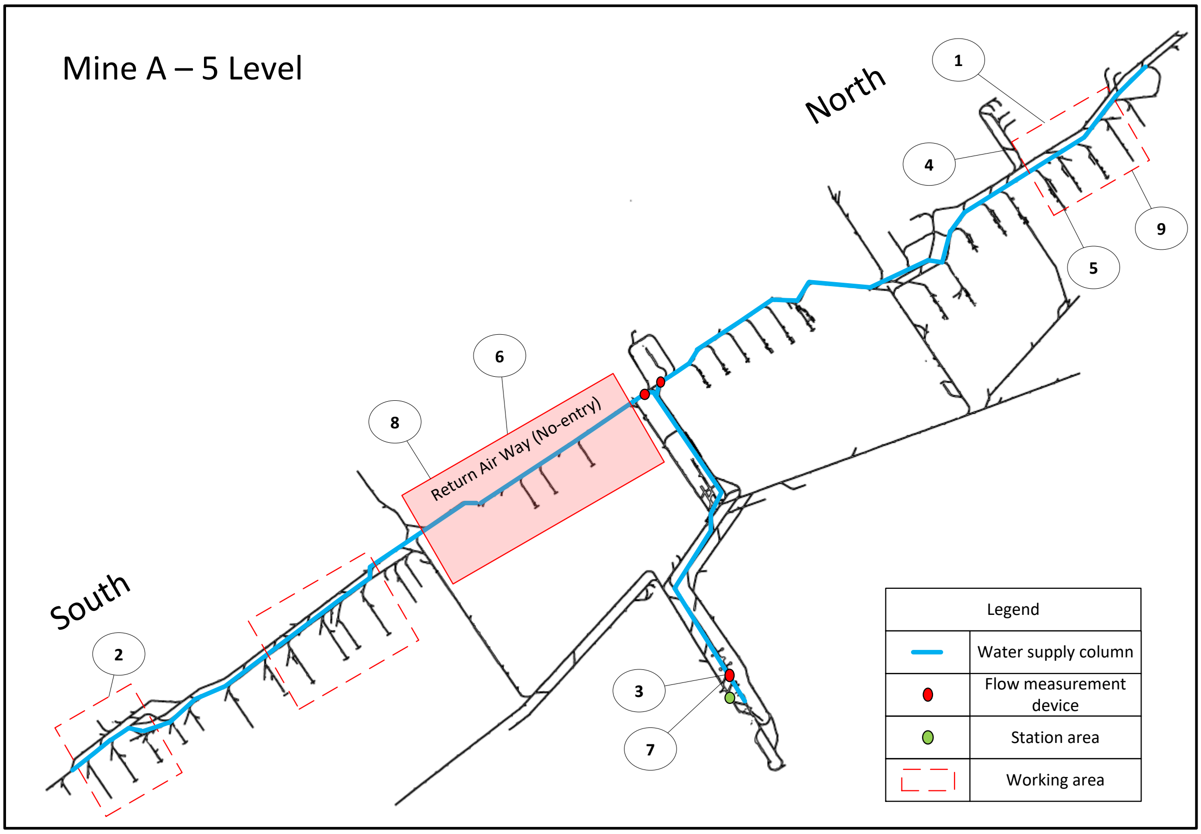

Figure 51: Top-view of 5 Level.

Appendix B: Audit examples of water-use inefficiencies

Water-use inefficiencies are represented in various forms and occur at various locations. The following examples of water-use inefficiencies were identified during implementation of the developed method.

Figure 52 displays a pipe burst that was located after an alarm notification led to further investigation and initiated an underground leak audit.

Figure 52: Burst pipe located during implementation.

Figure 53 illustrates the effect a burst column under high pressure can have. The working area was flooded to an extent where the locomotive rails were covered. This indicates that the localisation of water-use inefficiencies is important for safety and structural longevity.

Figure 53: Flooded working area due to leaking water columns.

An example of a malfunctioning valve can be seen in Figure 54. This occurs due to the high pressure exerted by the water distribution columns. When these valves are not properly maintained, they leak through, which can result in wastage as displayed in Figure 54.

Figure 54: Leaking valve identified during implementation.

The result of maintenance neglect is illustrated in Figure 55, which shows a leaking valve at the entrance of a working area. Miners typically will not report such incidents as they are concerned about losing production time for scheduled maintenance. The developed method assists with resource management without the need for human cooperation.

Figure 55: Leaking valve found at the entrance of a working area.

Figure 56 provides an illustration of a burst pipe. This picture emphasises the large volumes of water that can be lost through leakages in the water distribution system.

Figure 56: Column burst identified during implementation.

A flooded walkway can be seen in Figure 57. This illustrates how leaks in the system can impact all factors of production. Travelling to the working area, low pressure on working fluid, and underground temperatures can be impacted through leaks in the water distribution system.

Figure 57: Flooded area as a result of a burst pipe.

Appendix C: Raw data for upper control limit calculations and results

Displayed in Table 13 are dataused to illustrate how noise filtering is applied, as discussed in 2.4. The flow meter measured a flow rate of -49.80 L/s between 00:00 and 07:00 due to there not being any fluid present in the pipe. This data can be excluded from the data set.

Table 13: Hourly date containing noise.

Time	Flow rate (L/s)
00:00	-49.80
00:30	-49.80
01:00	-49.80
01:30	-49.80
02:00	-49.80
02:30	-49.80
03:00	-49.80
03:30	-49.80
04:00	-49.80
04:30	-49.80
05:00	-49.80
05:30	-49.89
06:00	-49.91
06:30	-49.91
07:00	-49.91
07:30	15.95
08:00	37.48
08:30	35.94
09:00	44.37
09:30	52.11
10:00	50.51
10:30	51.82
11:00	56.24
11:30	51.19
12:00	49.73
12:30	53.34
13:00	53.12
13:30	72.90
14:00	73.21
14:30	75.65
15:00	64.78
15:30	71.37
16:00	72.64
16:30	69.65

17:00	84.42
17:30	85.64
18:00	75.42
18:30	27.70
19:00	-0.17
19:30	-0.25
20:00	-0.21
20:30	-0.14
21:00	-0.14
21:30	-0.25
22:00	6.88
22:30	4.24
23:00	4.24
23:30	0.76

Figure 58 displays the plotted data. The graph indicates a constant value below the minimum limit from 00:00 to 07:00. This can be excluded from the data set.

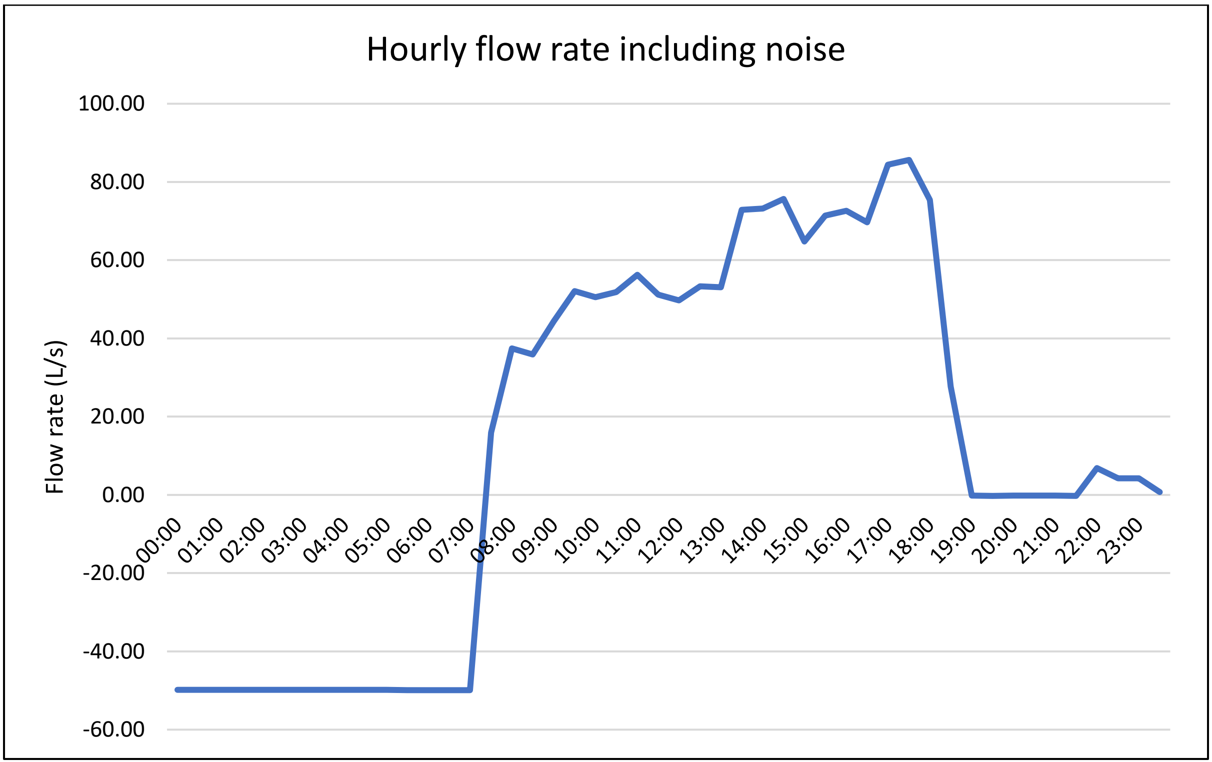

Figure 58: Plotted graph for data quality.

Table 14 summarises the difference in the daily average between data with and without noise. The average flow rate had a 26 L/s difference when using a data set including noise.

Table 14: Daily average flow rate with and without noise.

Daily average with noise (L/s)	Daily average without noise (L/s)	Difference (L/s)
12	38	26

Displayed in Table 15 are the data used to determine the upper control limit which was applied to the model.

Table 15: Upper control limit data.

Date	Captured flow rate (L/s)				
	1 Level South	2 Level North	3 Level South	5 Level South	5 Level North
Day 1	18	15	32	33	29
Day 2	27	14	36	33	30
Day 3	16	12	31	31	26
Day 4	6	0	5	3	3
Day 5	16	10	45	33	36
Day 6	12	9	56	36	29
Day 7	15	12	30	35	30
Day 8	20	16	29	34	27
Day 9	13	16	28	36	33
Day 10	18	16	28	32	25
Day 11	9	18	9	8	4
Day 12	17	12	31	35	28
Day 13	18	9	26	36	27
Day 14	10	6	29	0	0
Day 15	19	8	45	7	10
Day 16	20	9	30	40	32
Day 17	14	10	31	32	24
Day 18	2	3	7	5	5
Day 19	24	5	32	44	31
Day 20	26	6	36	44	26
Day 21	24	9	61	43	31
Day 22	24	6	32	47	32
Day 23	19	8	35	47	42
Day 24	26	13	50	50	47
Day 25	9	1	19	18	16
Day 26	20	12	45	49	40
Day 27	19	11	35	41	31
Day 28	19	10	36	46	34
Day 29	23	11	40	47	33
Day 30	28	0	3	58	67
Average	19	11	36	37	29

Table 16 displays the results for the calculated values, using Equation 2 to determine the upper control limit of each individual water flow meter on the various active mining levels at Mine A. These limits were determined over a sample size of 30 days, displayed in Table 15.

Table 16: Upper control limit results.

Variable	1 Level South	2 Level North	3 Level South	5 Level North	5 Level South
$\bar{x}$	19	11	36	29	37
σ	4	3	9	9	11
N	30	30	30	30	30
UCL	22	12	41	34	43

Found in Table 17 is the raw data captured during the implementation of the developed method. The daily average flow was captured to determine whether the water flow rate exceeded the calculated upper control limit.

Table 17: Captured data during implementation.

Day	Captured flow rate (L/s)				
	1 Level South	2 Level North	3 Level South	5 Level North	5 Level South
Day 1	18	15	32	29	33
Day 2	27	14	36	30	33
Day 3	16	12	31	26	31
Day 4	6	0	5	3	3
Day 5	16	10	45	36	33
Day 6	12	9	56	29	36
Day 7	15	12	30	30	35
Day 8	20	16	29	27	34
Day 9	13	16	28	33	36
Day 10	18	16	28	25	32
Day 11	9	18	9	4	8
Day 12	17	12	31	28	35
Day 13	18	9	26	27	36
Day 14	10	6	29	0	0
Day 15	19	8	45	10	7
Day 16	20	9	30	32	40
Day 17	14	10	31	24	32
Day 18	2	3	7	5	5
Day 19	24	5	32	31	44
Day 20	26	6	36	26	44
Day 21	24	9	61	31	43
Day 22	24	6	32	32	47
Day 23	19	8	35	42	47

Day 24	26	13	50	47	50
Day 25	9	1	19	16	18
Day 26	20	12	45	40	49
Day 27	19	11	35	31	41
Day 28	19	10	36	34	46
Day 29	23	11	40	33	47
Day 30	22	8	38	36	50
Day 31	15	10	34	21	42
Day 32	0	0	6	0	3
Day 33	18	14	50	36	52
Day 34	21	11	46	25	52
Day 35	22	8	30	31	41
Day 36	18	8	31	32	60
Day 37	20	11	32	24	58
Day 38	18	9	30	24	30
Day 39	-1	-1	5	2	2
Day 40	22	8	30	34	30
Day 41	16	10	33	36	28
Day 42	16	11	31	32	30
Day 43	25	10	33	29	31
Day 44	19	13	30	31	36
Day 45	16	5	30	30	46
Day 46	8	2	18	14	20
Day 47	24	12	41	27	49
Day 48	25	9	50	29	43
Day 49	25	9	54	27	45
Day 50	25	10	39	27	29
Day 51	21	12	26	29	31
Day 52	21	12	31	35	33
Day 53	15	2	15	13	16
Day 54	20	8	26	24	32
Day 55	20	13	26	35	40
Day 56	24	12	32	34	32
Day 57	21	11	37	36	28
Day 58	17	10	26	27	36
Day 59	1	1	5	0	17
Day 60	1	-2	5	0	0

Appendix D: Power and cost saving calculations

The average flow reduction of 11 L/s was calculated to be equivalent to 0.808 MW using energy intensity and Equation 10. This power calculation was distributed evenly throughout the day to determine the daily energy consumption in kWh.

Table 18: Calculated daily power reduction.

Hour of day	Baseline (kW)
0	808
1	808
2	808
3	808
4	808
5	808
6	808
7	808
8	808
9	808
10	808
11	808
12	808
13	808
14	808
15	808
16	808
17	808
18	808
19	808
20	808
21	808
22	808
23	808
Total (kWh)	19 400

The electricity tariff is distributed across the three tariff periods, namely weekday, Saturday and Sunday. Table 19 summarises the summer tariff structure according to the 2022/2023 demand season [22].

Table 19: Summer electrical tariff structure.

Summer Tariff (c/kWh)			
	Weekday	**Saturday**	**Sunday**
0	82.05	82.05	82.05
1	82.05	82.05	82.05
2	82.05	82.05	82.05
3	82.05	82.05	82.05
4	82.05	82.05	82.05
5	82.05	82.05	82.05
6	119.01	82.05	82.05
7	164.78	119.01	82.05
8	164.78	119.01	82.05
9	164.78	119.01	82.05
10	119.01	119.01	82.05
11	119.01	119.01	82.05
12	119.01	82.05	82.05
13	119.01	82.05	82.05
14	119.01	82.05	82.05
15	119.01	82.05	82.05
16	119.01	82.05	82.05
17	119.01	82.05	82.05
18	164.78	119.01	82.05
19	164.78	119.01	82.05
20	119.01	82.05	82.05
21	119.01	82.05	82.05
22	82.05	82.05	82.05
23	82.05	82.05	82.05
Average	116.23	92.83	82.05

The hourly cost in Rand for the summer/low-demand season is given in Table 20. This was calculated by multiplying the kWh value from Table 18 by the relevant tariff structure displayed in Table 19.

Table 20: Summer electrical cost reduction.

Summer Impact			
	Summer Tariff (R)		
	Weekday	Saturday	Sunday
0	663.25	663.25	663.25
1	663.25	663.25	663.25
2	663.25	663.25	663.25
3	663.25	663.25	663.25
4	663.25	663.25	663.25
5	663.25	663.25	663.25
6	962.02	663.25	663.25
7	1 332.00	962.02	663.25
8	1 332.00	962.02	663.25
9	1 332.00	962.02	663.25
10	962.02	962.02	663.25
11	962.02	962.02	663.25
12	962.02	663.25	663.25
13	962.02	663.25	663.25
14	962.02	663.25	663.25
15	962.02	663.25	663.25
16	962.02	663.25	663.25
17	962.02	663.25	663.25
18	1 332.00	962.02	663.25
19	1 332.00	962.02	663.25
20	962.02	663.25	663.25
21	962.02	663.25	663.25
22	663.25	663.25	663.25
23	663.25	663.25	663.25
Total	22 548.16	18 009.36	15 918.00

$$Average\ summer\ tariff\ daily\ cost = \frac{5 \times weekday + Saturday + Sunday}{7}$$

$$Average\ daily\ cost = R20\ 952.59$$

The electricity tariff is similarly distributed across the three tariff periods for the winter period. Table 21 summarises the winter tariff structure according to the 2022/2023 demand season [22].

Table 21: Winter electrical tariff structure.

Winter Tariff (c/kWh)			
	Weekday	**Saturday**	**Sunday**
0	92.00	92.00	92.00
1	92.00	92.00	92.00
2	92.00	92.00	92.00
3	92.00	92.00	92.00
4	92.00	92.00	92.00
5	92.00	92.00	92.00
6	468.20	92.00	92.00
7	468.20	154.32	92.00
8	468.20	154.32	92.00
9	154.32	154.32	92.00
10	154.32	154.32	92.00
11	154.32	154.32	92.00
12	154.32	92.00	92.00
13	154.32	92.00	92.00
14	154.32	92.00	92.00
15	154.32	92.00	92.00
16	154.32	92.00	92.00
17	468.20	92.00	92.00
18	468.20	154.32	92.00
19	154.32	154.32	92.00
20	154.32	92.00	92.00
21	154.32	92.00	92.00
22	92.00	92.00	92.00
23	92.00	92.00	92.00
Average	198.94	110.18	92.00

The hourly cost for the winter/high-demand season is given in Table 22. This was calculated by multiplying the kWh value from Table 18 by the relevant tariff structure displayed in Table 21.

Table 22: Winter electrical cost reduction.

Winter Impact			
	Winter Tariff (R)		
	Weekday	**Saturday**	**Sunday**
0	743.68	743.68	743.68
1	743.68	743.68	743.68
2	743.68	743.68	743.68
3	743.68	743.68	743.68
4	743.68	743.68	743.68
5	743.68	743.68	743.68
6	3 784.69	743.68	743.68
7	3 784.69	1 247.44	743.68
8	3 784.69	1 247.44	743.68
9	1 247.44	1 247.44	743.68
10	1 247.44	1 247.44	743.68
11	1 247.44	1 247.44	743.68
12	1 247.44	743.68	743.68
13	1 247.44	743.68	743.68
14	1 247.44	743.68	743.68
15	1 247.44	743.68	743.68
16	1 247.44	743.68	743.68
17	3 784.69	743.68	743.68
18	3 784.69	1 247.44	743.68
19	1 247.44	1 247.44	743.68
20	1 247.44	743.68	743.68
21	1 247.44	743.68	743.68
22	743.68	743.68	743.68
23	743.68	743.68	743.68
Total	38 594.77	21 374.68	17 848.34

$$Average\ daily\ cost = \frac{5 \times weekday + Saturday + Sunday}{7}$$

$$Average\ winter\ tariff\ daily\ cost = R33\ 170.98$$

The total saving was then calculated by the sum of the calculated summer (low-demand) period in Table 20 and the winter (high-demand) period from Table 22. Summarised in Table 23 are the values used to calculate the annual cost saving.

Table 23: Annual cost saving.

Savings category	**Summer**	**Winter**
Average daily saving	R20 952.59	R33 170.98
Total saving	R5 657 583.11	R3 017 289.97

$$Total\ saving = Winter\ saving + Summer\ saving$$

$$Total\ annual\ cost\ saving = R8\ 674\ 873.08$$