



Improving deep-level mine water usage through dynamic baselines and accountability methods

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Abstract

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South African gold mines are extremely complex and dynamic operations in terms of several factors such as logistics, depth of mining, infrastructure and variable geological conditions. These operations progress deeper, well below 4 000 m, searching for new gold-bearing ore reserves. As mines progress deeper, additional cooling and ventilation requirements are needed to combat the high virgin rock temperatures. This results in bigger and more complex water reticulation systems that provide cooling and services to underground end users.

Gold production is decreasing while operational costs continue to increase, reducing the profitability and sustainability of mining operations. External factors such as rising electricity tariffs, declining gold grade, and unstable gold prices contribute to this trend, but remain beyond the mine's control. Inefficient operations, particularly water losses from leaks and misuse or malpractice, which account for up to 50% of underground water use, present a key opportunity for intervention. To decrease operational costs, focus must be placed on identifying and addressing water inefficiencies.

Water leaks tend to occur closer to the working areas as this is where personnel spend most of their time. However, current methods used to localise water leaks in working areas are time and resource intensive. Furthermore, these methods fail to continuously identify water leaks in the working areas as they occur due to their static and infrequent nature. Zero-waste baselines (ZWBs) were highlighted as the best method for wastage identification. Still, limitations in current approaches include static and broad applications. These are typically implemented only up to half levels and rely on fixed timetables and best operating points for equipment.

Identification alone will not solve the problem and leak mitigation is often overlooked where focus is placed on supply-side initiatives such as water isolation and pressure management.

These measures are only effective during non-operational times. Furthermore, large leaks are only attended to when normal production is disrupted, making them part of everyday operations, which neglects smaller leaks. Furthermore, no reliable system is in place to confirm whether leaks have been fixed. Employees also rarely fix and report leaks themselves as the operation's focus lies with production and roles regarding leak fixing remain unclear.

To address the problem, the study introduces an accountability framework that applies dynamic ZWBs to identify and mitigate water leaks within operational working areas. The framework incorporates core accountability components to improve performance and drive sustainable operational improvements. The development of dynamic ZWBs will enable faster and more accurate detection of inefficiencies within working areas. Additional metering is installed in working areas with a life of mine over one year to measure the actual water consumption, compare it to the ZWB and identify wastage. Using accountability will ensure that water leaks are not only identified but mitigated to reduce operational costs.

The developed method was implemented on a South African gold mining operation, referred to as Mine A. ZWBs were developed for each working area, which reduced the identification period significantly when compared to current methods. The ZWBs were used as performance measures where a responsible person was assigned to each working area to ensure that identified leaks were mitigated. A monthly cost saving of R235 000 was obtained for the case study working area, resulting in a payback period of 9 days for the installed equipment. This equates to an annual cost-benefit of approximately R28.7 million for Mine A. The results obtained validate the effectiveness of the developed method. All objectives of the study have been met by the evaluation and the validation thereof.

Publications from Research

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Improving deep-level mine utility usage through dynamic baselines

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Feature papers are submitted upon individual invitation or recommendation by the scientific editors and must receive positive feedback from the reviewers.

- The full article can be viewed in Appendix A: Journal Article.

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The research presented in this thesis is my own work, and all external sources have been appropriately credited through references. Any errors or omissions identified will be promptly addressed and corrected.

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Nomenclature

Abbreviation	Description
AI	Artificial intelligence
AEN	Autoencoder
ATD	Average topological distance
BAC	Bulk air cooler
cm	Centimetre
R^2	Coefficient of determination
XC	Crosscut
CFM	Cubic feet per minute
°C	Degrees Celsius
DN	Diameter nominal
DMA	District metered area
EMIS	Energy management information system
GPS	Global positioning system
g/t	Grams per tonne
IEMS	Integrated energy management strategy
IWN	Intelligent water network
kg	Kilogram
km	Kilometre
kW	Kilowatt
kWh	Kilowatt-hour
kW/CFM	Kilowatt per cubic feet per minute
L	Level
LOM	Life of mine
LDA	Linear discriminant analysis
l	Litre
l/min	Litre per minute
l/s	Litre per second

LOF	Local outlier factor
MAPE	Mean absolute percentage error
MI	Megalitre
MW	Megawatt
m	Metre
mm	Milimetre
MPL	Missing Persons Locator
NNET	Neural networks
OLE	Object linking and embedding
OPC	OLE for process control
%	Percentage
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
Bar	Pressure
PN	Pressure nominal
PRV	Pressure-reducing valve
PLC	Programmable Logic Controller
RFID	Radio frequency identification
RDO	Rock drill operator
R	South African Rand
SCADA	Supervisory Control and Data Acquisition
TOU	Time of use
VAT	Value added tax
VSD	Variable speed drive
VRT	Virgin rock temperature
WDS	Water distribution system
WRS	Water reticulation system
WB	Wet bulb temperature
ZWB	Zero-waste baseline

CHAPTER 1: INTRODUCTION & BACKGROUND

“After all, the ultimate goal of all research is not objectivity, but truth.” – Helen Deutsch.



¹ Personal photo taken by the author.

1 Introduction & Background

Chapter 1 highlights the importance of the water reticulation system (WRS) in South African deep-level gold mines and addresses the main challenges impacting its performance. It also gives a critical analysis of existing inefficiency detection techniques, focusing on localised detection and mitigation of identified inefficiencies. This was done to identify all shortcomings in the field. The literature study conducted determined the problem statement, research objectives, and novel contributions of the thesis.

1.1 Water reticulation concept in the deep-level mine environment

South African deep-level gold mining operations are complex and dynamic systems, influenced by several factors such as logistics, depth of mining, infrastructure and variable geological conditions, with some mines reaching depths of up to 4 000 m below the earth's surface [1], [2]. As mining operations extend to greater depths in search of new gold ore deposits, the virgin rock temperature (VRT) increases [3]. This necessitates bigger and more complex WRSs, inclusive of pumping and refrigeration, to provide underground air cooling and chilled water for various mining activities to ensure adequate working environments and gold production [1].

1.1.1 Importance of water reticulation systems in deep-level gold mines

Gold mining has been a significant contributor to the South African economy since the discovery of gold in 1880 [4], [5]. Since then, operations continued to extend to greater depths in search of new gold-bearing ore bodies [6]. In deep mines, the VRT reaches temperatures of up to 65°C and increases by 12°C per vertical kilometre [7]. According to the Health and Safety Act, 20 of 1996, the wet bulb (WB) temperature may not exceed 32.5°C in the working areas [8]. Therefore, as mines progress deeper, additional ventilation and cooling requirements are needed to comply with the Health and Safety Act [1], [9].

The WRS consists of refrigeration and pumping systems as depicted in Figure 1. The process starts with large surface refrigeration plants cooling the water to the desired temperature of typically between 3-5°C [7]. Refrigeration plants are usually located on the surface but are also introduced underground as mining activities progress deeper [10]. Bulk air coolers (BACs) located on the surface use chilled water to decrease the air temperature sent underground. The chilled water is transferred to surface holding dams before being distributed underground.

Given the depth at which these mines operate, cascading chilled water dams are strategically positioned on descending levels to store water for fluctuating demand [11].

The chilled water is typically gravity fed in pipe columns, reaching extreme pressures. The water pressure in these columns increase by approximately 1 000 kPa for every 100 m of vertical head pressure [7]. The cascading dam system assists in reducing the water pressure. The chilled water gets distributed to mining, where it absorbs heat through various operational processes involving heat transfer. After use, the water is transferred to underground settler systems to remove debris, and large dewatering pumps return the heated water to the surface to re-enter the cycle [12]. Cascading hot water dams are used for dewatering due to the head pressure to be pumped, which typically varies between mining operations depending on the specific mine layout and depth.

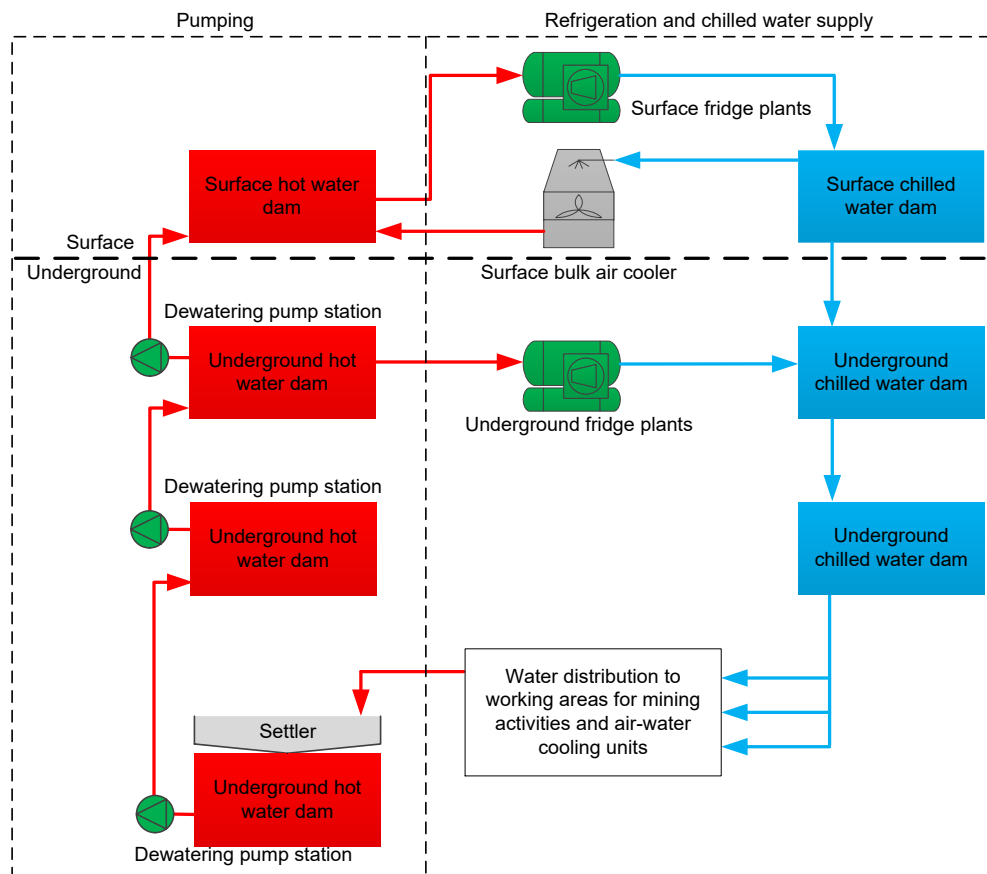


Figure 1: Schematic of a WRS on a typical deep-level gold mine.

Chilled water plays an important part in maintaining underground air temperatures. It is, however, not only used for underground air cooling but also for various mining activities [13], [14]. The chilled water pipeline network, which extends over 65 km, is extremely complex and supplies chilled water to end users located up to 4 000 m below the earth's surface [15]. Figure

2 displays the complexity of a typical deep-level gold mine. Chilled water pipelines are installed from the surface to all working areas.

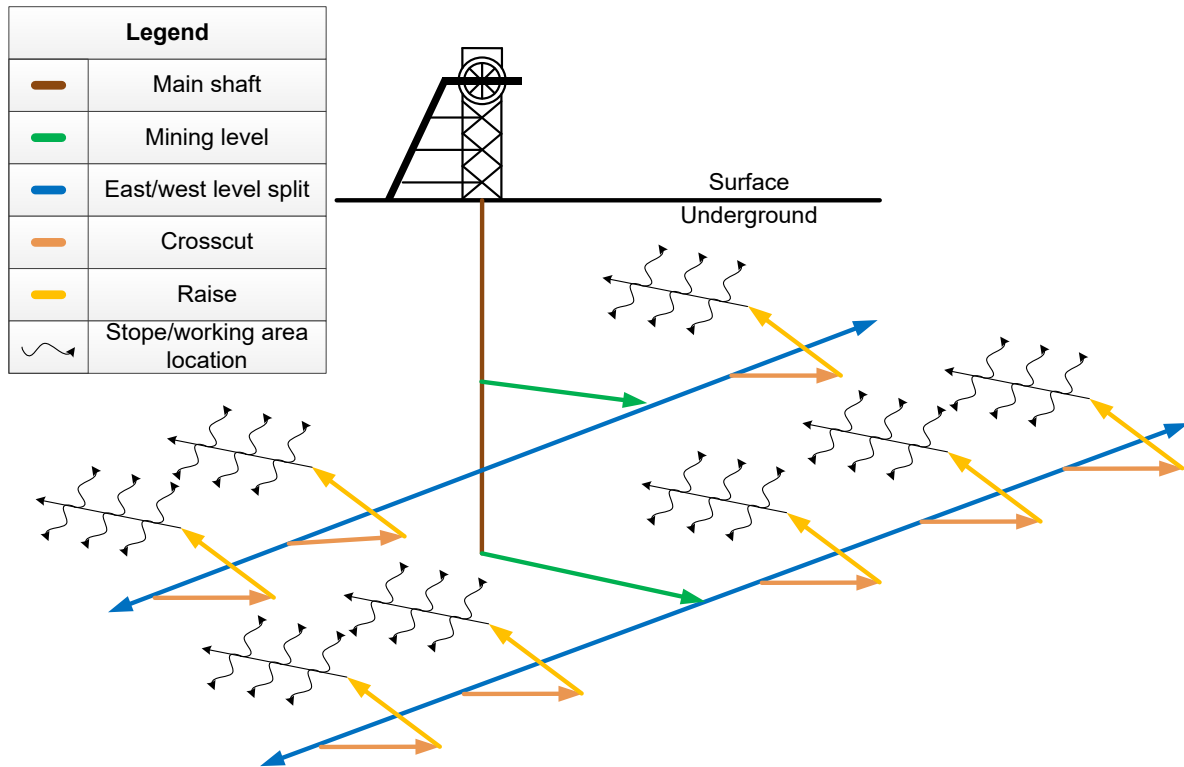


Figure 2: Typical deep-level gold mine layout (adapted from [16]).

The specific mining shift and the equipment used for various mining activities within each duty cycle determine the water demand in a typical gold mine [17]. The most common underground chilled water end users include [18]:

- Air-water cooling units such as cooling cars and BACs;
- Rock drills;
- Cleaning equipment such as waterjets; and
- Supporting equipment.

The underground mining process is divided into several steps, performed in shifts across a 24-hour cycle. The typical shift schedule in a South African gold mine, along with the primary water-consuming equipment for each shift, is seen in Table 1. Note that this may vary for each mining operation.

Table 1: 24-hour shift cycle on a typical deep-level gold mine [16], [19]–[21].

Shift name [time]	Description
Drilling [06:00 – 14:00]	Rock drills are used to drill holes in the rock face. Chilled water is used to cool rock drill bits.
Explosive charge-up and blasting [14:00 – 16:00]	Explosives are inserted into the drilled holes to blast the rock face. No personnel are allowed near the blast site during this period. Theoretically, no water should be consumed here.
Blasting and non-entry period [16:00 – 21:00]	The blasting of the rock face exposes dust and harmful gases. A non-entry period is allowed after blasting to ensure that harmful gases are ventilated from the area. Again, no water should be consumed here as no personnel are allowed underground.
Cleaning and sweeping [21:00 – 04:00]	When all dust and harmful gases are extracted from the mine, personnel may enter again. The broken rock is moved to a collection point using scrapper winches and waterjets.
Shift change [04:00 – 06:00]	Shift changes occur between the drilling and cleaning/sweeping shifts. Personnel clocking out make their way from the working areas to the shaft station, where they are hoisted to the surface. Conversely, personnel clocking on will make their way to the working areas. Little to no water should be consumed during shift changes as personnel are routed to and from the working areas.

Each mining operation may follow unique timetables for each duty cycle, but the fundamental method of operations remains the same. Even though mining operations aim to adhere to these schedules, this is not always the case due to the dynamic nature of mining operations which are subject to change [22].

Air-water cooling units generally consume water throughout the day to maintain the air temperatures below the legal limit of 32.5 °C. However, existing research has shown that water supply to these units can be halted during times when no personnel are underground [19],

[23], [24]. Conversely, mining equipment should only consume water when operated by an end user [25]–[27].

The WRS plays a vital role in gold mining operations. However, these large, complex systems often face challenges. Their efficiency and the safety of mining personnel are influenced by multiple factors, some of which are beyond the control of the mining operation. These factors will be elaborated on in the following section.

1.1.2 Challenges impacting the water reticulation performance

In 2009, South Africa was the world's top gold producer, but since then, gold production has experienced a significant decline as depicted in Figure 3 [28]–[30]. This decreased could possibly be due to several factors such as lower ore grades and general increases in operational costs [7].

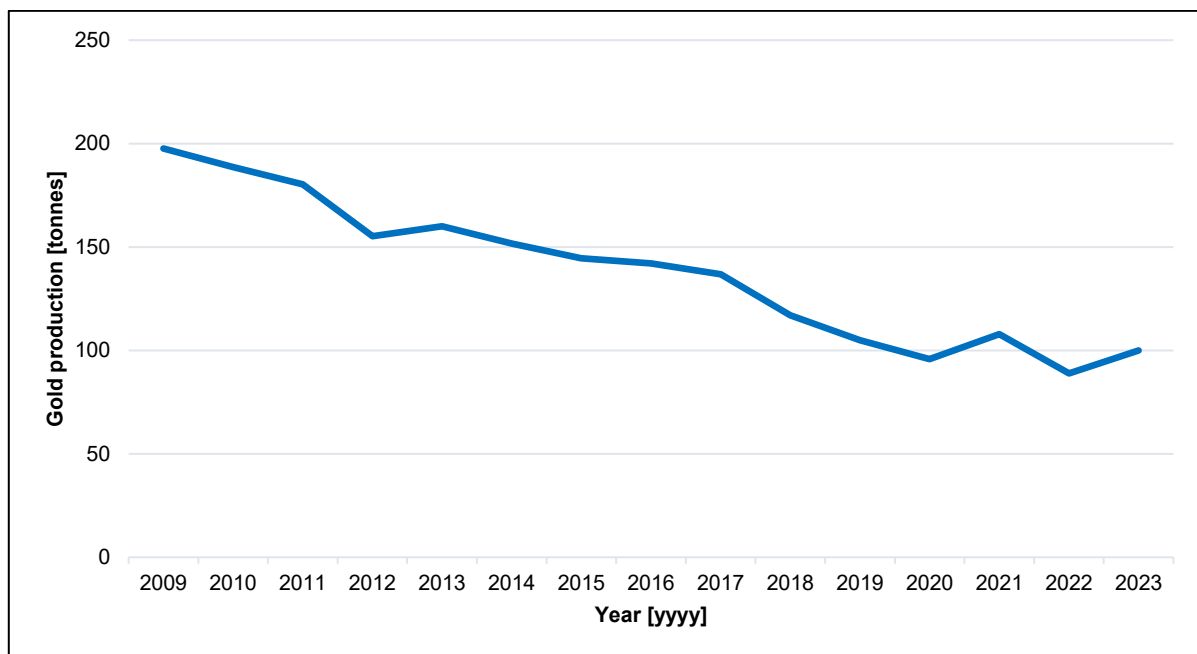


Figure 3: South Africa's historic gold production trends [31].

This raises concerns regarding the sustainability and profitability of the mining industry as operating costs continue to increase despite the decline observed in gold production [6], [32]. Between 2013 and 2022, one of the country's largest gold mining companies saw its average operating costs increase by about 54% [33], [34]. This is largely due to operations expanding to greater depths, requiring more cooling and ventilation, leading to higher electricity consumption [35], [36].

Adding to the challenge, South Africa's electricity tariffs skyrocketed by 653% between 2007 and 2022, far outpacing the 129% rise in inflation over the same period [37]. Studies show that even a 1% increase in electricity tariffs can reduce gold production by 2.02%, illustrating how rising energy costs directly impact the output [38]. To further worsen the matter, the average gold grade in South Africa decreased from 12 g/t in 1970 to 5 g/t in 2022 [39]. This decline, coupled with fluctuations in gold prices [1], put further pressure on mining operations.

The South African gold mining industry is highly energy intensive, accounting for around 30% of the total power supplied by Eskom [40]. The WRS, which includes pumping and refrigeration, consumes 39% of the total energy consumed by a typical gold mining operation, as shown in Figure 4 [39].

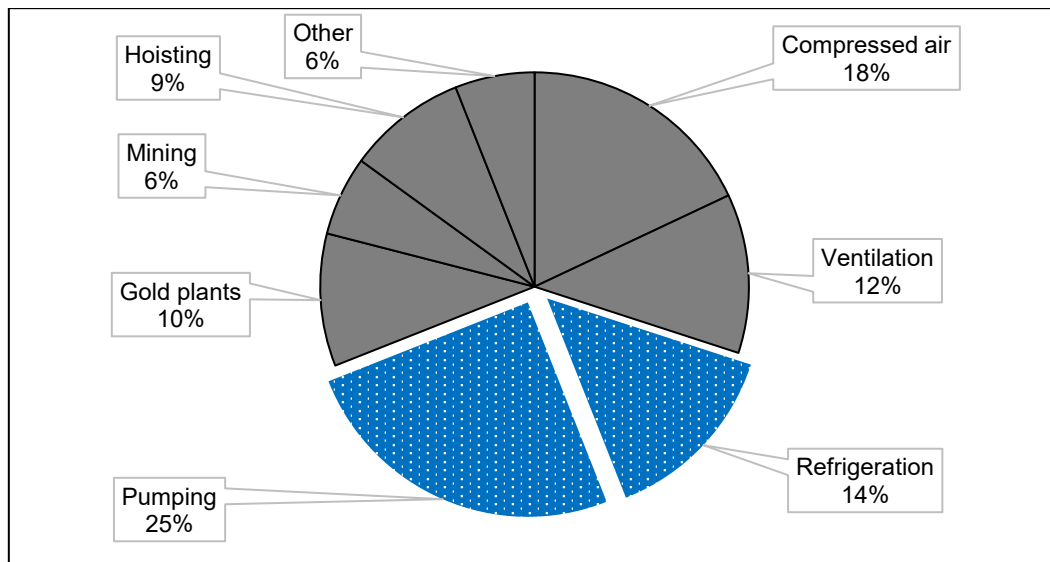


Figure 4: Electricity distribution on a typical South African deep-level gold mine [39].

The performance of the WRS in South African gold mines is influenced by several factors. These factors can be divided into those outside or inside the mine's control. Factors categorised within the mine's control are inefficient operations, whereas factors outside their control include rising electricity tariffs, declining gold grades, and fluctuating gold prices [1].

The complexity of the WRS, together with the harsh underground conditions, leads to inefficiencies [15], [41], [42]. These inefficiencies substantially increase operating costs, offering no return on the expenses incurred to supply water that goes to waste. This means that additional water is supplied to underground operations (which need to be dewatered as well) to overcome inefficiencies and satisfy the water requirements for normal operations [43], [44]. Mining companies thus need to incur additional costs due to inefficiencies. Inefficiencies

increase together with the expansion of operations, meaning that the larger and more dynamic the system, the more inefficiencies are present within the system [44], [45].

Most of these inefficiencies occur near the working areas where the gold-bearing ore is mined as this is where workers spend most of their time when working [25], [44], [46]. Past researchers found that 30-50% of the total water supply can be attributed to inefficiencies which occur in the form of [47]–[49]:

- Leaks; and
- Misuse and malpractice.

Chilled water pipelines deteriorate due to harsh underground conditions, which include high humidity and temperatures that lead to corrosion. Rockfalls and heavy machinery often puncture pipelines, while leaks are also frequently found on pipe flanges and connections [50], [51]. Misuse of chilled water further worsens the matter, often due to a lack of awareness regarding the cost of chilled water and a culture that normalises such behaviour underground [52]. Common misuse and malpractice include the deliberate alteration of equipment to enable continuous water consumption in the absence of active use, typically done to ease operation during shifts, and the failure to isolate inactive working areas [16].

In addition to financial implications, inefficiencies reduce the system's performance by [18], [43], [44], [53], [54]:

- Decreasing operating pressures;
- Reducing water availability for mining activities;
- Increasing the risk of flooding; and
- Washing away fine gold ore.

Since service water inefficiencies are controllable within mining operations, it is essential to focus on their mitigation to lower operational costs [49]. Gunson *et al.* [48] emphasise the importance of this by stating: “*Increasing energy efficiency and reducing water consumption are two of the key requirements in moving toward a more sustainable mining industry*”. This is echoed by Joseph *et al.* [55], who highlight that efficiency and sustainability are among the main challenges facing the water sector.

Before mitigation can occur, inefficiencies must first be identified to determine the true extent of the issues [16]. This is considered a very difficult and time-intensive process due to the complex nature, harsh environment and magnitude of South African gold mining operations [16], [49], [56]. Numerous methods exist for the identification of inefficiencies; however, a study

done by Le Roux [57] identified and compared the primary methods to determine the most effective approach. The four primary methods are identified as:

- Leak detection: Identification and elimination of leaks;
- Valve control: Flow reduction during off-peak periods;
- Measure baselines: Use of historical data to develop baselines; and
- Zero-waste baselines (ZWBs): Baselines developed from consumer demands.

The study conducted by Le Roux [57] compared the above-mentioned techniques through implementation on a mutual case study and concluded that ZWBs are the best method as they can identify the true extent of wastage.

This was confirmed by Marais [58] who compared ZWBs to historic baselines and valve control and concluded that ZWBs are more accurate than other methods of identifying waste.

The implementation of ZWBs is a relatively new concept with the majority of research published on this topic being within the last two years; however, it has already shown promising results [57]. ZWBs represent the theoretical minimum consumption in an idealised scenario with 100% efficiency and no wastage [17]. Wastage identification is done by using data to obtain a reference point to be compared to the actual usage to identify wastage.

1.2 Problem statement

Operational costs in the gold mining industry continue to increase as the depth of mining increases, negatively impacting profitability and long-term sustainability. While external factors such as increasing electricity tariffs, declining gold grades, and unstable gold prices contribute to this trend, they remain largely beyond the mine's control.

In contrast, inefficient operations, particularly water wastage in the form of leaks and misuse, which account for up to 50% [47]–[49] of the total water supplied, represent a key opportunity to decrease operational costs. The majority of water wastage occurs in the working areas where gold ore is mined. Addressing these inefficiencies is essential to reduce operational costs and improve both profitability and sustainability.

Therefore, considering the complex and dynamic nature of the WRS, specific methods are required for faster analysis of these systems, especially water wastage detection in working areas where it frequently occurs. This is because the faster and more frequent detection can take place, the faster issues can be rectified and unnecessary costs avoided. However,

emphasis is placed on the mitigation of inefficiencies as detection alone does not solve issues and inefficiencies continue to exist.

Problem statement: Operational costs in deep-level gold mining are increasingly driven by water inefficiencies in working areas, highlighting the need for faster and more effective methods to detect and mitigate water wastage at these locations.

1.3 Water reticulation system inefficiency detection – A literature review

High water consumption is an issue across various sectors, not just mining, and several techniques have been explored to address this issue [59]. In deep-level gold mines, water wastage presents significant challenges, as discussed in the previous section. These issues not only increase the operating costs, but also negatively impact the system's performance. Considering the state in which mining operations find themselves, issues such as unnecessary water wastage should be addressed to lower operating costs and improve system performance. However, before inefficiencies can be mitigated, they first need to be identified.

Therefore, a literature review focusing on water inefficiency detection and mitigation was conducted. This review established a framework for the method developed in this study. By analysing existing detection and mitigation methods, key shortcomings were identified to guide the methodological development presented in this thesis. This determined the objectives and novel contributions of this thesis.

A systematic literature review was performed to identify research related to the topic [60]. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) structure, as seen in Figure 5, was used to develop the state-of-the-art analysis.

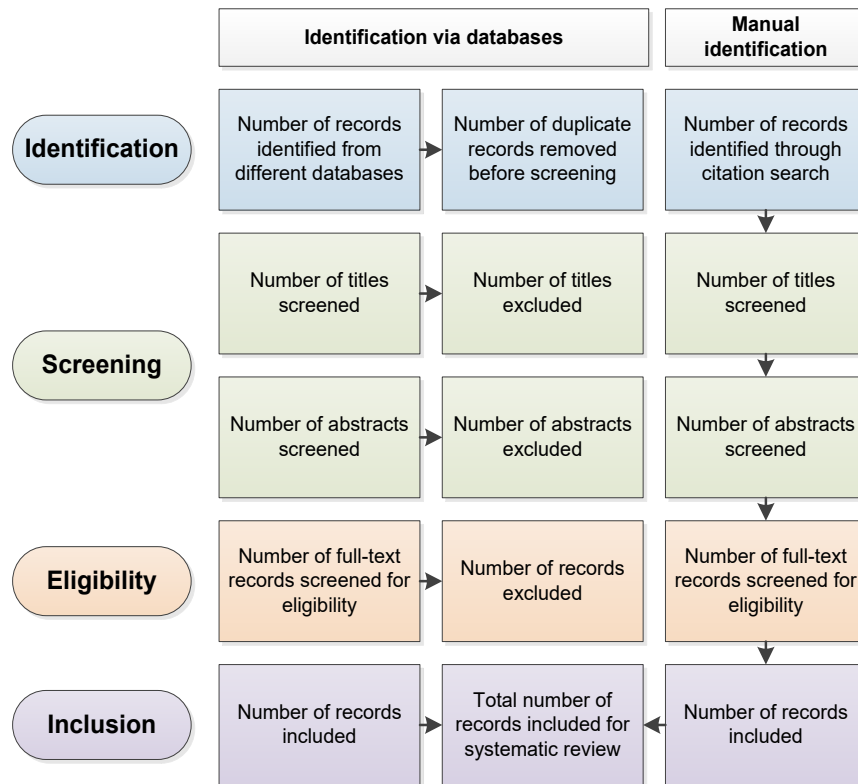


Figure 5: PRISMA structure used for evaluation of literature search process (adapted from [60]).

1. **Problem formulation** – the problem was formulated from the research conducted in Section 1.1, which aims to reduce operational costs by investigating existing water inefficiency detection techniques with a focus placed on mitigation and localisation of inefficiencies.
2. **Identification:** The literature review aimed to obtain broad field research related to the problem. This was done by identifying selected keywords and combinations to be used as inputs in various databases such as Google Scholar, Science Direct, SpringerLink, Scopus and Web of Science. The core keyword included “water”, which was used in combination with “deep-level mine”, “waste”, “wastage”, “leaks”, “identification”, “locate”, “reduction” and “mitigation”. “Compressed air” was also used as a search term in combination with the above-mentioned terms. Furthermore, critical reviews from previous studies were conducted to identify studies not initially included in the database search procedure. All duplicate studies were removed before screening.
3. **Screening:** The considered studies were evaluated based on whether they included identification or mitigation of inefficiencies. Emphasis was placed on flow inefficiencies such as water and compressed air. All studies that focused on waste products or general water management were excluded as they dealt with a different kind of waste from that mentioned in this thesis. Low-quality sources were excluded.

4. **Eligibility:** Next, full-text screening was done for a deeper assessment of the remaining studies to determine if they met the outlined criteria.
5. **Inclusion:** All identified studies were reduced to 30 recent, high-quality (peer-reviewed) studies that were included in the state-of-the-art analysis. Of the included studies, 70% (21 papers) fall within the last 10 years, 30% (9 papers) fall within the last 5 years and 30% (9 papers) fall outside the last 10 years.

1.3.1 State-of-the-art analysis

The state-of-the-art analysis entails a critical review of the considered studies. Predefined criteria, based on the identified problem statement, were used to refine the focus and structure of the proposed method and to highlight shortcomings in existing literature. The existing research was evaluated based on five main criteria, each of which addresses the challenges outlined in Section 1.1. The criteria were:

- Deep-level mine;
- Water system;
- Localised inefficiency detection;
- Zero-waste approach; and
- Cost benefit through mitigation.

Wastages occur across various industries, typically involving inefficiencies in resource use such as energy, water, materials, and labour [59]. However, considering the complexity of mining operations, they may require a different approach than other sectors [61]. Approaches used in other sectors were still evaluated as they may offer valuable insights. Therefore, deep-level mining was used as the first criterion.

The second criterion highlighted whether the study had been applied to water systems. Several methods exist to identify wastages in other systems, such as compressed air [62]; however, these methods may not have been implemented on water systems.

The third criterion was added to determine if the method was able to identify and localise flow inefficiencies. Several methods exist to identify wastage, but localised detection in working areas is crucial to ensure prompt pinpointing to mitigate issues. Here, localised detection refers to the identification of inefficiencies at the end users which are located in the working areas.

ZWBs have been identified as the best method for wastage detection [15]. Therefore, studies were reviewed to determine if they used a zero-waste approach.

A criterion should highlight if studies had focused on the mitigation of inefficiencies as identification alone does not solve issues. Considering the existing problem experienced with rising operating costs, this criterion determined if an actual cost benefit had been obtained through mitigation.

Available research on wastage identification and mitigation is summarised below. Each study was evaluated based on the criteria set out in this section.

Study 1: Van der Merwe *et al.* – Using zero-waste baselines to identify compressed air system inefficiencies in deep-level mines, 2022 [17]

Van der Merwe *et al.* made use of ZWBs in combination with simulation software to identify and quantify wastages on a deep-level mine compressed air system. ZWBs were developed for all mining levels using fixed operational schedules and best operating points for compressed air-consuming equipment obtained from their specification sheets. Furthermore, the amount of equipment on a specific level was assigned to a certain mining shift and all equipment was assumed to be operational in that specific shift. The ZWB was input into a simulation model to determine the theoretical demand required by the system and compare it to the actual compressed air consumption. This allowed for successful inefficiency detection and quantification using existing installed metering on active mining levels.

This study meets only two of the five criteria. The method was implemented on a deep-level mine and used ZWBs as an identification method. The study neither implemented the method on a water system nor included localised detection in the working areas, only per level. Identified issues were not mitigated to obtain a cost benefit.

Study 2: Gruting *et al.* – Investigating the link between compressed air wastage and ventilation shortfalls in deep-level mines, 2022 [63]

This paper established the correlation between compressed air wastage and ventilation shortfalls in a deep-level mine. This paper used ZWBs to identify compressed air wastage per mining level. Underground audits were conducted on crosscuts (XCs) of problematic levels to identify wastages on XC levels. The ZWB consisted of a mathematical calculation where the reference flow of equipment (obtained from specification sheets) was used together with the actual pressure and the reference pressure. Air-consuming equipment was assigned to fixed

mining shifts. Together with audits conducted, air temperature readings were obtained to determine the link between compressed air wastage and ventilation shortfalls.

The author recommended that additional metering equipment should be installed to reduce the total size of areas considered and enable better monitoring with fewer errors than using mathematical calculations. Only three evaluation criteria were met by the study. The study was implemented on a deep-level mine where ZWBs were used to identify inefficient levels. Localised detection in working areas was done by conducting underground audits on the problematic levels. The study did not implement the method on a water system and did not achieve any cost-benefit through mitigation of issues.

Study 3: Desmet and Delore – Leak detection in compressed air systems using unsupervised anomaly detection techniques, 2017 [64]

This paper applied an anomaly detection technique to detect leaks in compressed air systems of mobile surface mining machinery. The approach utilised a machine learning algorithm to address the challenges of detecting leaks by analysing pressure drops in air accumulators when compressed air components were operated.

Firstly, a training data set/baseline was established. This consisted of fault-free records representing normal operating conditions of the compressed air system, specifically focusing on grease spray systems. The algorithm was implemented on the actual data where it produced a value for each time step which represented how “abnormal” it was compared to the baseline.

The study compared two anomaly detection techniques: the local outlier factor (LOF) technique and the autoencoder (AEN) technique. The LOF achieved higher accuracy but required significant computational resources, limiting real-time monitoring. The AEN, while faster, was less accurate in anomaly detection but showed potential for integrating additional indicators to improve detection sensitivity.

The system offers real-time anomaly detection, enabling quicker response to dynamic changes in air systems. This machine learning approach adapts to environmental variations, allowing for sustainable operation through continuous monitoring. Additionally, this approach minimises human intervention for recalibration, which is critical given the operational scale and frequency of maintenance on air systems.

This method met only one of the evaluation criteria. While it was able to localise leaks at the end-user level, its scale was significantly smaller compared to mining operations.

Study 4: Du Plooy *et al.* – Local benchmarking in mines to locate inefficient compressed air usage, 2019 [2]

This paper developed an inefficiency detection method that made use of benchmarking techniques to establish a correlation between compressed air usage and production in a deep-level mine.

Here, the compressed air usage per level was compared to the production on the corresponding level. This was done for all active mining levels. Inefficiencies within the compressed air system were identified when the compressed air consumption increased but the production remained constant. Full and comprehensive audits were performed on mining levels with high compressed air wastage to determine and localise inefficiencies. This method reduced the need for full comprehensive audits that take up to three months to complete by only identifying levels wasting compressed air. However, this method could only be conducted for levels where production was taking place, neglecting development and inactive areas.

Audits were conducted on problematic levels to identify the type of leak and actions to be taken to fix the identified issues. Even though minor leaks were found in almost all the working areas, it was assumed that they had little impact and were neglected. Mitigation was done by informing management personnel to seal off compressed air lines feeding inactive areas and to install control valves to regulate the compressed air supply, only focusing on the major issues.

This paper satisfied three of the five criteria. The method was implemented on a deep-level mine which enabled localised detection in working areas through audits. Cost savings were achieved by informing management personnel to rectify the issues. Focus was only placed on major issues, neglecting small leaks which, cumulatively, can have a significant impact. Furthermore, areas where no production was taking place were neglected, therefore not all leaks were considered. The study did not implement this method on a water system and ZWBs were not used for detection.

Study 5: Zietsman – Novel solutions for compressed air demand management on deep-level mines, 2020 [16]

Zietsman developed a novel solution for compressed air management in a deep-level mine. This research introduced a benchmarking model and streamlined leak audit techniques adapted from other industries to prioritise shafts for potential energy savings based on their demand reduction scope.

Firstly, a benchmarking technique was developed that prioritises mining shafts with the highest potential for compressed air demand reduction. This was done by comparing the compressed air demand and network size. This offered a more targeted approach compared to previous methods.

Next, mass balance calculations and step-testing were used to identify compressed wastages within the selected mining shaft. Simple mass balance calculations were done by using a portable flow meter to determine the difference between the compressor supply flow and the flow to the active mining areas. The difference represents the wastage in the system. Furthermore, step-testing was done during periods when fewer personnel and equipment were in operation, focusing on wastages outside the normal operating periods. This involved closing valves progressively throughout the system while installing portable pressure- and flow loggers to detect changes in pressure and flow, and in doing so, identify areas with high demand. Audits were conducted in problematic areas to identify, report and mitigate wastages.

Three of the five evaluation criteria were met. Localised detection was achieved in deep-level mine working areas by performing step tests and audits. Identified compressed air wastages were mitigated to achieve cost benefits. However, it was stated that focus was only placed on large leaks, neglecting development- and stoping areas and smaller leaks which, when added up, can have a significant impact. Zietsman further recommended that the installation of additional flow meters closer to working areas will allow the automation of leak detection, but is difficult due to the capital costs.

Study 6: Cloete *et al.* – Reducing compressed air wastage by installing new technology in underground mines, 2013 [25]

This paper focused on the development of an intelligent mechanical valve to reduce the compressed air consumption in a deep-level mine. It should be noted that the valve was never implemented, and all results presented were theoretically calculated as the valve was still being manufactured.

The idea was to connect the valve at the inlet of the working areas, where it would automatically close if a flow increase is observed. The benefit of the valve would be to reduce compressed air wastage in the working areas by reducing the allowable compressed air flow to that of the drilling equipment.

Leak detection in a deep-level mine's compressed air system was done by performing underground audits. This revealed that most inefficiencies occur in the operational working

areas. It was determined that installing the proposed valve would achieve a monthly benefit of R1.5 million; however, no actual cost savings were achieved.

This paper thus satisfied only two of the evaluation criteria. The method was applied to a deep-level mine and enabled localised detection through audits. The study did not use ZWBs for detection and was not done on a water system.

Study 7: Van Rensburg *et al.* – Energy efficiency via optimisation of water reticulation in deep mines, 2011 [65]

This paper implemented three water reduction techniques on a deep-level mine. They were leak management, stope isolation and supply water pressure control.

Firstly, leak management was done. Here, personnel were tasked to complete visual inspections of water columns throughout the mine. Leak reports were distributed to the person responsible for the section in which it was identified, with regular feedback requested regarding the repair status of identified issues.

Next, XC isolation valves were installed that were controlled via the centralised blasting system. In addition, pressure transmitters and flow meters were installed on each mining level as part of continuous monitoring.

Finally, pressure setpoint control was implemented on the existing water control valves located on the upper production levels. Here, the main valve closes with the bypass valve controlling the water flow according to the pressure setpoint.

Of the three methods implemented, leak management delivered the most promising results, showcasing the benefits of reducing leaks.

The study met four of the evaluation criteria. Localised detection of water inefficiencies in deep-level mine working areas was done through audits. Issues were mitigated to achieve a cost benefit by reporting it to management. The study did not use ZWBs to detect inefficiencies.

Study 8: Sun *et al.* – Leak Localization in Water Distribution Networks Using Pressure and Data-Driven Classifier Approach, 2019 [66]

This paper introduced a novel method for localising leaks in water distribution networks using a data-driven approach based on pressure measurements. The method consists of two stages:

1. Machine Learning Classification – Two different classifiers, linear discriminant analysis (LDA) and neural networks (NNET), were developed to estimate the probability of a leak occurring at each node within the water distribution network.
2. Bayesian Temporal Reasoning – This technique is applied to refine and update the probability estimates over time, enhancing the accuracy of leak localisation after detection.

The approach was tested on the hypothetical district metered area (DMA) benchmark, evaluating performance using fitting accuracy and average topological distance (ATD). A reservoir served as the inlet node for the DMA. During the simulation phase, it was assumed that every node in the network has a sensor, disregarding the actual sensor placements within the real network which may affect the results obtained. This assumption ensured comprehensive data generation for all nodes, allowing for an idealised analysis of the leak localisation method.

Firstly, a simulation was done using EPANET 2. This was used to simulate each leak scenario. A zero-waste approach was used as a reference (no leaks). Leaks were detected by identifying the node with the biggest difference between the reference model and the real-time model.

This paper satisfied three of the evaluation criteria. The method enables localised detection on a water distribution system. A zero-waste approach was used to identify wastage by comparison to a real-time model. The study did not implement the method on a deep-level mine and did not obtain a cost-benefit through the mitigation of identified issues.

Study 9: Datta *et al.* – Sensitivity analysis of water wastage in Indian households, 2023 [67]

This study identified and quantified key sources of household water wastage, with the main goal of mitigating them. Four main sources of water wastage were identified, which were:

- Leaking tap;
- Leaving the tap running while washing hands/ brushing teeth;
- Toilet flushing; and
- Water purifiers.

Furthermore, five main factors affecting water wastage were identified which included:

- Climate/season change;

- Time of the day;
- Number of people in the household;
- Economic conditions of household; and
- Pandemic lockdown.

Data collection was obtained through surveys conducted with 10 000 people. Survey questions were aimed at the above-mentioned sources and factors. From the results obtained, it was found that 45 l of water is wasted per capita per day.

The study met two of the five evaluation criteria. Household water wastage was identified and localised at the end users through means of surveys. The paper did not focus on the implementation of deep-level mines and detection was not done through ZWBs. Also, no cost benefits were achieved through the mitigation of issues.

Study 10: Gupta and Kulat – Leakage reduction in water distribution system using efficient pressure management techniques. Case study: Nagpur, India, 2018 [68]

This study focused on water wastage reduction in a water distribution system (WDS), emphasising the relationship between water wastage and operating pressures. Pressure management techniques that combine variable speed pumps and pressure-reducing valves (PRVs) to minimise wastage were introduced.

The EPANET simulation software was used to simulate the WDS to obtain hydraulic parameters. Next, pressure-driven demand equations were used to calculate the actual demand required. The recalculated demand was used as inputs to the simulation to obtain and store newly calculated hydraulic parameters. Wastage identification was done by using pressure-based leakage equations that determine the leakage at a certain node over the length of a pipe.

Variable speed pumps were used to adjust the pressure dynamically, based on the water demand. During periods of high demand, the pump speeds up to meet the requirements, while during low demand, the speed is reduced to decrease excess pressure, subsequently reducing leakage rates.

In addition to variable speed pumps, PRVs were installed for further pressure reduction. A modified reference pressure algorithm was proposed for optimal valve placement, improving existing algorithms that previously failed to identify suitable locations for PRVs. This allowed the optimisation of PRV control values, focusing on adapting to varying demand patterns and

minimising water wastage. This modified algorithm successfully identified two effective valve locations, enhancing the efficiency of the pressure management system.

The implementation of this pressure management technique resulted in a leakage reduction of 16.57% to 26.30%, translating to an average daily savings of 5.066 million litres for the WDS.

The study met three of the evaluation criteria. The study was conducted on a water system which allowed for localised detection at consumers/node points. Identified issues had been mitigated to achieve water savings which directly correlates to cost benefits. The study was not implemented on a deep-level mine and ZWBs were not used as a detection method.

Study 11: Cilliers – Benchmarking electricity use of deep-level mines, 2016 [69]

Cilliers developed benchmarking models aimed at evaluating energy efficiency in high-demand mining systems. New models for average and best practice benchmarking were constructed by using actual data obtained from mining operations. High energy demand systems such as compressed air, cooling, dewatering, ventilation and hoisting were considered.

The author first applied dual variable regression analysis, a statistical method used to examine the relationship between two variables, typically one independent and one dependent, to validate correlations between system energy consumption and selected variables, followed by creating system-specific functions for benchmarking based on these correlations. An overall model was also developed to account for multiple systems, introducing a scoring method that enables efficiency comparisons against industry averages. Furthermore, frontier benchmarking methods were used to establish best practice benchmarks, offering a comprehensive framework for individual and combined high-demand systems.

Using benchmarking scores, the author ranked high-demand systems based on efficiency, helping mining operations prioritise where energy-saving initiatives would be most effective. This assisted with the identification of compressed air and water leaks.

Furthermore, a new method for forecasting operational energy budgets, which showed improved budget accuracy, was introduced, with case studies revealing dynamic adjustments that aligned monthly targets based on performance.

The study met two of the five evaluation criteria. A novel benchmarking model was developed for all high energy-consuming systems, including water systems, on a deep-level gold mine. Through this, inefficient systems were identified to be selected for energy initiative

implementation. However, no actual saving was obtained through the mitigation of identified issues. Furthermore, the study did not focus on localised detection in working areas and did not include the use of ZWBs.

Study 12: Jiménez-Cabas *et al.* – Localization of Leaks in Water Distribution Networks Using Flow Readings, 2018 [70]

The use of pressure sensors to detect leaks in water networks is favourable due to the low cost, fast detection and operation. The method proposed in this study was designed to be used in conjunction with pressure meters, mainly when they are damaged or uncalibrated or to include different diagnostics made with other approaches.

This study utilised hydraulic modelling and flow sensor data to detect and locate leaks in water distribution networks. The method models a water distribution system using equations for each pipeline section. These equations cannot be solved directly, so the pipeline is divided into smaller sections, and the equations are solved step by step using flow measurements at the pipeline junctions.

If there are no leaks, the flow in each section of a pipeline stays the same. If there is a leak, the flow changes in the sections near the leak. By comparing the actual flow to the expected flow, the method identifies where the leak is because the difference (called a residual) will be smallest at the leaking section.

Dividing the pipeline into smaller sections enhances the accuracy of leak detection and localisation thereof. This approach successfully identified leaks by pinpointing abnormal flow patterns, improving system efficiency. It highlighted the importance of accurate flow sensors and real-time data processing to detect and address leaks.

This paper met two of the five criteria as localised leak detection was done on a water system. However, this was not done on a mining operation, and no mitigation of identified leaks was done. Furthermore, ZWBs were not used as a detection method.

Study 13: Verde *et al.* – Practical Issues of Leak Diagnosis in Pipelines, 2011 [71]

The study focused on addressing the challenges associated with detecting and diagnosing leaks in pipelines. The aim was to improve the design and implementation of leak detection systems while adhering to the standards of the American petroleum industry.

A pilot study was conducted which consisted of a 132 m long and 10.4 cm diameter pipeline. This pipeline was equipped with flow and pressure meters to monitor the behaviour during different scenarios. Three approaches were considered:

1. Model-based detection (using mathematical models to predict leaks),
2. Identification-based detection (using system behaviour to identify anomalies), and
3. Data-driven detection (using historical and real-time data for analysis).

The study highlighted several challenges experienced with pipeline leak detection, which included sensor limitations in accuracy and bandwidth, model discrepancies due to real-life conditions and misalignments between the model assumptions and actual boundary conditions which can lead to diagnostic errors.

Emphasis was placed on the need to address practical issues such as measurement noise, sensor placement and the dynamics of the fluid flow.

The study demonstrated that each method had advantages and limitations depending on pipeline characteristics and data accuracy. The methods effectively identified leaks, but adjustments like adaptive thresholds were suggested to reduce false alarms and improve reliability.

The findings are applicable across various industries such as petroleum, water distribution, and chemical processing, stressing the need for improvements in both hardware and software to develop reliable leak detection systems.

The study met two of the five evaluation criteria. The method was implemented on a water system and enabled localised inefficiency detection as identification was done over several nodes of a network. This was relatively easy considering the small scale of the network. The study did not implement the solution on a deep-level mine where the scale of the network is significantly more complex and dynamic. Furthermore, no cost benefit was achieved through mitigation of issues and ZWBs were not used as a detection method.

Study 14: Le Roux – Identifying water wastage in deep-level mines using novel simulation-based zero-waste baselines, 2024 [15]

Le Roux developed a simulation-based method that successfully identified and quantified service water wastages in a deep-level mine. The study applied four main wastage identification techniques, concluding that ZWBs are the best method as they can identify the true extent of wastage.

The study considered six previous papers that focused on ZWBs and addressed the shortcomings of previous studies (application to deep-level mine water systems for wastage quantification). Le Roux developed a simulation-based ZWB.

Water flow equations were derived for each mining shift. They include:

- Baseload flow – Consistent flow throughout the day for cooling infrastructure;
- Drilling flow - Calculates the minimum water required to drill the planned number of holes for each activity in the working area. The equation adjusts the water consumption based on each area's performance. Firstly, the equation calculates the water flow rate needed to complete the planned drilling within the shift. Secondly, a production factor is determined by comparing actual/planned ore tonnes with expected tonnes as per mining and drilling standards. These components are combined to scale water demand relative to performance, creating a ZWB prediction for each area; and
- Cleaning flow – Calculates the minimum water required to clean a panel. Firstly, a time-based factor is determined by using the ratio of the expected time to clean a panel and the time of the cleaning shift. This is multiplied by the flow rate of all cleaning equipment and a production factor.

Le Roux developed ZWBs for the water consumption in each working area of a deep-level mine using specified equipment flow rates and conducting tests on in-house manufactured equipment to determine their water flow. These baselines were used as inputs for a simulation model to determine the optimal theoretical water consumption, satisfying three of the evaluation criteria. However, inefficiency detection was only possible at the mining level, as flow meters were installed per level to compare theoretical and actual consumption. Therefore, localised detection within working areas was not possible. Additionally, the study did not focus on mitigating identified inefficiencies to achieve cost benefits.

Study 15: Ozevin and Harding – Novel Leak Localization in Pressurized Pipeline Networks Using Acoustic Emission and Geometric Connectivity, 2012 [72]

Leaks in pressurised pipelines cause turbulent flow at the leak location which generates propagating elastic waves. Therefore, an acoustic emission technique, combined with geometric connectivity to detect and locate leaks, was introduced and tested on a laboratory-scale air system. Acoustic emission sensors were installed over a pipeline to capture sound waves caused by the turbulence caused by leaks, with arrival time differences calculated by cross-correlation functions to determine leak locations. This method enables real-time localised leak detection.

The study successfully identified and localised leaks in a simulated environment. The developed method demonstrated the potential for real-time leak detection in a pressurised system. However, certain adjustments for material attenuation and wave frequency were needed to ensure the effectiveness of the method for various pipeline types.

The study only met one of the five evaluation criteria which was localised leak detection. This was only possible due to the small size of the application where detection was done at each leak location. Even though the paper mentions that the method can be implemented on all pressurised networks such as water, it was only tested on an air system.

Study 16: Bredenkamp et al. – Reconfiguring mining compressed air networks for cost savings, 2014 [73]

This study focused on the reconfiguration of a deep-level mine surface compressed air system to achieve energy cost savings. This was achieved by interconnecting a pipeline between two shafts to distribute air more effectively together with the automated control of an isolation valve.

Firstly, network inefficiencies had to be identified to determine the feasibility and success of the proposed reconfiguration. The minimum and maximum demand of each compressed air user was used to estimate a theoretical baseline. The baseline was constructed using fixed mining shifts. The actual compressed air profile was compared to the theoretical baseline to determine compressed air wastage and shortfalls. The reconfiguration resulted in energy cost savings of R8.1-million by reducing the number of operational compressors.

Bredenkamp's work met three of the evaluation criteria. The dissertation used ZWBs to identify compressed air inefficiencies in a deep-level mine. The system was reconfigured to achieve a power saving correlating to cost savings. Furthermore, compressed air leaks were fixed to achieve an additional power reduction. However, the study did not implement the method on a water system and did not enable localised detection in the mine's working areas.

Study 17: Adedeji et al. – Leakage Detection and Estimation Algorithm for Loss Reduction in Water Piping Networks, 2017 [74]

This study focused on detecting and estimating background leakage, which occurs through small cracks or deteriorated joints. Unlike burst-type leaks that cause sudden pressure drops, background leaks produce diffuse flow, making them harder to detect with standard instruments.

The proposed algorithm integrates a leakage model into a classical water distribution network hydraulic model to estimate network leakage flows. It was tested on two different water networks, demonstrating its ability to:

- Identify critical network segments or pipes with higher leakage outflows; and
- Indicate probable locations for pressure control interventions.

While the algorithm effectively assesses the state of water networks, further work is needed to pinpoint exact leak locations on pipes and determine optimal placements for pressure control elements.

This paper successfully met two of the five evaluation criteria. Localised detection was done on a water distribution system by identifying critical nodes on the network. The study did not implement the method on a deep-level mine and no cost benefit was obtained by the mitigation of issues. Furthermore, ZWBs were not used.

Study 18: Marais – A zero-wastage approach to benchmark energy efficiency on platinum mines, 2023 [58]

Marais introduced a novel zero-wastage benchmark approach to improve energy efficiency in deep-level mines. Firstly, intensity benchmarking was done on the selected case study to determine the largest energy consumer within the mine. The case studies included compressed air- and water systems. Next, theoretical ZWBs and simulation software were used to identify inefficient operation and energy efficiency potential within the identified system.

Theoretical approach: The theoretical ZWB for each mining level was determined by using the rated consumption of each compressed air/water user and assigning it to a specific, fixed mining shift. Through this, a theoretical zero-waste baseload profile was obtained and compared to the actual consumption. The difference between the two indicates inefficient operation. Next, a scaling factor was determined to obtain an achievable target for the mining operation.

Simulation approach: Simulation software was used to construct a digital twin of the mining operation. After verification of the simulation model, the zero-waste baseload was simulated and compared to the actual consumption, with differences indicating wastage. Again, an achievable target was calculated for the operation.

The thesis compared the proposed solution to other existing methods including historic baselines and valve control. It was concluded that the zero-waste benchmarking approach is a more accurate method to identify compressed air wastages.

The thesis met three of the five evaluation criteria. The method was successfully implemented on a deep-level mine water system and used ZWBs to identify inefficiencies. However, localised detection was not possible as identification was only done per production level. Furthermore, no cost benefits have been achieved through mitigation of inefficiencies.

Study 19: Perez *et al.* – Leak Localization in Water Networks: A Model-Based Methodology Using Pressure Sensors Applied to a Real Network in Barcelona [Applications of Control], 2014 [75]

The study focused on the efficient distribution of water in water distribution networks, emphasising the detection and localisation of leaks that can lead to significant economic losses, infrastructure damage, and environmental concerns.

The research introduced a model-based leak localisation methodology that utilises pressure sensors combined with node pressure sensitivity analysis to detect and isolate leaks in DMAs. This approach compares real-time sensor measurements against predictions from a well-calibrated hydraulic model to analyse residual differences to identify potential leaks. The study was applied to an actual water distribution network in Barcelona, demonstrating its effectiveness in detecting and localising leaks with reasonable accuracy.

Key findings highlight the importance of sensor placement, model calibration, and uncertainty management in improving leak detection reliability. The methodology, integrated into a decision-support software tool, provides an efficient approach for utilities to manage water losses in real time.

This paper satisfied two of the evaluation criteria. The method was applied on a water system and enabled localised detection using pressure sensors and data analyses. The study did not implement this on a deep-level mine and did not achieve any cost benefits through the mitigation of issues. Furthermore, ZWBs were not used in this study to identify leaks.

Study 20: Ullah *et al.* – Pipeline Leak Detection System for a Smart City: Leveraging Acoustic Emissions Sensing and Sequential Deep Learning, 2024 [76]

The study introduces a novel pipeline leakage detection approach that combines acoustic emission signalling technology with time-series deep learning. Traditional leak detection methods often require direct contact or visual inspection, whereas the proposed method

enables real-time, non-intrusive detection for safer and more efficient pipeline monitoring, particularly in smart city applications. Here, acoustic emission sensors are installed on a pipeline to gather data. The data are sorted, and deep learning models are applied to classify leaks.

Key aspects of the approach include:

- Acoustic emission-based framework: Utilises acoustic emission signals to detect leaks based on subtle signal state changes;
- Deep learning models: Implement sequential models such as long short-term memory, bi-directional long short-term memory, and gated recurrent units to classify leaks into minor seepage, moderate leakage, and major ruptures;
- Sensor deployment: Three acoustic emission sensors are installed in different configurations on a pipeline to collect data; and
- Performance evaluation: The models are tested using different performance measures to see how well they detect leaks. Among them, bi-directional long short-term memory performed the best, correctly identifying leaks 99.78% of the time under different settings.

This research advanced pipeline integrity monitoring by enhancing accuracy and reliability in detecting leaks, contributing to more efficient pipeline management in liquid and gas transportation systems.

This paper met two of the evaluation criteria. First, localised water leak detection was done by the installation of acoustic emission sensors. However, it should be noted that the method was only tested on a small scale. The study did not implement the method on a deep-level mine or real-world basis and thus did not achieve any cost benefits through mitigation of issues. This raises questions about whether the results obtained on smaller systems would remain consistent if implemented in a deep-level mine. ZWBs were also not used in this paper.

Study 21: Doyle and Cosgrove – An approach to optimising compressed air systems in production operations, 2016 [77]

In this paper, Doyle and Cosgrove explore a low-cost, non-intrusive method to quantify energy losses due to leaks in compressed air systems across five industrial sites. Energy monitoring was conducted using data loggers to compare electricity consumption during production and non-production periods, allowing the estimation of energy wasted due to leaks.

During production, energy usage supports production activities, while during non-production, the compressor continues running, and its energy usage can be monitored to determine the energy required to fill and maintain the pressure in the reservoir due to leaks in the compressed air distribution system. By comparing the energy consumed during production and non-production periods, the percentage of energy used to compensate for leaks can be identified.

For a case study conducted, leaks were identified using the method described above. In addition, walk-through audits of production areas were conducted to identify compressed air tools using compressed air when not in use.

The study met only one criterion which was to incorporate localised detection. This was done through walk-through audits performed to detect wastage at end users.

Study 22: Sharma *et al.* – Compressed air monitoring system for textile industry, 2019
[78]

Sharma *et al.* developed a compressed air monitoring system to improve energy consumption in the textile industry. The system aims to identify inefficiencies caused by leakages, to assess the real-time compressor performance and to develop a method to proactively assess compressed air losses.

The NITRA compressed air monitoring software was used to centrally monitor the performance of the compressors and the overall compressed air system throughout the day. The monitoring system uses industrial-grade Wi-Fi protocol where each measurement unit is equipped with several sensors that send the measured data to a central server.

The monitoring system uses the measured data to determine the compressed air demands and suggests the compressor configuration to be used to achieve energy efficiency. This tool enables the identification of losses due to leakages and poor efficiency of the compressors. It also quantifies losses and monitors the system's performance. Energy performance measures such as kilowatts per cubic foot per minute (kW/CFM) are used to determine the efficiency of the compressors.

Only one of the evaluation criteria was met by this paper. Localised detection was done by installing pressure, flow and temperature sensors on different sections of a plant and using the NITRA monitoring software to identify inefficient end users.

Study 23: Saidur *et al.* – A review on compressed-air energy use and energy savings, 2010
[50]

Saidur *et al.* provided a comprehensive review of compressed air energy consumption, energy efficiency and energy savings strategies. This includes computer tools used for compressed air analysis, strategies such as efficient motors, variable speed drives (VSDs), leak prevention, outside air consumption, decreasing pressure drop, heat recovery, efficient nozzles and variable displacement compressors.

Research found that, when using an electrical motor, significant energy savings are achievable when using efficient motors and VSDs. Other strategies have also been investigated. Energy audits were found to be an effective tool to identify energy waste and assist with the implementation of necessary measures. Furthermore, it was found that repairing leaks has the most energy savings potential of 30% or more. Hence, focus should be placed on fixing leaks as this is a simple procedure to realise the largest amount of savings. Compressed air leaks account for 20-30% of a plant's compressed air demand. This impacts the system using pressure losses and reduced equipment efficiencies. In addition, research highlighted that awareness and education play an important part in energy savings.

Saidur *et al.* met only one evaluation criterion. Localised detection was enabled through detailed energy audits. Several mitigation strategies were mentioned, but no cost benefits were achieved in this paper.

Study 24: Friedenstein *et al.* – Simulating operational improvements on mine compressed air systems, 2018 [79]

The work conducted by Friedenstein *et al.* focused on the development of a compressed air simulation model on a deep-level mine to investigate energy and operational improvement strategies.

Underground audits were conducted, which reviewed that refuge bays consumed a significant amount of compressed air. A test on the case study was conducted to close refuge bays to determine the impacts; however, not all could be closed due to the complexity of the operation. Therefore, the benefits of throttling the compressed air to refuge bays could not be quantified for the entire operation. A simulation model was developed to simulate the impacts on the entire mine to quantify the energy benefits of the project.

The simulation model successfully quantified the benefits of throttling the compressed air to refuge bays. This showed a potential energy savings benefit of R6.3 million per annum and increased the pressure on working sections.

This paper successfully satisfied two of the evaluation criteria. The study was implemented on a deep-level mine's compressed air system where localised leak detection was done by audits. No cost benefits have been achieved through the actual implementation of mitigation techniques.

Study 25: Joseph *et al.* – Development of an intelligent urban water network system, 2022 [55]

This paper explored how urban water systems can be improved by using "smart" technologies to create intelligent water networks (IWNs). Traditional water systems, which have been in place for over a century, struggle with problems like leaking pipes, water wastage, and ageing infrastructure. These challenges are made worse by growing populations, climate change, and increased demand for water. Furthermore, traditional systems have challenges in quantifying losses and pinpointing the location of the leaks. They also included a time delay to respond to the issues. Focus is thus placed on the identify-localise-pinpoint strategy.

The authors proposed using advanced technologies such as smart sensors, artificial intelligence (AI), and real-time monitoring systems to detect and mitigate issues like leaks and bursts quickly. This was done by pressure fluctuations, measuring water flow rates across different sections of a pipeline to detect changes in flow and AI to determine water patterns. These systems can collect and analyse data to predict issues before they happen, improve water quality, reduce costs, and ensure better service for communities.

The paper also introduced a framework for designing these intelligent networks, which includes tools like geographic information systems for mapping, smart meters for tracking water use, and Supervisory Control and Data Acquisition (SCADA) systems for monitoring. By integrating these tools, water utilities can save water, reduce costs, and improve their ability to manage water resources sustainably. Leak reduction can be achieved through pressure management and proactive maintenance and repairs. By rapidly identifying leaks compared to traditional methods and pinpointing their location, repairs can be addressed more quickly and efficiently.

The paper highlights how modern technology can make water systems more efficient, reliable, and prepared for future challenges.

The study met two of the evaluation criteria. The method was implemented on an urban water system. Artificial neural networks were used to determine the precise location (localised detection) of leaks through pressure fluctuations. The paper did not implement the proposed

method on a deep-level mine and did not incorporate ZWBs. Furthermore, no cost-benefit was achieved through the mitigation of identified leaks.

Study 26: Herman *et al.* – Using big data for insights into sustainable energy consumption in industrial and mining sectors, 2018 [80]

This study explored how big data can be used to make energy use more efficient in the industrial and mining sectors, which are some of the biggest energy consumers in the world. These industries often rely on fossil fuels, which contribute heavily to greenhouse gas emissions. While these sectors generate a lot of data, they have not been making full use of it to improve energy efficiency or reduce waste.

The researchers developed a new system that uses big data to track and analyse energy usage in industrial and mining operations. The system was designed to be flexible and adaptable, using tools like microservices and containers to process large amounts of data. The system was tested on seven case studies through a company that works with industrial and mining clients. It helped identify areas where energy was being wasted, such as air leaks in mining equipment, inefficient gas use in steel plants, and unnecessary power use in cement factories.

One case study was done on a deep-level mine's compressed air system. Sensors installed along the network measured volumetric airflow rates at multiple locations. This data was collected and processed by the big data system to compare the amount of air being supplied to the system with the amount being used. The difference between these two values indicated air losses due to leaks.

To mitigate the leaks, the identified areas of the network were inspected, and repairs were made to the pipes and equipment responsible for the losses. As a result, the operation reduced its compressed air wastage by 57.8%, which significantly improved energy efficiency and reduced associated costs. The average energy saved per month was calculated at 4 222 MWh.

The study focused on providing insights to employees at all levels of a company, from workers on the ground to senior managers. By delivering the right information to the right people, the system helped companies take steps to fix problems and reduce energy waste. Through seven case studies, the researchers showed that this approach can save large amounts of energy, cut down on carbon emissions, and conserve water. The study demonstrated how big data

can play an important role in helping industries use energy more sustainably and reduce their environmental impact.

This study met three of the evaluation criteria. Localised detection was done on a deep-level mine's compressed air system via inspections/audits. Identified compressed air leaks were mitigated to achieve cost benefits. The study did not use ZWBs and was not implemented on a water system.

Study 27: Snyman – Integrating various energy saving initiatives on compressed air systems of typical South African gold mines, 2011 [81]

Snyman focused on compressed air initiatives in a deep-level mine to reduce the electrical demand. The study combined several existing methods to reduce the compressed air requirements. Equipment specification sheets, mining schedules and meetings with site personnel were used to establish the theoretical requirements of the compressed air demand. A minimum and maximum requirement was established and compared to the operation's actual compressed air consumption. This identified that several inefficiencies were present within the system. A compressed air leak documentation system was developed where leaks were noted to be fixed. Leaks were found on the surface and underground through visual inspection.

The study implemented the following methods to reduce the wastage:

- Compressed air control valves were used on each mining level to regulate the flow. Flow meters were used to monitor the consumption;
- A system was developed where identified wastages are displayed, raising awareness; and
- The compressed air system was reconfigured for optimised control.

Of the five criteria, four were met by this study. The study was implemented on a deep-level mine's compressed air system. A zero-waste approach was followed to determine the pressure requirements of the shaft. Localised detection was done through visual inspections/audits. Identified issues were rectified to obtain a cost benefit. The study did not implement the proposed solution on a water system.

Study 28: Boyle *et al.* – Intelligent Metering for Urban Water: A Review, 2013 [82]

This paper examines the development and use of smart water meters in urban networks, focusing on their ability to detect leaks, reduce water wastage, and improve water

management for both utilities and customers. Smart meters collect real-time data, helping to monitor and manage water usage. By identifying unusual water consumption patterns, such as constant water use when no one is home, leaks can be detected immediately when they occur. In Sydney, smart meters identified leaks in 80% of households, where leaks accounted for up to 17% of water use. They also flagged high-use buildings, such as schools, as major sources of leakage. Additionally, smart meters help manage water pressure to prevent leaks.

Smart meters send alerts to utilities and customers when leaks are detected, enabling quick repairs before significant damage occurs. They also provide detailed water usage data via apps or displays, empowering customers to identify and address unusual consumption. Utilities can use this data to focus repairs on high-leak areas to save costs.

However, adopting smart meters comes with challenges, including high installation costs, technical issues like poor signal coverage, and customer resistance due to a limited understanding of the benefits. Utilities must address these concerns, including costs, and build customer trust.

The study concluded that smart meters are a valuable tool for reducing water waste and improving urban water management. To ensure wider adoption, future efforts should focus on making the technology more affordable and educating customers on its benefits.

Two of the five criteria were met by this study. The method was implemented on a water system where localised detection was done by using smart metering to detect leaks in households (end user in this study). The study did not implement this method on a deep-level mine and did not use ZWBs to detect water leaks. Furthermore, identified issues were not mitigated to obtain a cost benefit.

Study 29: Mosetlhe et al. – Appraising the Impact of Pressure Control on Leakage Flow in Water Distribution Networks, 2021 [83]

This paper addresses the issue of water loss caused by leaks in urban water distribution systems, which is a major problem in ageing infrastructure worldwide. Leaks are often triggered by excessive pressure in pipelines. The goal of this study was to reduce water leaks by controlling the pressure in the system. The authors focused on identifying “critical nodes” or weak points in the network where pressure changes the most under varying water demand. These nodes/points are prone to leaks.

To address the water leaks, an analysis was conducted on how water leaks from the pipeline by modelling the relationship between the water pressure and pipeline conditions. This

information was used to quantify the leak. PRVs were introduced to reduce the pressure in specific areas of the system, which in turn reduced water leaks. The study used reinforcement learning, a type of artificial intelligence, to optimise the PRVs. Unlike traditional methods that rely on pre-built models of the system, reinforcement learning adapts in real-time, learning from the system's behaviour and adjusting PRV settings to achieve the best results. This dynamic approach allows for more effective pressure management and reduces reliance on prior knowledge about the system.

The results showed that the method effectively reduces leaks, with the greatest benefits seen near the valves, but with improvements also extending to more distant areas. By controlling pressure more evenly across the network, water leaks were minimised, achieving cost savings.

The study satisfied three of the five criteria. The method was implemented on a water system where localised detection was done using the greedy algorithm to identify critical nodes over a network. The method was not implemented on a deep-level mine and ZWBs were not used. The paper mentions that leaks were reduced, which directly correlates to cost benefits, but no reference was made to this.

Study 30: Bredenkamp – An integrated energy management strategy for the deep-level gold mining industry, 2016 [49]

Bredenkamp developed an integrated energy management strategy (IEMS) for a deep-level mine. This strategy provides a framework enabling mining operations to implement effective energy management practices aimed at reducing electricity consumption. It aligns with the ISO 50001 energy management standards, ensuring continuous improvement of the projects carried out under the strategy.

The developed strategy was implemented in a South African mining group following the plan-do-check-act steps. This entailed the following:

Plan: Firstly, benchmarking was used to select the mining shaft (from the mining group) with the most potential for IEMS integration. Mineshaft B was selected. Team members were divided to be responsible for different areas of concern, making it more manageable. Next, the accuracy of power metering installed on different systems was verified. Lastly, improvements were selected based on calculated electrical intensities of the different systems on the shaft. A baseline document for power consumption on the mining shaft was also established to

measure the improvements against. An action plan was developed to achieve targets and deliverables.

Do: A system analysis was conducted to understand the system and how certain systems interacted with each other. Next, checklists were used to audit systems and identify any constraints that may affect the implementation of the IEMS. Thereafter, the historical data were analysed to determine the potential for energy improvements. These included mitigation techniques such as fixing leaks, reducing pressures, switching off redundant equipment, fan clipping, water flow control etc. Leaks, in particular, were identified by performing underground audits. Emphasis was placed on continuous leak detection and mitigation.

Check: This phase was included to determine the benefits of the implemented projects. This also included reporting structures to create awareness regarding the performance of the projects. Reports were distributed to top management personnel to ensure that objectives were achieved and that nonconformities were addressed.

Act: Here, progress meetings were incorporated to discuss the performance of the projects. In addition, action plans were used to address any issues and team members were evaluated against the outcomes of the action lists. This ensured effective IEMS implementation. The improvements achieved in 2015 became the new baseline for 2016 ensuring that the benefits are continuous.

The implementation of the IEMS of Mineshaft B resulted in an 18.5% electrical energy cost reduction for a 12-month period (approximately R75 million). The study met all five criteria as set out.

Bredenkamp's thesis satisfied four of the five evaluation criteria. The method did not use ZWBs to detect inefficiencies. Localised detection was done through underground audits.

1.3.2 Research summary and comparison

A state-of-the-art matrix as seen in Table 2 summarises the research conducted. The matrix was used to highlight which of the evaluation criteria was met by each study considered.

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Table 2: State-of-the-art summary on water inefficiencies.

Study number	Reference number	Year	Deep-level mine	Water system	Localised inefficiency detection	Zero-waste approach	Cost-benefit through mitigation	Localisation method
Study 1	[17]	2022	Yes	No	No	Yes	No	None
Study 2	[63]	2022	Yes	No	Yes	Yes	No	Audits
Study 3	[64]	2017	No	No	Yes	No	No	Machine learning outlier factor and AEN
Study 4	[2]	2019	Yes	No	Yes	No	Yes	Audits
Study 5	[16]	2020	Yes	No	Yes	No	Yes	Audits and step-testing
Study 6	[25]	2013	Yes	No	Yes	No	No	Audits
Study 7	[65]	2011	Yes	Yes	Yes	No	Yes	Audits
Study 8	[66]	2019	No	Yes	Yes	Yes	No	Additional metering and data-driven approach
Study 9	[67]	2023	No	Yes	Yes	No	No	Surveys
Study 10	[68]	2018	No	Yes	Yes	No	Yes	Additional metering and pressure-based leakage equations - dividing into smaller sections
Study 11	[69]	2016	Yes	Yes	No	No	No	None
Study 12	[70]	2018	No	Yes	Yes	No	No	Additional metering and hydraulic modelling - dividing into smaller sections

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Study 13	[71]	2011	No	Yes	Yes	No	No	Flow and pressure sensors for model-based observer and data-driven approach
Study 14	[15]	2024	Yes	Yes	No	Yes	No	None
Study 15	[72]	2012	No	No	Yes	No	No	Acoustic emission
Study 16	[73]	2014	Yes	No	No	Yes	Yes	None
Study 17	[74]	2017	No	Yes	Yes	No	No	Hydraulic modelling
Study 18	[58]	2023	Yes	Yes	No	Yes	No	None
Study 19	[75]	2014	No	Yes	Yes	No	No	Pressure sensors and data analysis
Study 20	[76]	2024	No	Yes	Yes	No	No	Acoustic emission sensors
Study 21	[77]	2016	No	No	Yes	No	No	Audits
Study 22	[78]	2019	No	No	Yes	No	No	NITRA software and additional measuring units
Study 23	[50]	2010	No	No	Yes	No	No	Energy audits
Study 24	[79]	2018	Yes	No	Yes	No	No	Audits
Study 25	[55]	2022	No	Yes	Yes	No	No	Artificial NNET
Study 26	[80]	2018	Yes	No	Yes	No	Yes	Audits

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Study 27	[81]	2011	Yes	No	Yes	Yes	Yes	Audits
Study 28	[82]	2013	No	Yes	Yes	No	No	Smart metering
Study 29	[83]	2021	No	Yes	Yes	No	Yes	Greedy algorithm
Study 30	[49]	2016	Yes	Yes	Yes	No	Yes	Audits

Table 2 shows the leading work done in inefficiency detection and mitigation in different sectors. Firstly, no study has met all five of the evaluation criteria. Moreover, the need to decrease operational costs on deep-level mining operations has been highlighted; however, of the 30 studies considered, only 30% (9) achieved an actual cost benefit through the implementation of mitigation techniques. Of these, only four focused on water systems. This indicates that inefficiency detection to reduce operational costs is often overlooked, despite the financial struggles faced by mining operations.

1.3.3 Research comparison discussion

This section explores the shortcomings and opportunities identified in the literature review and state-of-the-art research. The primary objective is to mitigate water wastage; however, before mitigation can occur, accurate identification is needed. The following discussion, based on the literature study, addresses these two key aspects.

Wastage identification

Focus was placed on localised inefficiency detection to address the issue of identification of inefficiencies in working areas where the majority occur. Localised detection can be classified into two categories from the studies considered in Table 2:

- Walk through audits; and
- Installation of additional metering to gather actual data for analysis.

Walk-through audits involve employees physically inspecting the entire network to identify inefficiencies. While they can pinpoint problem areas, they are both time consuming and resource intensive as they must be conducted across all levels. This is also easier to do on non-mining industries considering the size of the network to be inspected.

Moreover, results (detecting inefficiencies) are obtained only during audits, limiting their frequency and making continuous, automated detection impossible. Some studies have incorporated additional techniques to identify problem areas to decrease the size of the network to be audited. However, the fact remains that these methods are resource- and time intensive and are only able to provide results when the techniques are performed. This means that if a leak occurs in one of the working areas, the entire network will be influenced.

Due to the timely way identification is done, additional water needs to be supplied and dewatered to counter the negative impact on the network. This leads to additional fridge plants and dewatering pumps being started, and in doing so, increases the electricity bill. If the start-

up of additional equipment cannot counter the negative impact of the inefficiencies, gold production can be influenced and with it, the profits. This is not even considering the leaks already present within the system, which are divided between leaks due to deteriorated equipment and leaks due to malpractice.

The installation of additional metering equipment has proven to be an effective method to localise inefficiencies. Nevertheless, from Table 2, it is clear that this approach is favourable for non-mining industries. However, it has been found that leak auditing in deep-level mines can be automated by the installation of additional measuring equipment in the working areas [16]. Currently, deep-level mining operations generally only install metering equipment up to the half-level splits, which measures the consumption of several working areas together as depicted in Figure 6.

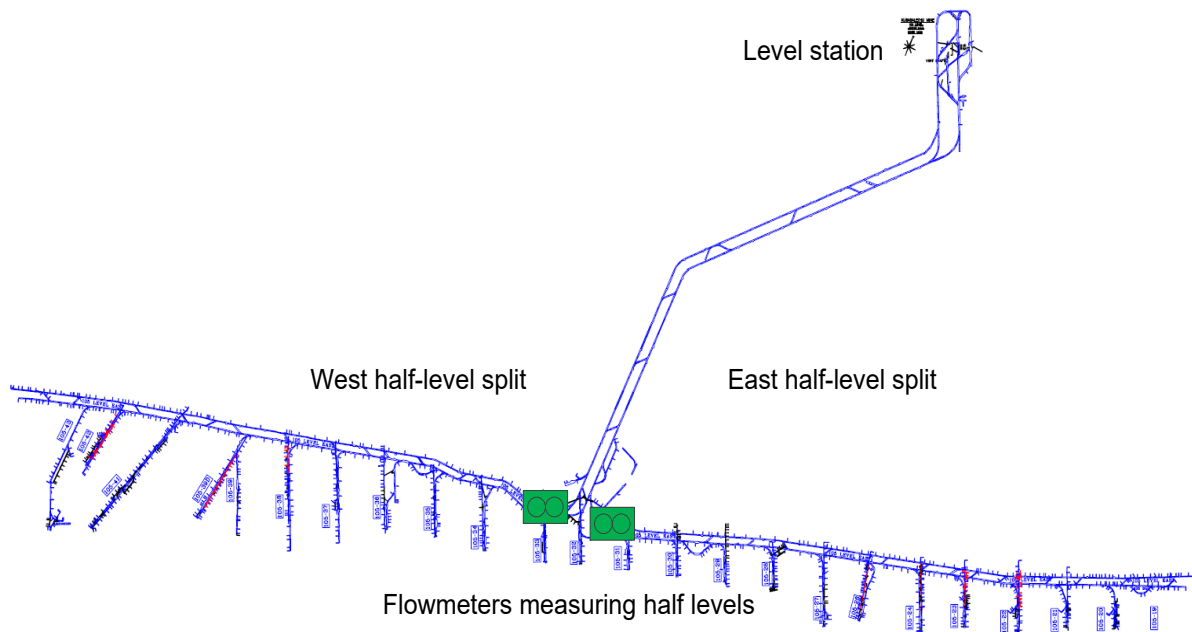


Figure 6: Mining level top view displaying flow meter locations.

The installation of additional measuring equipment in deep-level mine working areas faces several challenges. High capital costs of instrumentation are a significant barrier. Subsequently, the dynamic nature of mining operations means that the equipment will need to be relocated frequently [16]. A large capital investment in measuring equipment can be justified by the significant benefits it provides. Studies show that properly functioning instrumentation plays a crucial role in energy efficiency initiatives [49], [84]. On the other hand, a lack of instrumentation can result in energy efficiency projects never being implemented [2], [85]–[87].

A survey by Axora highlights why mining operations are hesitant to invest in digital solutions [88]. According to the survey, only 60% of mining budgets allocated for digital transformation are utilised. The remaining 40% remains unspent, largely due to a lack of understanding regarding the potential benefits of such investments. This underlines the importance of measuring equipment, as it can provide the data needed to identify and justify energy efficiency projects.

When data is available, it can be analysed to highlight areas for improvement and determine the necessity of specific projects, as noted for non-mining industries. However, instrumentation should only be installed when absolutely necessary [89].

Proper planning is critical before installing flow meters in working areas. For example, considering the area's life of mine (LOM) before installation can help address the issue of frequently relocating equipment. This ensures that investments in instrumentation are both effective and sustainable.

ZWBs have been identified as the most effective approach to identifying waste. However, current applications are limited to mining-level analyses and rely on static schedules and equipment manufacturer specifications, thus lacking a dynamic and accurate approach. This means that identification is only done per mining level, still requiring timely techniques to localise issues before mitigation can occur. Table 3 displays a summary of all the studies in Table 2 that used a zero-waste approach. These studies were evaluated to highlight the lack of a dynamic zero-waste approach, and in doing so, emphasise the shortcomings identified.

Table 3: State-of-the-art summary for a dynamic zero-waste approach.

Study number	Reference number	Year	Deep-level mine	Localised inefficiency detection	Zero-waste approach	Dynamic approach
Study 1	[17]	2022	Yes	No	Yes	No
Study 2	[63]	2022	Yes	Yes	Yes	No
Study 8	[66]	2019	No	Yes	Yes	No
Study 14	[15]	2024	Yes	No	Yes	No
Study 16	[73]	2014	Yes	No	Yes	No
Study 18	[58]	2023	Yes	No	Yes	No
Study 27	[81]	2011	Yes	Yes	Yes	No

Table 3 clearly shows that no dynamic approach is available when using a zero-waste approach. The limitations mentioned need to be addressed. Additionally, strategic investments in instrumentation, coupled with thorough planning, can help overcome current obstacles and enhance energy efficiency in mining operations.

Wastage mitigation

Once water leaks have been identified, they should be repaired promptly to avoid production losses and reduce electricity consumption. As mentioned, previous researchers have not placed a focus on obtaining actual cost savings through leak repair on water networks in deep-level mines. Moreover, emphasis is generally placed on compressed air systems. In many cases, mining operations prioritise supply-side initiatives, such as water isolation and pressure management to reduce the water to end users. However, these initiatives are only effective during non-operational times to avoid disrupting production.

Numerous authors have highlighted the significant benefits of fixing water leaks [2], [16], [49], [65], [68], [73], [80], [81], [83]; however, little focus is placed on this due to unclear roles and responsibilities. Fixing a leak once is not good enough and leak prevention should be implemented to ensure that leaks do not reoccur [78]. In practice, leaks are often addressed only when they disrupt production, with priority given to larger leaks, while smaller leaks, which collectively can have a significant impact, are neglected [2], [16]. Furthermore, Snyman [81] mentions that, even though this is a basic principle, it is rarely effectively implemented in mining operations. Typically, leaks are repaired by reporting them to top management who tasks employees to address issues [16], [49], [65]. However, there is no way for top management to confirm if the leak has been fixed other than by word of mouth or by performing timely identification/verification techniques [2], [16], [49], [65]. Additionally, mining and engineering teams rarely take responsibility for fixing or reporting leaks, as roles and responsibilities regarding leak fixing are unclear and their focus lies on reaching production targets [16], [49]. Fixing leaks and making sure they are fixed promptly as they recur will increase the sustainability of mining operations.

To ensure sustainability, a leak prevention method is essential. Research indicates that sustainability efforts are most effective when accountability is enforced [90]. For example, research showed that outcomes improve significantly when employees are held responsible [2], [16]. Currently, no research incorporates accountability mechanisms to ensure water leaks in deep-level mines are consistently repaired and monitored for sustainability.

A need exists for a method to continuously and accurately identify and localise water leaks within working areas of deep-level mines. After identification, personnel must be assigned to promptly address leaks and held accountable for their resolution. Sustainability monitoring of repaired leaks should occur closer to working areas, as recommended by researchers [17], [63].

It was observed that teams often fail to take responsibility for addressing water leaks because they are unclear about what is expected of them. Establishing accountability and clearly defining roles and responsibilities can serve as a critical link between inefficiency detection and sustained improvement.

Before developing the proposed method, research was conducted that focused on the concept of accountability.

1.4 Accountability concept

The previous section highlighted the challenges in addressing water leaks within deep-level mining operations and the absence of a structured approach to ensure timely and effective mitigation. Accountability offers a potential solution by creating clear responsibilities for addressing identified leaks. This research examined accountability in detail, focusing on its definition, practical implementation, and the potential benefits and challenges associated with its use in mining operations.

1.4.1 Accountability – An overview

Accountability is often seen as a complex and evolving concept, with different authors offering definitions based on the context of their work [91]–[94]. However, it can be simply described as being held responsible for one's actions by a recognised authority [95]. This refers to an expectation that a specified outcome will be achieved for assigned tasks and failure to do so will result in an explanation with regards to actions and decisions where the impact and consequence will be determined by the authority to whom account is given [96]. Therefore, holding individuals accountable for their actions and performance is an effective way to control their behaviour and outcomes [97]. Accountability within organisations is categorised into formal - and informal sources, which are divided into self-, peer-to-peer -, managerial – and systems accountability [94], [96], [98].

Informal accountability:

Informal accountability refers to the unwritten mechanisms within an organisation that influence behaviour but are not explicitly included in its formal policies or procedures. It includes organisational norms, values, culture and interpersonal relationships [98]. This source of accountability is often difficult to manage as it lacks clear expectations for personnel to follow. As a result, it is challenging to hold employees accountable since they are unsure

what they are responsible for [99]. Self-accountability and peer-to-peer accountability are categorised under informal accountability.

Self-accountability [94], [96], [98]: This involves an individual taking responsibility for their actions. It is coupled with an individual's upbringing, values and motivation for inner satisfaction and the desire for achievement. A key aspect includes the concept of one's reputation, which forms part of self-criticism, self-monitoring and self-management. Research suggests that a supervisor's ability to hold themselves and the team accountable strongly influences this behaviour [100].

Peer-to-peer accountability [96], [98]: Peer-to-peer accountability refers to reciprocal relationships and a sense of responsibility among individuals on the same hierarchical level, where peers keep each other accountable for actions and decisions. Peer-to-peer accountability is based on collaboration and trust between peers rather than on formal hierarchical systems. However, in the absence of a clear hierarchy, resolving goal conflicts can become challenging, as individuals may focus more on protecting themselves when dealing with higher authorities than on addressing issues collaboratively with peers. Therefore, while peer-to-peer accountability encourages teamwork and encouragement, it can also lead to ambiguity, bias, and conflict.

Formal accountability:

Formal accountability includes formalised processes and mechanisms such as reporting, performance evaluations, performance monitoring, reward systems and disciplinary procedures [94], [96], [98]. This form of accountability usually makes use of hierarchical approaches [101]. Moreover, research highlights that the use of such systems has positive effects on performance [102]. Formal accountability systems clearly define the relationship between performance and rewards or penalties [103]. Managerial accountability and systems accountability are included under formal accountability types.

Managerial accountability [96], [98]: Managerial accountability follows a hierarchical approach where managers hold employees accountable for their actions and performance. Managers are given the power to reward or punish employees, which impacts their behaviour and performance. Research indicates that this form of accountability works best when employees directly interact with their managers and provide explanations for their performance. Moreover, accountability for outcomes arises when managers clarify expectations and monitor employee performance to ensure that expectations are met [97]. Therefore, managers should focus on accountability processes and input mechanisms. Furthermore, research stresses that

managers should not only recognise failures but should also recognise good performance [104].

Systems accountability: This involves formal systems and processes established within an organisation to oversee, control, and guarantee accountability for employee performance [98]. Research conducted on systems accountability within organisations stresses that the implementation of control and monitoring systems is crucial to ensure that the organisation remains competitive [98]. This form of accountability allows for performance standards to be clearly defined, along with rewards and penalties for compliance and non-compliance [96]. Using these standardised procedures ensures that employees cannot shift the blame or accept credit for successful outcomes. However, appropriate accountability systems should be established to limit the negative consequences of accountability [96]. Therefore, while systems accountability has significant impacts, it is important that performance measurements and monitoring are accurate.

Formalised mechanisms such as reporting, processes and procedures are needed within an organisation as it has a positive effect on performance and define the relationship between performance and rewards or penalties [102], [103]. In addition, informal mechanisms such as culture, values and interpersonal relationships are also used to drive accountability in organisations and are often the result of the implementation of formal mechanisms [105].

Brandling *et al.* [96] examined the sources of accountability at different levels within a mining organisation to improve safety and performance. In-depth interviews were conducted to determine how workers, supervisors and managers view accountability in the mining sector. The study found that mechanisms promoting accountability include [95], [96]:

- Clarified roles and responsibilities;
- Open interpersonal communication and feedback ;
- Standardised policies and procedures; and
- Financial incentives tied to performance.

Brandling *et al.* [96] mention that financial incentives are tied to performance, but it is not limited to these incentives. Social pressure, where others will know if expectations are met, career impact or praise and/or critique will also suffice [106]. This correlates to a study that was done based on ratings. Raters who believed that they would be held accountable for their decisions were more accurate in the ratings provided without any incentives [97]. Furthermore, financial incentives should be carefully implemented and even avoided to decrease the risk of labour strikes and disputes. An example is shown in the work conducted by Cloete *et al.* [25].

This paper showed that compressed air wastage led to decreased air pressures needed for mining activities. As a result, rock drill operators (RDOs) had to work harder to reach production targets which are tied to bonuses. While bonuses can motivate employees to work harder, they can also cause problems, such as strikes, if the bonuses are taken away due to unforeseen circumstances.

Pearson *et al.* [98] explored the factors that influence accountability in organisations and how they can be effectively implemented to improve employee performance. Pearson conducted 20 semi-structured, in-depth interviews with chief executive officers, executives, human resource experts, senior managers and consultants across eight industries in South Africa. This study found that the key factors driving accountability and improving operational performance include:

- Organisational systems;
- Culture;
- Role clarity; and
- Leadership and individual attributes.

From this research, the following main components/drivers were identified that should be included to ensure accountability and are summarised in Table 4.

Table 4: Accountability components/drivers.

Clarified expectations	A direct link has been made between outcomes and clarified expectations [97]. Clear expectations should be defined so that employees know what is expected of them. This includes defining clear hierarchical structures to identify “who” they report to and specifying “what” they are responsible for [94], [95], [98], [107]. Isacowitz [108] further highlights that where clear success metrics are absent they should be defined so that employees will know what success looks like. This correlates with research stating that accurate performance measures and performance monitoring are important to obtain impacts. These metrics should be standardised, so that employees are evaluated.
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Policies and procedures	Clear policies and procedures should be made available so that standardised processes are followed.
Open communication	Performance monitoring and evaluation compare the actual performance to the success metrics. Regular feedback sessions should be held so that the performance is reviewed and discussed, together with the way forward.
Consequences	Finally, the consequences of meeting or failing to meet performance goals should be outlined. While financial incentives may not always be ideal, social pressure, career implications, praise, or constructive feedback can also motivate employees effectively.

Informal accountability is often difficult to manage as no structure is provided and no clear expectations are stated. Managerial accountability, which refers to hierarchical approaches, has been found to be favoured as it ensures holistic goal alignment, supports disciplined decision-making, and coordinates actions that drive organisational success. Together with this, systems accountability plays a crucial role in ensuring clear communication, defining roles, and fostering transparency. In this way, managerial accountability lays the foundation that ultimately influences the effectiveness of other forms of accountability.

The implementation of accountability ultimately leads to the benefits displayed in Table 5.

Table 5: Accountability benefits.

Transparency and fairness	Transparency is ensured as all information is made available to all employees [95]. Furthermore, all employees are held to the same standards, ensuring fairness [109].
Improved performance	According to Brandling <i>et al.</i> , accountability improves employee- and operational performance [96]. Performance measurement and monitoring are used to assess employees and hold them accountable [110], which in turn supports the organisation's continuous learning and development.

Risk management	Certain risks are identified and prevented by proactive measures. By ensuring that rules, ethical guidelines and best practices are followed, organisations can lower the chances of costly mistakes, legal liability and damage to their reputation [95], [96].
Goal alignment	Aligning personal and organisational objectives ensures that all employees are working towards the same goals [97], [107]. Organisations can increase their efficiency when linking individual performance to their priorities and strategies [110].
Employee engagement and motivation	Employees are motivated when they receive recognition for their contributions [97], [98]. Accountability culture leads to employees keeping themselves and others accountable. This fosters employee involvement, motivation, and dedication toward achieving the organisation's objectives [96].

1.4.2 Accountability for inefficiency mitigation

Key challenges have been highlighted in managing inefficiencies in deep-level mining, especially in water systems. Current methods are not well-suited to quickly and accurately identify and localise problems in these complex and dynamic environments. These methods also lack continuous and automated detection. Mitigation efforts are also not prioritised, often focusing on short-term fixes rather than long-term solutions.

A major issue is the lack of accountability, which could play a critical role in improving how inefficiencies are addressed. Accountability has proven to be a driver towards increased performance, as discussed in Section 1.4.1. However, previous research conducted on mining operations did not use accountability as a method and only reported issues to top management to be rectified [16], [49], [65]. Table 6 evaluates the leading work done in inefficiency detection and mitigation (as seen in Table 2) to highlight the fact that accountability is not used for inefficiency mitigation within the mining industry. Accountability here refers to clear roles, improved monitoring, performance evaluations, and timely actions that can help ensure that problems are not only identified but also resolved effectively.

Table 6: State-of-the-art summary for accountability for inefficiency mitigation.

Study number	Reference number	Year	Deep-level mine	Accountability incorporation for mitigation
Study 1	[17]	2022	Yes	No
Study 2	[63]	2022	Yes	No
Study 3	[64]	2017	No	No
Study 4	[2]	2019	Yes	No
Study 5	[16]	2020	Yes	No
Study 6	[25]	2013	Yes	No
Study 7	[65]	2011	Yes	No
Study 8	[66]	2019	No	No
Study 9	[67]	2023	No	No
Study 10	[68]	2018	No	No
Study 11	[69]	2016	Yes	No
Study 12	[70]	2018	No	No
Study 13	[71]	2011	No	No
Study 14	[15]	2024	Yes	No
Study 15	[72]	2012	No	No
Study 16	[73]	2014	Yes	No
Study 17	[74]	2017	No	No
Study 18	[58]	2023	Yes	No
Study 19	[75]	2014	No	No
Study 20	[76]	2024	No	No
Study 21	[77]	2016	No	No
Study 22	[78]	2019	No	No
Study 23	[50]	2010	No	No
Study 24	[79]	2018	Yes	No
Study 25	[55]	2022	No	No
Study 26	[80]	2018	Yes	No
Study 27	[81]	2011	Yes	No
Study 28	[82]	2013	No	No
Study 29	[83]	2021	No	No
Study 30	[49]	2016	Yes	No

From Table 6, a clear gap exists regarding the incorporation and use of accountability to mitigate water inefficiencies and sustain the performance.

1.5 Need for the study

The mining industry faces rising operational costs, which threaten profitability and sustainability. A key contributor to these escalating expenses is water leaks, which account for 30-50% of the total water supply. This wastage not only results in excessive water

consumption, but also increases the electricity consumption which is wasted on refrigeration and dewatering operations tied to these inefficiencies. Beyond financial implications, the leaks impact the performance of the entire mining system, disrupting production and decreasing operational efficiency.

To mitigate these leaks, they must first be identified. However, leaks in working areas often go unnoticed and remain unresolved because current inefficiency detection methods cannot localise water leaks effectively. ZWBs have been identified as the most accurate approach to identify inefficiencies, but current approaches are static and broadly implemented, and thus unable to localise inefficiencies within the working areas. Currently, localisation of leaks in working areas remains a time- and resource-intensive process, and once identified, they are forwarded to top management without a clear mechanism to ensure timely resolution.

Verification of resolved leaks adds another layer of complexity. Confirming that a leak has been repaired requires revisiting inefficient detection methods, which wastes time and resources while leaks continue to disrupt operations. Additionally, existing water monitoring systems are installed up to half-levels, measuring multiple working areas simultaneously. This prevents accurate identification of specific leaks and hinders continuous system monitoring.

The absence of accountability mechanisms exacerbates the issue due to a lack of clarity regarding roles and responsibilities among underground personnel, which further delays repairs, resulting in recurring inefficiencies.

Need for the study: There is no system in place to actively ensure leaks are fixed and prevented from recurring. Consequently, the inefficiencies persist, driving up operational costs and undermining sustainability efforts.

1.6 Research objectives

From Section 1.3, there is a critical need for a dynamic, localised inefficiency detection method capable of continuously identifying leaks as they occur. Furthermore, implementing accountability mechanisms will ensure that identified leaks are repaired promptly and do not recur. Finally, sustainability monitoring must be integrated into operations to track progress, enhance system performance, and maintain long-term efficiency.

Therefore, the aim of this thesis is to lower deep-level mine operational costs by ensuring that water leaks are mitigated and monitored for sustainability. The aim is divided into smaller objectives, namely:

1. To install monitoring equipment in closer proximity to working areas to improve sustainability monitoring.
2. To develop and implement dynamic ZWBs to localise water leaks in working areas and enable continuous detection.
3. To develop and implement an accountability method for mining operations.
4. To detect and mitigate inefficiencies faster than with previous methods.
5. To quantify cost savings by mitigating water leaks.
6. To ensure sustainable water leak mitigation through continuous monitoring.

From the objectives, the novel contributions of the thesis arose, which the following section discusses. The method developed to address the novel contributions were implemented in a real-world case study to validate if the objectives of the thesis have been met.

1.7 Novel contributions

Leading research in the field has revealed that current inefficiency detection methods lack a localised and dynamic approach, as displayed in Table 2 and Table 3. These methods rely on infrequent, resource-intensive and static approaches to localise inefficiencies. Moreover, accountability, even though proven to be a successful driver of performance, is not currently incorporated to ensure that inefficiencies are mitigated, especially within the deep-level gold mining environment, as highlighted in Table 6. Lastly, profitability and sustainability within mining operations need to be improved, as highlighted in Section 1.1. Currently, when a leak has been fixed, no way exists to actively monitor the performance as monitoring equipment is only installed up to half-level splits, measuring more than one working area together. Working area monitoring is not currently done due to the high capital cost associated with it. However, monitoring equipment can unlock additional benefits. The novel contributions of the thesis are as follows.

Novel contribution 1:

Development of a localised inefficiency detection method using dynamic ZWBs to continuously identify water leaks in mine working areas.

Problem statement and existing research

In deep-level mines, up to 50% of the water supply is wasted, with most of this occurring in the working areas where gold-bearing ore is mined. Due to the complex and dynamic nature of mining operations, localisation of wastage is time and resource-intensive. Without successful identification, wastage cannot be effectively mitigated.

Ample research has been conducted on inefficiency detection in both mining and non-mining industries. Current research focuses more on broad and static approaches to identify and quantify wastage. Focus is generally placed on compressed air systems.

Limitations of existing research

Current identification techniques are unable to localise or continuously detect wastage within working areas. ZWBs are recognised as the most effective method for identifying waste. However, existing approaches rely on static ZWBs, where time-based equipment usage is aligned with fixed mining shifts. These baselines estimate equipment demand using manufacturer specification sheets, assuming the equipment operates at 100% capacity throughout the entire allocated period.

Contributions of this study

A dynamic ZWB which enables localisation of water leaks in working areas on a deep-level mine was developed. This ensures that continuous identification is conducted.

Novel contribution 2:

Incorporation of accountability to ensure that identified leaks are mitigated and operational costs decreased.

Problem statement and existing research

Identification of water leaks does not fix these issues. Mitigation is needed to lower the operational costs that threaten profitability and sustainability.

The focus in mining often lies on compressed air systems when it comes to fixing leaks. For water systems, focus is placed on supply-side measures like water isolation and pressure management, which are effective only during non-operational times. Despite the significant benefits of fixing water leaks, this issue is often overlooked. Leaks are often addressed only

when they disrupt production, with larger leaks prioritised while smaller ones are neglected. Subsequently, these initiatives are not properly implemented on mining operations.

Limitations of existing research

Literature has highlighted the need for a leak prevention technique to actively ensure that water leaks are mitigated to obtain cost savings. Fixing leaks typically involves reporting them to top management, but confirmation of repairs relies on word of mouth or timely verification methods. Unclear roles and a focus on production targets lead mining and engineering teams to avoid responsibility for leaks. Promptly addressing and ensuring the repair of leaks can enhance the sustainability of mining operations.

Contributions of this study

This thesis incorporated accountability and all its components/drivers to ensure that water leaks are fixed promptly as they are identified to decrease operational costs.

Novel contribution 3:

Integrated sustainability monitoring for deep-level mine working areas.
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Problem statement and existing research

The water consumption of mine working areas remains unmonitored, with current monitoring done up to half-level splits. This is mostly due to the lack of knowledge about the potential benefits that can be achieved. Large capital investments for the installation of monitoring equipment in working areas also pose concerns.

Benefits with regard to the installation of additional measuring equipment to divide the network into smaller areas have been achieved in non-mining industries, seeing that these industries are significantly smaller.

Limitations of existing research

Working areas in deep-level mining operations are not equipped with any form of water consumption monitoring. This means that water consumption monitoring is done too broadly, unable to focus on a certain area as the consumption of several areas is monitored together.

Contributions of this study

This thesis provides a solution for the installation of additional water consumption monitoring equipment in working areas to monitor the water consumption of each specific area individually to ensure the sustainability of improvement. The data obtained from the monitoring equipment are used to measure the working area's performance.

1.8 Research methodology

To achieve the objectives set out in Section 1.6, a solution was developed and implemented on a real-world scenario which yielded the results to be compared with literature. For the purpose of the thesis, the case study methodology was followed as the method was developed from literature [18]. A flow chart displaying the case study methodology [18] as well as the relationship between the methodology and thesis layout is seen in Figure 7.

The case study methodology was chosen as the most suitable approach for this research as it is most commonly used when [18]:

1. analysing specific changes or phenomena,
2. generating hypotheses, and
3. validating a developed method.

In this study, it helped reduce bias during the validation phase and allowed useful insights to be drawn through implementation on the case study [58]. It also made it easier to understand how the proposed solution would work in real mining conditions, supporting its use in other deep-level mines.

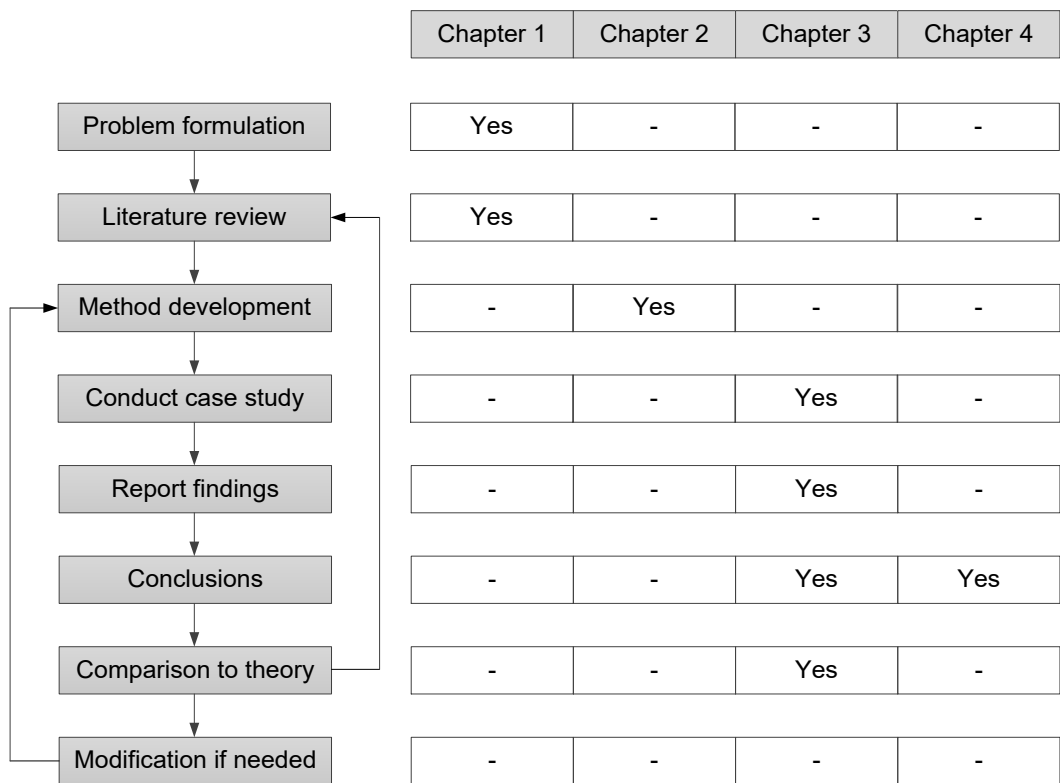


Figure 7: Flow chart of the Case Study Methodology (adapted from [18]).

1.9 Thesis overview

The following section provides a summary of the overview of the thesis.

Chapter 1 – Introduction and background

Chapter 1 provides insights into the WRS on deep-level mines. A critical need to curtail operational costs is highlighted. Water leaks are identified as a major issue that needs to be addressed. A systematic literature review was conducted, and studies were analysed to identify the gaps in current literature. Using this, problem statements were derived which were addressed by the novel contributions of this thesis.

Chapter 2 – Methodology

This chapter addresses the objectives outlined in Chapter 1. A method for localised inefficiency detection and mitigation through accountability measures on deep-level mines was developed. The strategy was developed following certain steps to ensure that the objectives set out in the previous section are met. This chapter also includes a discussion on the verification of the proposed method.

Chapter 3 – Results and evaluation

The developed method was applied to a real-world case study to determine the effectiveness thereof. This chapter presents the implementation results and includes a thorough validation of the novel approach. The chapter concludes with a summary of the key findings.

Chapter 4 – Conclusion and recommendations

This chapter concludes the thesis by summarising the research process undertaken to reduce operational costs in deep-level mining. Here, key findings are highlighted obtained from the implementation of the developed method. The results are discussed in relation to the research objectives and novel contributions. Additionally, recommendations for future research are provided as well as shortcomings identified.

CHAPTER 2: METHODOLOGY

“No methodology can guarantee success. But a good methodology can provide a feedback loop for continual improvement and learning.” – Ash Maurya.



² Personal photo taken by the author.

2 Development of an accountability method

Chapter 1 has highlighted the need for an inefficiency detection method for deep-level mines that can continuously, dynamically and accurately detect water leaks in the working areas where leaks commonly occur. The developed method should also detect water leaks in working areas faster than current methods to ensure faster mitigation. Since previous methods lack a post-identification method to address water leaks and ensure that they do not recur, accountability measures have been identified as a solution to this problem.

Therefore, the focus was to develop a novel method to address water leaks in working areas.

Note that the method discussed here was developed and implemented in the articles published by the author [111], [112].

2.1 Method development

This chapter details the method development process and demonstrates how it fulfils the research objectives. The method is outlined in a clear yet adaptable manner to ensure that the results can be reliably reproduced.

The steps shown in Figure 8 were derived from Table 2 and the study objectives, and was used to guide the development of the proposed method to ensure all objectives were successfully met.



Figure 8: Steps followed for method development.

The method consists of four steps. The initial identification and detailed investigation steps are done from the literature available. Next, the dynamic ZWBs are developed, which should

enable continuous and dynamic detection of water leaks within the working areas. Next, the incorporation of accountability is discussed to ensure that identified issues are mitigated and monitored for sustainability. The method is verified, and the objectives are validated.

2.2 Step 1: Initial identification

The initial identification phase involves analysing the mining operation using readily available data to assess whether water wastage is a significant issue. This assessment helps determine whether implementing the proposed method would be beneficial.

Intensity calculations are used as a preliminary indicator of inefficiencies in mining systems [15], [58]. Specifically, service water intensity calculations measure the total volume of water used per tonne of rock hoisted, as defined by Equation 1.

Equation 1: Service water intensity calculation

$$\text{Service water intensity} = \frac{\text{Total water used [tonnes]}}{\text{Total rock hoisted [tonnes]}}$$

A higher intensity value indicates that more water is consumed without a proportional increase in rock hoisted, suggesting inefficiencies and potential water wastage. An example is shown in Figure 9. Here, a significant increase is observed from year 4, indicating possible water wastage.

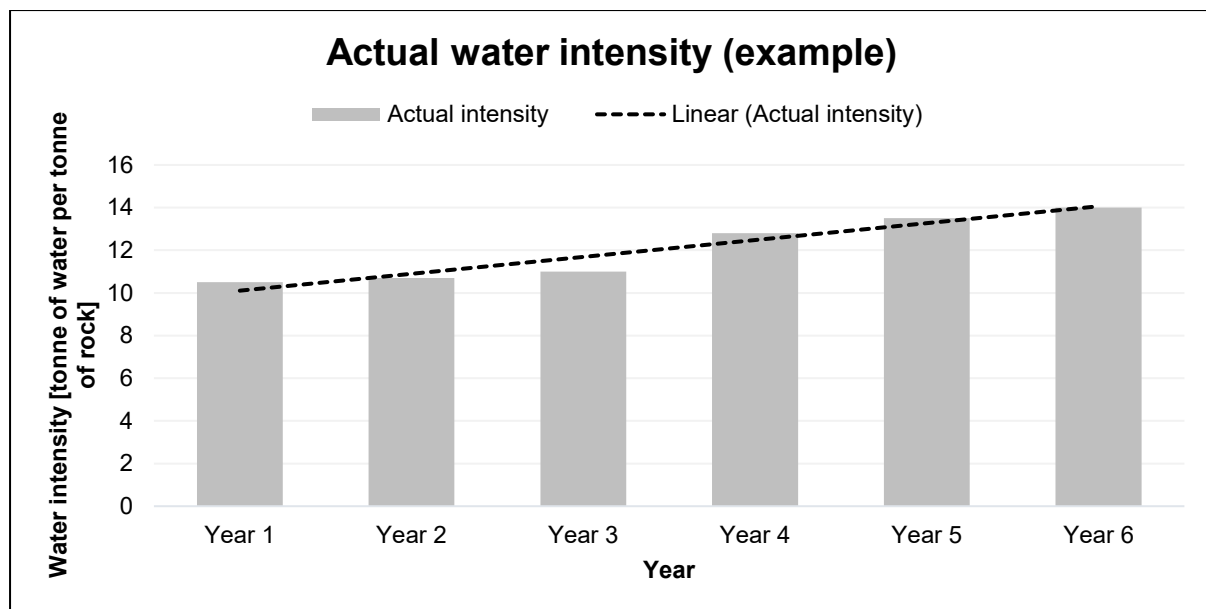


Figure 9: Typical example of water intensity on a deep-level mine.

Analysing a mining operation's water intensity helps determine whether water is efficiently used for rock production or wasted. This preliminary analysis serves as a valuable screening tool before conducting a more detailed investigation.

2.3 Step 2: Detailed investigation

Following the initial investigation, a detailed analysis is required to validate the preliminary findings. This in-depth assessment aims to accurately determine the extent of inefficiencies within the operation.

2.3.1 Scope identification

This step involves determining whether the specific case study would benefit from the implementation of the developed method. As discussed in Chapter 1, numerous methods exist for identifying water leaks within working areas. However, these methods often have limitations that hinder their effectiveness. Therefore, before implementing the developed method, the current methods used to detect water wastage within working areas of the specific case study should first be applied. These methods include:

- Step testing; and
- Walk through audits

The issues found should be discussed with top management to address, as observed from the literature discussed in Section 1.3.3. This helps to establish whether water leaks are a significant issue and provide a basis for comparison. By doing so, the effectiveness of the developed method can be evaluated. When scope identification reveals that water wastage presents a significant challenge and is not properly addressed by the above-mentioned methods, data are collected to develop and implement the proposed method.

2.3.2 Data collection

After sufficient scope has been identified for the proposed method, relevant data should be collected. This involves a thorough examination of the case study to gather and filter the necessary data. Some data will already be available from the initial- and scope identification phases. However, outstanding data need to be obtained by the researcher to ensure the effective development of the method. Typical data needed include:

- Type and number of water users;
- Water users' locations;

- Specification sheets of water-consuming tools;
- Working schedules;
- Production schedules;
- Underground layouts;
- Water flow data;
- Employee tracking data; and
- Hierarchical structures.

Next, the dynamic ZWBs are developed for each working area to ensure continuous and dynamic detection.

2.4 Step 3: Dynamic ZWB development

This section discusses the development of the ZWBs. The development consists of several steps, each discussed individually and integrated to form the dynamic ZWBs. These baselines can enable continuous and dynamic detection within gold mines' working areas to achieve faster localised detection compared to current techniques and, in doing so, address the gaps identified in Table 2.

2.4.1 Major water consumers on mines

As discussed in Chapter 1 (Section 0), water consumers in deep-level mines are divided between continuous and non-continuous water users [42]. Continuous water consumers refer to air-cooling units such as cooling cars and BACs which are used to maintain the underground environment below the legal limit of 32.5 °C. The focus of the method lies on the non-continuous consumers, referred to as intermittent water consumers. These include all handheld, manually operated equipment used by mining personnel for daily activities.

As observed from the literature, previous studies typically assumed a constant water consumption rate for intermittent water-consuming equipment, typically obtained from the manufacturer specification sheets. Specification sheets include the optimal performance of the tool which is obtained from tests conducted in controlled environments. However, underground operations differ significantly from the optimal operating point, meaning that the water consumption may be different. Furthermore, the actual underground water pressure in working areas also differs daily based on the operating conditions [22].

In addition, seeing that previous researchers have used manufacturer specification sheets to determine the water consumption of equipment, they neglected in-house manufactured

equipment that lack specification sheets. This point was incorporated by only one of the considered researchers [15]. However, again, a fixed water consumption value was used.

Therefore, to address this gap identified in the literature, tests were conducted on all identified water-consuming equipment used in the case study. This allowed for all water consumers to be accounted for, ensuring accurate measurement of their water usage. The researcher could compare the tested values with the specification sheet values to highlight any significant discrepancies, emphasising the need for this approach.

The proposed tests consist of an underground test bench, where the individual water consumption of all equipment can be measured by regulating the water pressure through means of a pressure regulating valve. Tests conducted in the underground environment where these tools operate ensure that actual operating data are obtained. An example of the test bench is seen in Figure 10. Measurements should be recorded at various pressure readings using a portable water flow meter and pressure gauge.

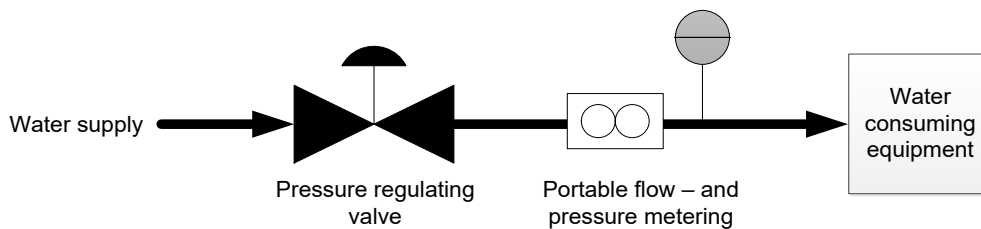


Figure 10: Schematic of a water test bench.

An example of the typical data expected during the tests should look like the values seen in Table 7. The more data points obtained, the better, as these are used to develop the baselines. The actual values obtained from the tests conducted are verified by ensuring that the metering equipment used is calibrated and accurate.

Table 7: Example of the data obtained from water tests.

Data point	Water pressure [bar]	Water flow [l/min]
A	0.5	3.5
B	1.0	3.8
C	1.5	3.9
D	2.0	4.3
E	2.5	4.8
F	3.0	5.2
G	3.5	5.6

The data presented in Table 7 should be displayed on a scatter plot. This enables the researcher to establish trendlines and determine which trendline best fits the data, which is the trendline with a coefficient of determination (R^2) value closest to one [113]. The equation of the selected trendline is used to represent the equipment's water consumption at varying pressures. An example is shown in Figure 11.

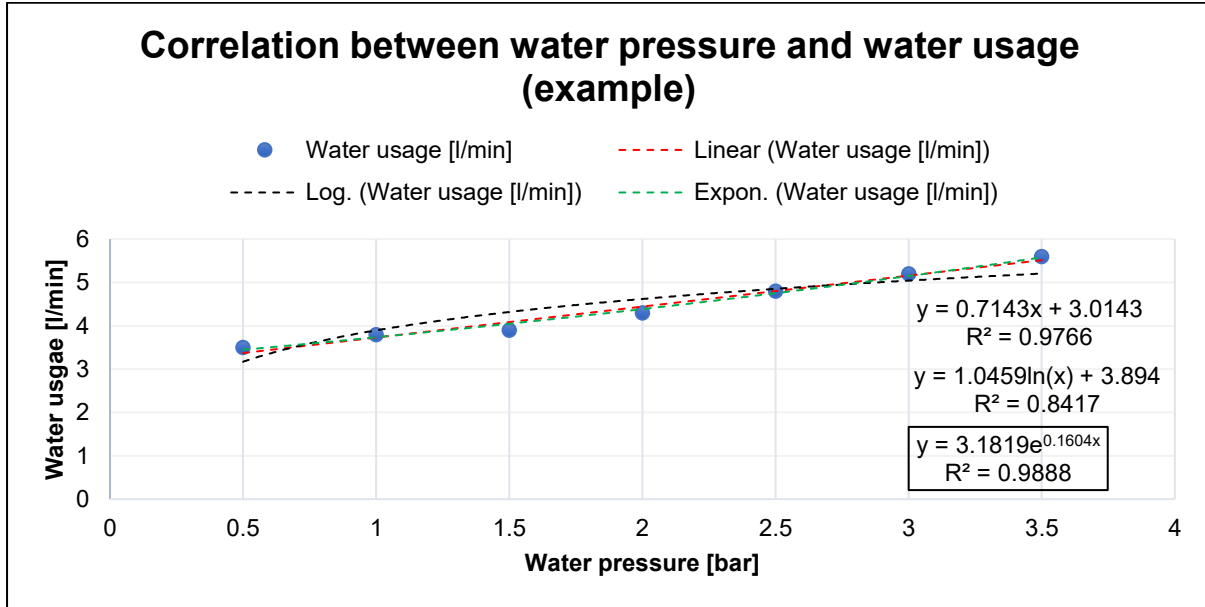


Figure 11: Example of scatter plot with trendlines.

The best fit of the data is represented by the exponential trendline equation with an R^2 value of 0.9888, shown in Equation 2. This equation is used to represent the water consumption of the specific equipment at different water pressures, which was obtained by actual tests.

Equation 2: Trendline equation for water consumption (example)

$$y = 3.1819e^{0.1604(x)}$$

Where:

y = water consumption in l/min

x = water pressure in bar

The accuracy of the equations can be determined using the mean absolute percentage error (MAPE) [114]. MAPE indicates the absolute error between a predicted and actual value, with a MAPE smaller than 10% being considered highly accurate [114], [115]. Equation 3 displays the MAPE equation.

Equation 3: MAPE equation

$$MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{A_t - F_t}{A_t} \right|$$

Where:

$MAPE$ – mean absolute percentage error [%]

n – number of entries [-]

A_t – actual value

F_t – predicted value

These equations represent the equipment's water consumption as a function of water pressure, allowing for accurate accounting under varying conditions. Next, the time of use (TOU) of the water equipment is determined.

2.4.2 Time of use calculations

Literature indicates that water allocation for current ZWBs is done using fixed timetables. These timetables correspond to the working shifts of the specific operation. However, it was determined that this is not an effective way of determining the TOU of the water equipment as mines do not always adhere to these schedules due to the dynamic nature of operations [22]. This step incorporates the dynamic TOU schedules of the novel ZWB.

As mentioned, intermittent water-consuming equipment includes handheld, manually operated tools used by employees. Therefore, these tools should theoretically consume water only when actively operated by an employee. Any water consumption by these tools during times when no personnel is present is seen as wastage.

Employees operating these handheld tools received specialised training beforehand to ensure safe and optimal usage. Therefore, only employees trained to use a rock drill, for example, may use one, so if no rock drill operator is present, the rock drill should remain unused.

Therefore, by knowing employee locations, water allocation can be done by directing it to specific water-consuming tools. This can be done by using the employee tracking systems generally employed in deep-level mines to locate employees in case of emergencies [116]. Occupancy sensing methods generally used in mining operations include [116]:

- Motion detection;
- Tracking and thermal cameras;
- Global positioning systems (GPS) tracking;
- Pressure sensors;
- Radio frequency sensors;
- Methane gas detectors; and
- Power meters.

However, the required system should not only track employee locations but also provide information about the employees to determine the type of user. This includes identifying the type of user and determining the number of such users within a specific area of interest. Of the above-mentioned methods, radio frequency identification (RFID) technologies have been identified as the best method to use [116].

These technologies are widely used in deep-level underground mines for zone-based tracking [116]. Pre-defined zones are equipped with fixed RFID tag readers that detect nearby RFID tags and send their unique codes to a central server. An example of the RFID tag readers installed on a mining level is seen in Figure 12. This enables accurate tracking of employees within the reader's coverage area, helping monitor movement and zone occupancy throughout the mine.

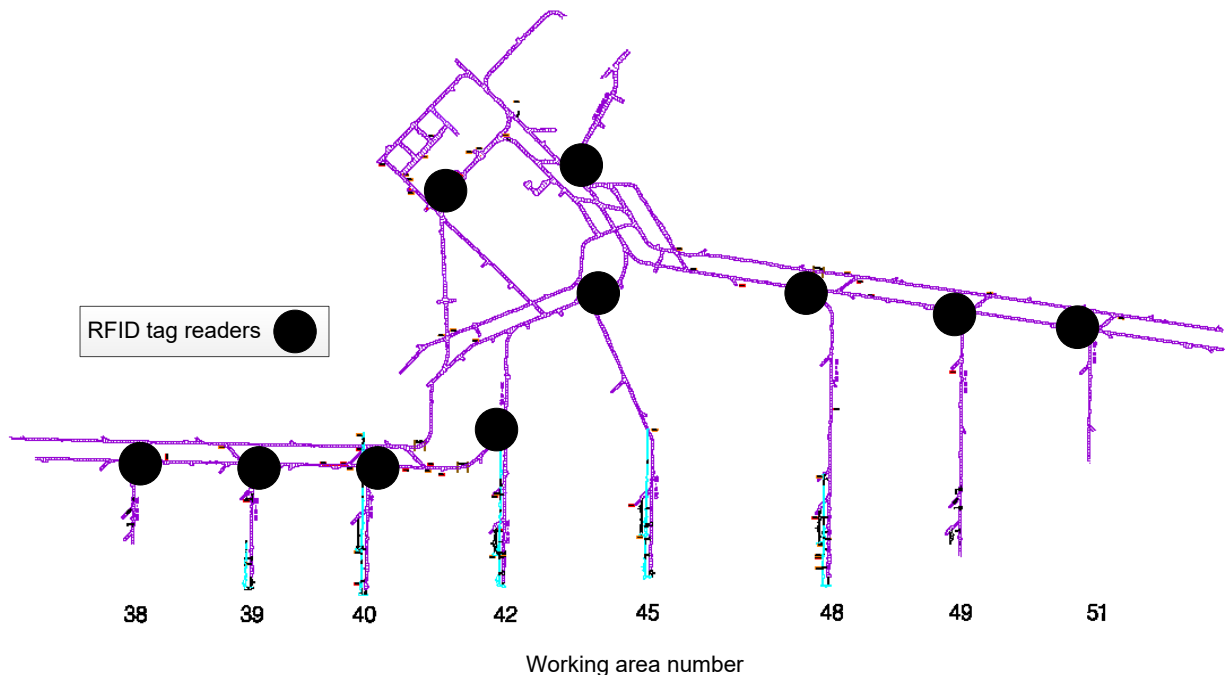


Figure 12: Example of RFID tag reader locations on a mining level.

RFID tags are integrated into employees' cap lamps and transmit unique identification codes intermittently as seen in Figure 13 [116].



Figure 13: Example of RFID tag installed in cap lamps^{1 2}.

These codes are linked to employees' clocking cards used upon entry to the mine, containing information such as employee name, employee number, operation name, zone and job description.

By using this system, knowledge can be obtained concerning employee movements, which directly correlates to the water consumption of intermittent water equipment. Such equipment should only be operated by trained personnel; therefore, in the absence of employees, water usage should not occur. This enables accurate TOU water allocation to specific water-consuming equipment as knowledge is obtained of user locations. In this way, employee data are not only transformed into information, but also applied as actionable knowledge to define the TOU characteristics of the ZWB.

The stored data include the locations of all personnel working in the mine. To ensure relevance, it must be filtered to extract information specifically for employees using intermittent water equipment. Additionally, since the data are stored on a general server, further filtering

¹ MSA Safety, "Mining Cap Lamp and RFID Solutions." [Online]. Available: <https://pe.msasafety.com/Mining-Equipment/Mine-Lighting/Luminator-Cap-Lamp/p/000020000900001000?locale=en>. [Accessed: 20-January-2025].

² Stylus Technologies, "Mining Cap Lamp and RFID Solutions." [Online]. Available: <https://www.stylus.co.za/rfid/>. [Accessed: 20-January-2025].

may be needed to isolate the specific area of interest. Any suitable filtering software can be used for this purpose. A flow diagram of the process is displayed in Figure 14.

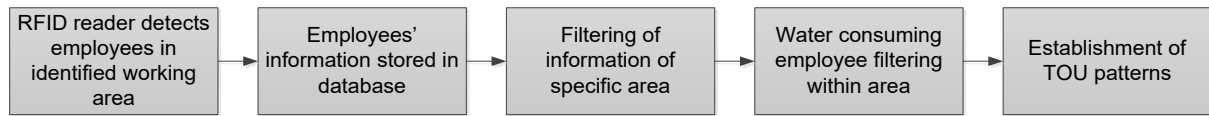


Figure 14: Flow diagram of the TOU allocation process [112].

Figure 15 provides an example and comparison of night shift cleaners' movements in a working area on two different days obtained by the tracking system, contrasted with the fixed schedules used by current approaches. The data clearly show that workers' entry and exit times vary daily and do not align with the fixed schedules provided by the mines.

When referring to Figure 15, current methods would have identified water usage after the data point marked as 04:30 as wastage, as the shaft schedules indicated that all personnel should have exited the area by then. However, mining operations are highly dynamic, and employees sometimes need to work beyond scheduled times to meet production targets. This is evident in Figure 15, where workers only exited the area at the data point corresponding to 09:00 on Day 2. Furthermore, previous methods would have allocated water usage at the data point marked as 19:30 to adhere to shaft schedules, yet the data clearly show that workers only entered the area closer to the data point marked as 21:00. This discrepancy highlights the inaccuracy of current approaches and reinforces the need for a more responsive water allocation strategy.

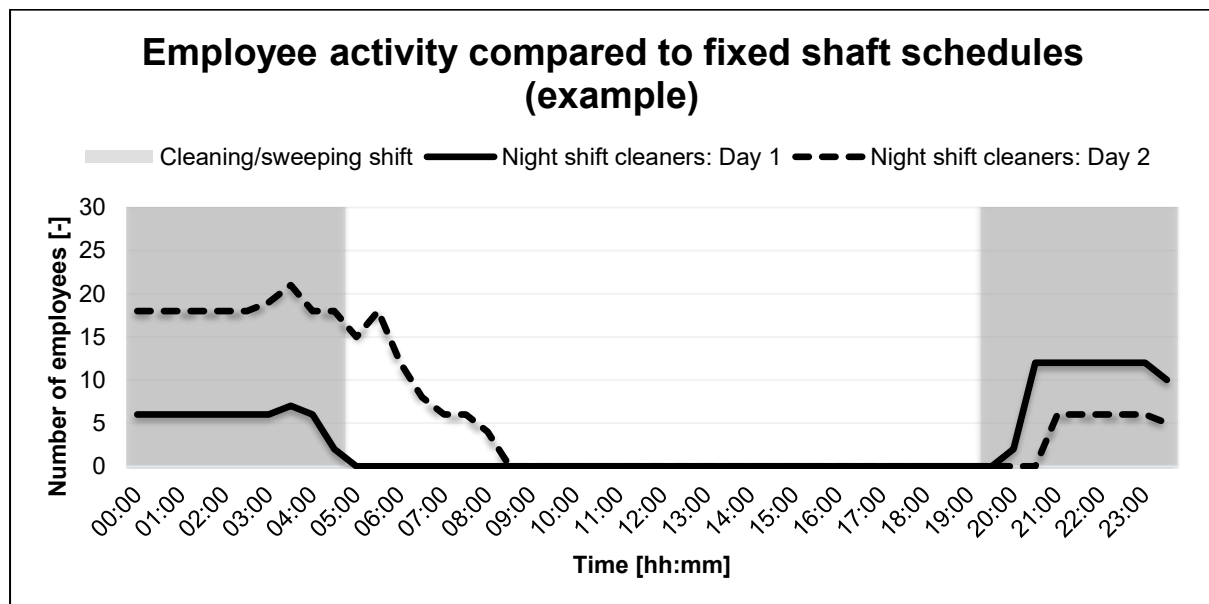


Figure 15: Example and comparison between employee movements and fixed schedules for a working area.

The data collected from the employee tracking system must be verified to ensure that the correct personnel are being tracked and that the system operates accurately. This verification can be conducted through an underground audit on a specific level, where the time at which personnel pass the underground sensors is manually recorded [116]. A layout such as the one shown in Figure 12 can be used to identify sensor locations and measure the time RFID tag readers are passed. The manually recorded data can then be compared with the data from the employee tracking system to confirm its accuracy.

2.4.3 Additional metering installation

ZWBs rely on data to establish a reference point/baseline. To identify water wastage, actual water consumption must be compared against this baseline. A ZWB will be developed for each working area, requiring actual water consumption data at the same level of detail.

Despite the proven benefits of additional metering in non-mining industries, its implementation in mining operations remains limited due to the challenges outlined in Chapter 1. One major barrier is the significant capital investment required. However, the potential benefits of additional metering could justify this cost. This can be done by determining the payback period of the project [49]. This entails comparing the cost-savings benefit against the capital costs. The shorter the payback period, the better the project [49]. However, for this application, a payback period of less than a year will be seen as a good investment. This is due to mining operations generally preferring this period.

Equation 4: Payback period calculation

$$\text{Payback period} = \frac{\text{Capital cost}}{\text{Monthly cost saving}}$$

A key challenge identified in the research is the dynamic nature of mining operations, where equipment may be frequently relocated. A potential solution is to incorporate production schedules to determine a specific area's LOM before installing metering. Additionally, accountability measures should be introduced by assigning responsible personnel to ensure that metering equipment is relocated when a working area is decommissioned. Figure 16 shows an example of how the installation location of measuring equipment in working areas can be determined. Installation locations are chosen based on working areas with the longest LOM. Any working area with a lifetime longer than one year can be considered to ensure that equipment is not frequently relocated.

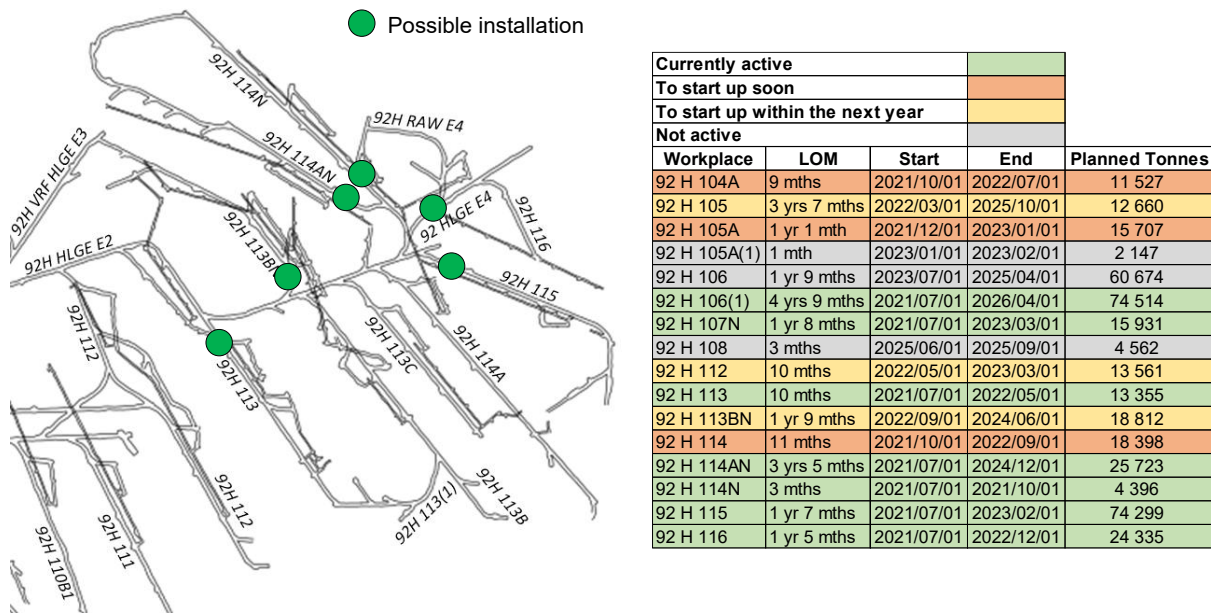


Figure 16: Example of LOM schedule and possible installation location.

There are various types of metering devices available for measuring water flow, such as ultrasonic, magnetic flow, and differential pressure flow meters [117]. For pressure measurement, both gauge and absolute pressure meters are used. Absolute pressure refers to the measurement taken against a complete vacuum (zero), while gauge pressure is measured relative to the surrounding atmospheric pressure [118].

The choice of metering equipment depends on several factors, including fluid characteristics, operating environment, required accuracy, and budget constraints [117]. However, the selection of specific metering devices falls outside the scope of this work. Researchers are free to use any metering equipment that meets their data requirements. While higher accuracy is always preferable, it often comes at a higher cost.

Furthermore, it is proposed that the metering is installed after the continuous water users to ensure that wastage within the working areas are identified. An example is displayed in the schematic diagram seen in Figure 17. Here, the supply line provides high pressure water to the continuous water user. Afterwards, the water pressure is decreased and supplied to mining operations and any water not used by mining is returned in the return water line.

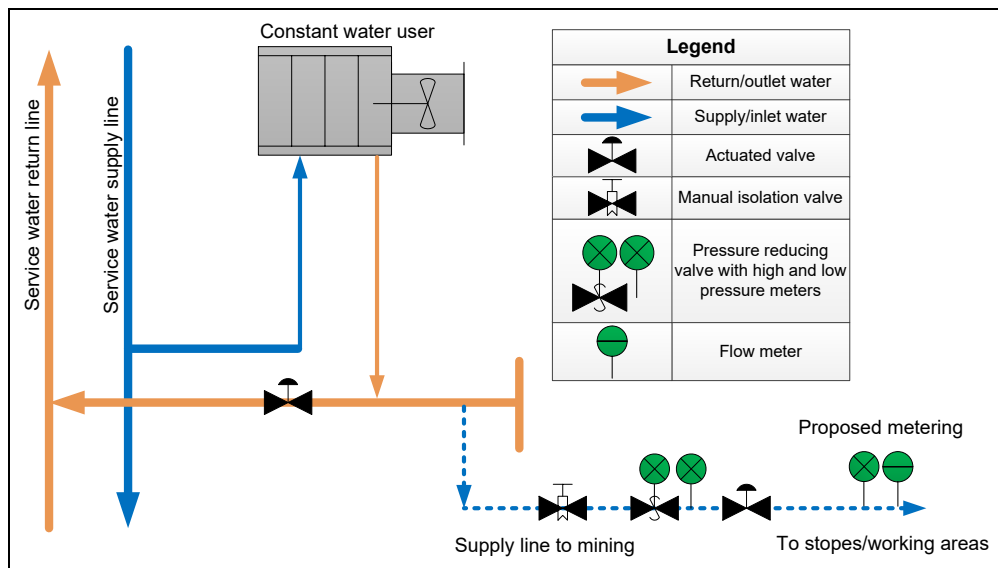


Figure 17: Typical schematic diagram of metering installation after continuous water users [111].

The values obtained from the metering equipment should be verified to ensure measurement accuracy. A simple and efficient approach is to install additional portable measuring devices to compare readings and identify discrepancies. MAPE can be used to quantify the accuracy.

Once the monitoring equipment has been verified, a system must be implemented to retrieve the data and enable remote access. In mining operations, SCADA systems are commonly used for this purpose [119].

The installed sensors continuously track parameters such as water flow and pressure. The collected data are transmitted as analog or digital signals, with analog signals first converted to digital format before being sent to Programmable Logic Controllers (PLCs) located on surface or underground depending on the operation [120].

PLCs serve as the primary data processing units, interpreting and digitising sensor signals [119]. To facilitate communication between PLCs and SCADA, object linking and embedding (OLE) for process control (OPC) servers are used. These servers standardise the data format from PLCs, ensuring compatibility with SCADA and other third-party applications such as historians and reporting tools [121]–[123].

Once processed, the data are transmitted to the SCADA system, where it is logged for historical analysis and trend monitoring. This structured data flow ensures continuous monitoring, quick decision-making, and automated responses, improving operational efficiency and sustainability in deep-level mining operations.

The physical installation of equipment, establishment of communication networks and integration with SCADA fall outside the scope of the study and are not discussed.

2.4.4 Dynamic ZWB establishment

The final step is to integrate all the preceding steps to form the dynamic ZWBs. The process begins with ensuring accurate water allocation, which is managed using the employee tracking system. Information such as crew names and job descriptions are linked to employee profiles. Each working area is allocated a certain crew. Since specific crews are assigned to designated working areas, only employees allocated to the area in question are considered.

Next, job descriptions are filtered to identify whether the employee entering the working area is a water consumer (this will differ from mine to mine). If so, the system identifies the type of water user to ensure the correct water-consuming tool is assigned. The equation developed, as seen from Equation 2, for that specific tool is used to determine the water consumption. The actual water pressure of the working area needs to be substituted into the equation. This is obtained from additional metering installed in the vicinity. Figure 18 displays a flow diagram used to visually explain the procedure.

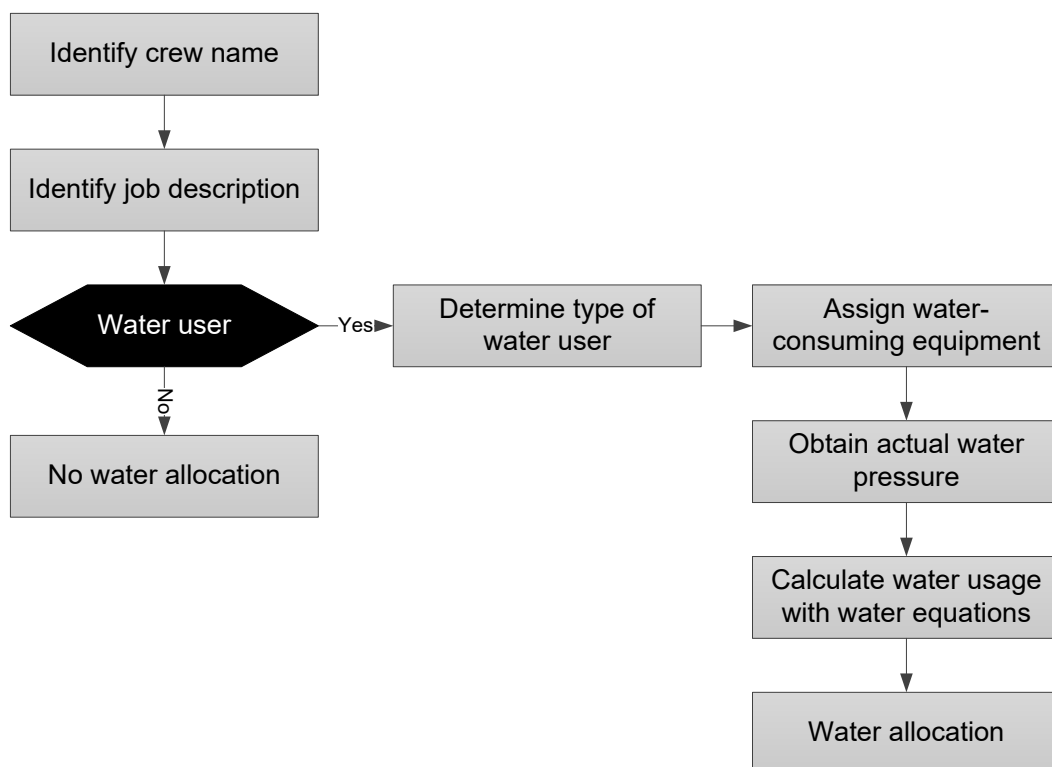


Figure 18: Dynamic ZWB development flow diagram (adapted from [112]).

An example of the above-mentioned procedure is illustrated in Figure 19. Four miners enter working area A, where an RFID reader A logs their activity. The miners are classified as follows:

- Miner A: Assigned to working area A and designated as a water user;
- Miner B: Assigned to working area A and designated as a water user;
- Miner C: Not assigned to working area A, but designated as a water user; and
- Miner D: Assigned to working area A, but not designated as a water user.

As a result, water allocation for working area A is only granted to Miners A and B. Water will not be allocated to miners C and D due to them being in the incorrect area or not designated as water users. Predefined water tools, corresponding to each miner's job description, are allocated. The water consumption for each miner is determined based on the equation associated with the assigned tool.

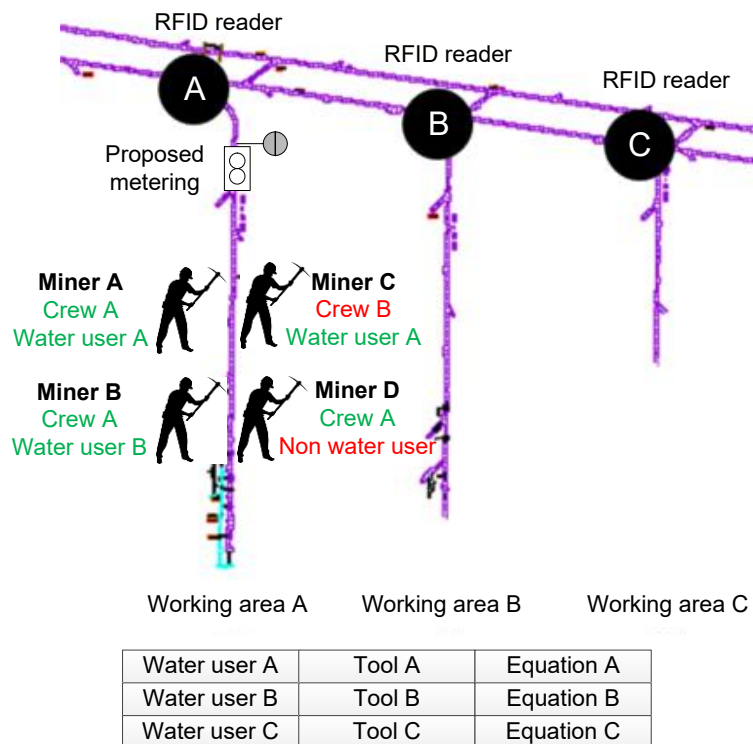


Figure 19: Example of water allocation.

The above-mentioned procedure is repeated for each employee entering the area. To strengthen verification, it is proposed that surveys be conducted to gather information on the type and quantity of water-consuming tools present in the specific working area. This data can

serve as an additional layer of validation. The filtering process should be automated to ensure it runs continuously with any suitable software capable of performing the required filtering.

This approach allows the developed baselines to dynamically adjust, reflecting both operating conditions and employee movements. By comparing the dynamically updated baselines with the actual water consumption from the additional metering, continuous detection and monitoring can be done.

An example of the dynamic ZWB compared to actual water usage in a working area is shown in Figure 20.

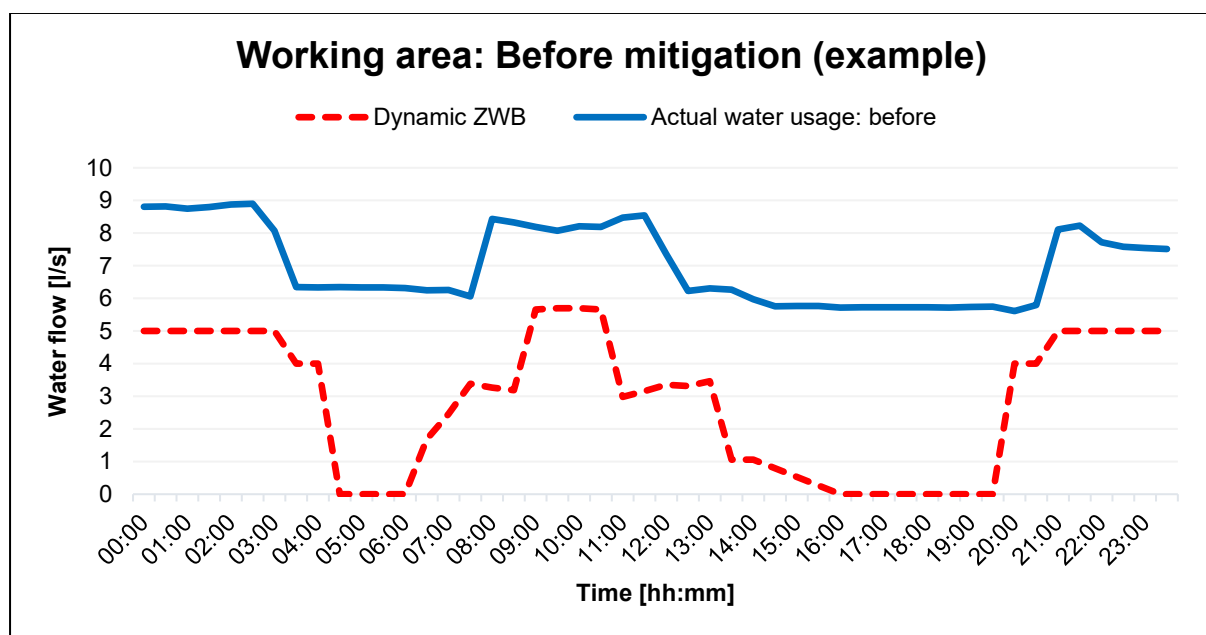


Figure 20: Comparison between the actual water usage in the working area and dynamic ZWB (example).

Before implementing these baselines, verification is needed to ensure their accuracy. This step confirms that the baselines are realistic and achievable, rather than unrealistic targets that employees can never meet. Setting unattainable baselines makes them ineffective and demotivating, even when efforts are made to improve water usage. Research found that the acceptable verification range for water wastage is between 22 – 84% [15]. Therefore, the difference between the actual water usage and dynamic ZWB should be determined to ensure that the wastage falls within the specified range. Table 8 depicts the results referring to Figure 20.

Table 8: Example values for verification

Total daily actual water usage [MI]	0.61
Total daily dynamic ZWB water usage [MI]	0.25
Total daily water wastage [MI]	0.36
Total daily water wastage [%]	59

In this case, the wastage is calculated to be 59%, which falls within the acceptable verification range. Furthermore, Figure 21 displays the profile throughout the day, showing that the wastage remains within the verification range. As such, it is considered an acceptable result for use.

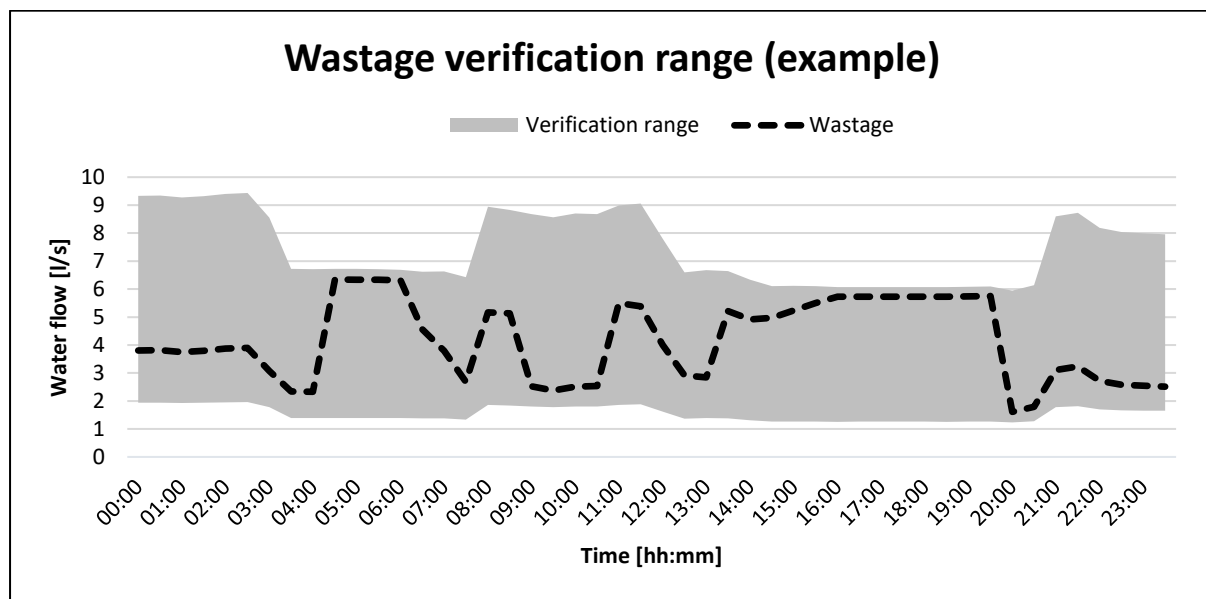


Figure 21: Wastage verification range example for a working area (example).

Verification is further reinforced by measuring how closely the dynamic ZWB aligns with actual consumption after employees have confirmed the mitigation of any issues. This ensures that the baseline accurately reflects improvements in water usage.

The developed baselines need to be made available to the mine to identify wastage by comparing them to the actual water consumption measured by the metering. Considering the dynamic nature of these baselines, it is proposed that they be automatically calculated and displayed daily by a program or system to ensure frequent and dynamic identification. Any program or system that can achieve this may be used by the researcher. The specific system used in this thesis is mentioned in Chapter 3.

2.5 Step 4: Accountability incorporation

Accountability is used to ensure that identified issues are mitigated and monitored for sustainability. From Section 1.4, accountability drivers and benefits have been established from literature. To ensure the successful implementation of this method, all accountability drivers must be addressed. The effectiveness of incorporating accountability into mining operations is verified by meeting these established drivers/components. Adhering to the key aspects of accountability, as highlighted by previous researchers, ensures a successful integration, as supported by literature.

A bespoke accountability model should include four main components, which are *define*, *assess*, *execute*, and *communicate* [106]. These steps serve as the core of the method, and it should be ensured that all four steps are addressed. Figure 22 displays the four steps together with the main outcome that should be addressed within the corresponding step as obtained from the literature study conducted in Chapter 1 (Section 1.4).

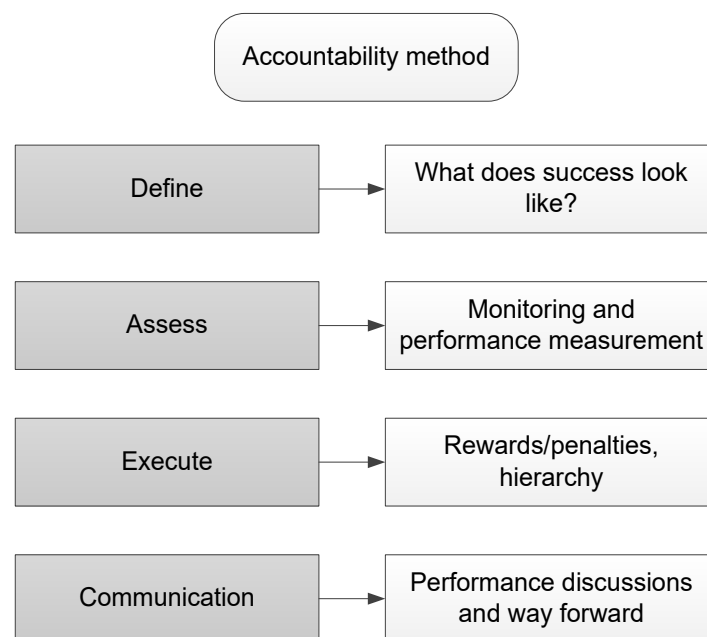


Figure 22: Accountability method [112].

2.5.1 Define

The first and most important part of accountability is to clearly define expectations as a direct link has been made between clear expectations and outcomes [97]. Emphasis should be placed on clearly defining “who” accountability is given to and “what” employees are responsible for.

It has been found that hierarchical structures are critical to ensure that accountability is enforced. Mining operations already have hierarchical structures in place that can be used. It is proposed that employees working within the areas are responsible for fixing issues. The person in charge of each working area should ensure that employees are held accountable. The responsible person needs to report to the top management. An example of a typical hierarchical structure in a deep-level gold mine is given in Figure 23.

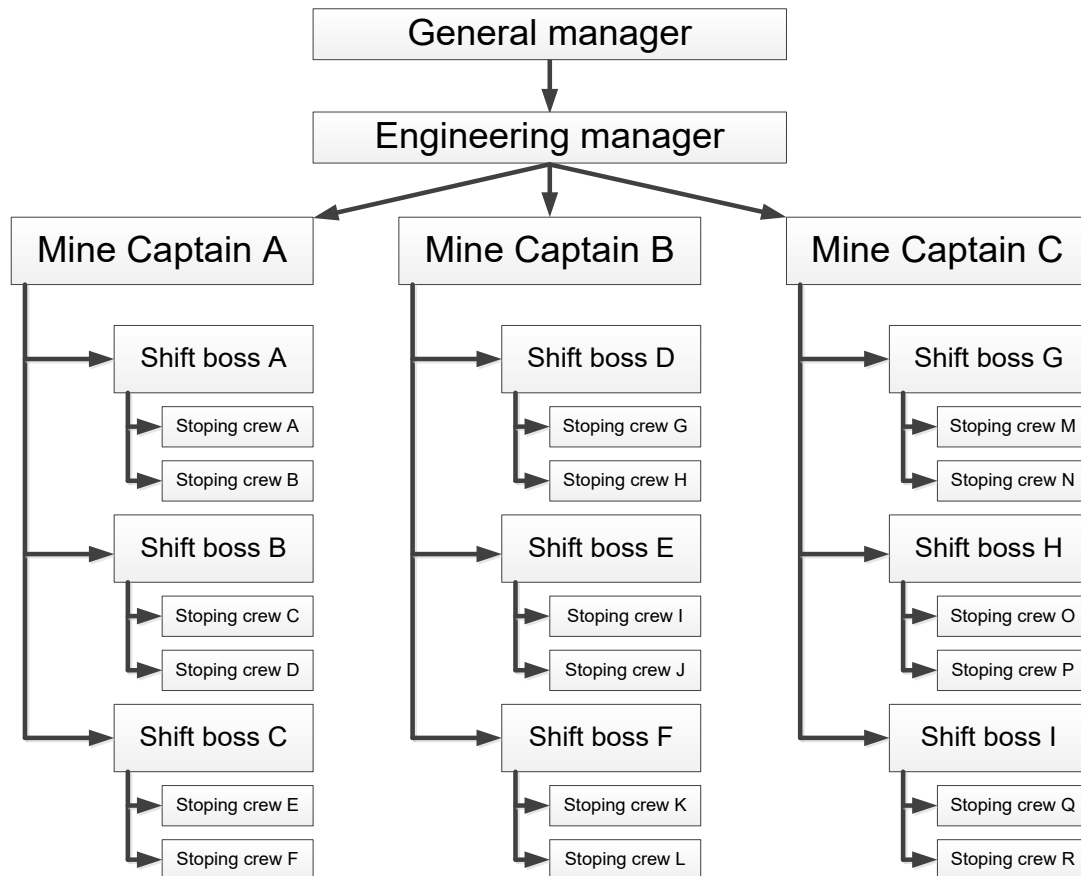


Figure 23: Typical example of hierarchical structure on deep-level gold mine [16], [49].

Next, success metrics should be established, defining what success should look like. In this context, success is represented by the dynamic ZWBs, which serve as the operational standard for best practices in water consumption.

Each working area will have its own dynamic baseline, developed to its operational conditions and employee movements. Since these baselines adapt dynamically, they can help maintain employee motivation by aligning with production needs. Unlike static baselines, which may become obsolete or feel unattainable, dynamic baselines adjust as necessary, ensuring realistic and achievable targets.

Ensuring that employees understand what is expected of them fosters transparency and supports the alignment of both organisational and personal objectives.

2.5.2 Assess

Once the expectations have been clarified, performance monitoring should be incorporated to compare the actual performance to the success metrics. Here, the dynamic ZWBs should be compared to the actual water usage in the working area which is obtained through the installed equipment. Performance assessments should be readily accessible to all stakeholders to promote transparency. Numerous methods exist to monitor performance. These include:

- Reporting structures;
- Online applications; and
- Email correspondence.

Goosen [124] has shown the benefits of using an energy management information system (EMIS). This system enables data processing from different sources to a generic format and stores it within a database. Thereafter, the data are extracted, analysed and presented in energy reports or dashboards. This includes, but is not limited to:

- System tracking – performance monitoring of different energy-consuming areas; and
- Custom views – includes user-specific analysis and reporting.

However, any form of performance tracking can be used, as long as the performance of each individual working area is measured. This assists with the continuous monitoring of each working area to ensure sustainability. Employees responsible for each area need to answer for the performance.

By incorporating accurate performance measures and monitoring, impacts are obtained, and employees are evaluated fairly and to the same standards.

2.5.3 Execute

Execution refers to the repercussions if expectations are not met. Employees must be aware of the consequences of failing to meet expectations. Employees failing to meet targets are held accountable by having to answer to higher authorities. Here, the hierarchical structure is used as it has been noted to be an effective driver of accountability. Hierarchical structures are essential for defining how responsibilities are distributed among departments. This allows

for a bottom-up approach, allowing employees at lower levels to resolve identified issues before they are publicly announced.

Literature conducted in Section 1.4.1 has revealed that even though financial incentives have positive impacts, they should be avoided to decrease the risks of labour strikes and disputes. Social pressure, career implications, praise or constructive feedback can also be used.

It is important to give employees time to fix identified issues, but strict timelines should be established to ensure that issues are fixed promptly. Employees who fail to meet deadlines need to answer to higher authorities.

Moreover, research has highlighted that focus should not only be placed on employees failing to meet targets but also on giving recognition to employees exceeding expectations. This includes public acknowledgement for good performance. This can include public acknowledgement by displaying employee names on public platforms or awarding them unique clothing as a mark of outstanding performance.

2.5.4 Communication

Lastly, the performance as measured by the baselines must be discussed. Here, employees being held accountable should be granted an opportunity to explain why inefficiencies occur within the working area. Moreover, the way forward also needs to be discussed to ensure that all employees are aligned.

Literature has highlighted the importance of open lines of communication. This can be achieved through regular meetings, private messages, notice boards in working areas, and similar methods where issues, solutions and timelines are displayed and discussed.

It is important that all stakeholders are present and made aware of all communications to ensure transparency throughout.

2.5.5 Sustainable improvement

By following and implementing the accountability method outlined above, a sustainable improvement is achievable. Accurate and dynamic baselines are used to continuously detect water wastage in working areas. These baselines serve as clear and transparent success metrics for employees to follow.

Performance monitoring is incorporated to track the water usage performance. Responsible personnel are assigned to fix identified issues within strict timelines, ensuring that problems

are addressed promptly. Open communication allows for ongoing discussions regarding performance and the way forward.

To ensure proper enforcement, a hierarchical structure is in place to manage responsibilities and actions aimed at reducing water wastage. Employees failing to mitigate issues within the communicated period must answer to higher authorities as this has proven to be a successful driver. At the same time, good performance is recognised, encouraging employees to maintain high standards. This recognition avoids financial incentives to prevent potential issues that may arise from monetary rewards.

Accountability has been proven to be a powerful driver of performance when implemented correctly. Since this approach has never been applied to mining systems, a phased rollout may be necessary. However, if implemented correctly, significant benefits can be achieved. The accountability method developed here incorporates all critical components and considers all key aspects to ensure long-term success and deem the method as verified.

2.6 Verification of proposed method

The developed method consists of several steps. These steps need to be tested to ensure that they are implemented correctly to achieve what they were set out to do. This is referred to as the verification of the method. The verification of each step is discussed throughout Chapter 2. Table 9 presents a summary that highlights the solution criteria achieved, thus verifying the method through demonstrated compliance with the defined objectives. These criteria are selected to align with the study objectives of the thesis, thereby ensuring that the problem and need are addressed.

Table 9: Assessment of the study criteria compared to developed method for verification.

Item	Addressed	How	Section	Step
Develop dynamic ZWBs	Yes	Baselines dynamically adjust according to the operating conditions and employee movement for each working area. Water tools' consumption adjusts according to actual tested performance.	2.4	3

Chapter 2: Methodology

Localise water wastage within working areas	Yes	Baselines for each working area are developed and compared to the actual consumption in the area measured by the installed metering.	2.4.3 and 2.4.4	3
Detect continuously	Yes	Actual readings are continuously compared to the ZWBs to detect wastage. Daily performance monitoring is done using the developed platforms.	2.5.2	3
Incorporate accountability for mining operations	Yes	Accountability is incorporated to define, assess, communicate and execute, including all important drivers from literature.	2.5	4
Promptly identify and mitigate issues	Yes	Identification can occur within the working areas, helping to localise issues more quickly. This is made possible by the dynamic ZWB and the installed metering. In addition, accountability has been implemented so that employees understand what is expected of them and take responsibility for fixing issues. The metering also allows for continuous monitoring to ensure that water consumption stays below the ZWB.	2.4 and 2.5	3 and 4
Achieve sustainable improvements	Yes	Sustainability monitoring is done by assessment platforms. Together with the baselines and accountability, issues are promptly detected and mitigated as they occur, seeing that a clear plan is available and all employees know their expectations, ensuring sustainable improvements.	2.5.5	4

Obtain actual cost savings	Yes	Actual cost savings are achieved as water leaks are mitigated and confirmed by the comparison between the baselines and actual water usage.	2.4.4 and 2.5.5	4
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Next, the verified method should be implemented in a real-world application to test the effectiveness thereof. The method is considered successful if its implementation achieves the predefined objectives. Successfully meeting these objectives through real-world application serves as validation of the method.

2.7 Conclusion

The method developed here consists of scope identification, data gathering, dynamic ZWB development and accountability incorporation. The method adheres to the study objectives which are:

1. To install monitoring equipment in closer proximity to working areas to improve sustainability monitoring.
2. To develop and implement dynamic ZWBs to localise water leaks in working areas and enable continuous detection.
3. To develop and implement an accountability method for mining operations.
4. To detect and mitigate inefficiencies faster than with previous methods.
5. To quantify cost savings by mitigating water leaks.
6. To ensure sustainable water leak mitigation through continuous monitoring.

An overview of the developed method is displayed in Figure 24.

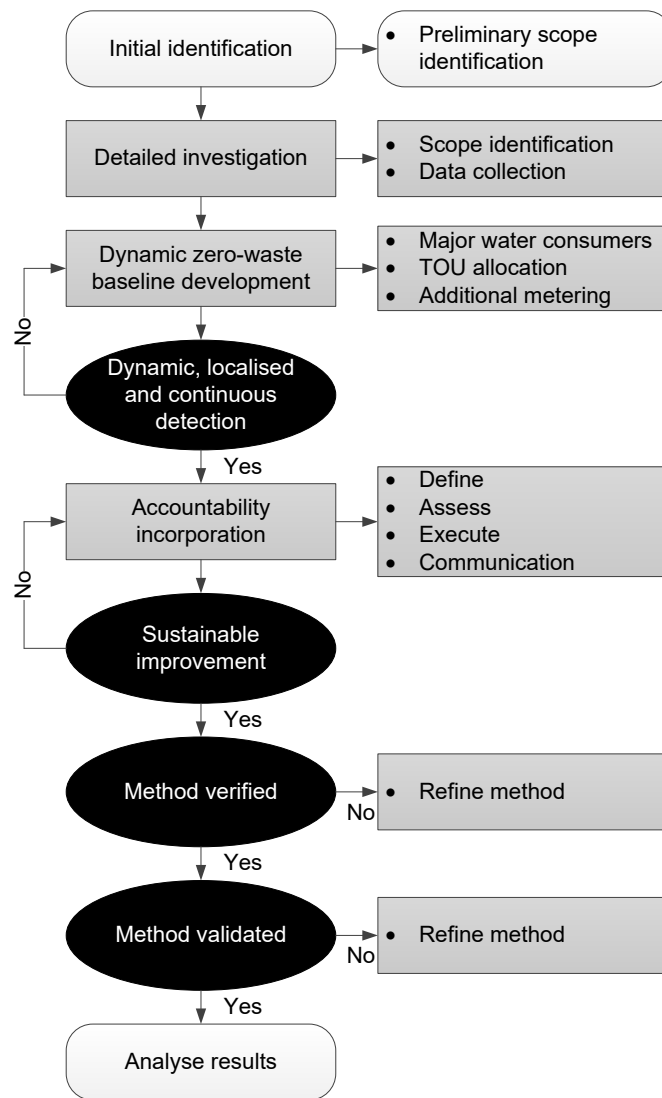


Figure 24: Flow diagram of the developed method.

Chapter 3 discusses the implementation and subsequent results of the proposed method in one case study. This will assist to determine the reliability on a practical mining system.

CHAPTER 3: RESULTS & EVALUATION

"Vision without execution is just hallucination." – Thomas Edison



³ Personal photo taken by the author.

3 Results & Evaluation

Chapter 3 focuses on the implementation of the verified method in a real-world scenario to validate it. The results section is followed by the conclusion and recommendations of the thesis.

3.1 Case study introduction

The method developed in Chapter 2 (Figure 24) was applied in a case study to evaluate its effectiveness in a real-world setting. For confidentiality reasons, the case study mine is referred to as Mine A.

Mine A is a deep-level mine located in the North-West province near Klerksdorp, South Africa. The mine's geology is structurally complex, comprising three distinct mining areas. Its primary orebody is the Vaal Reef, which is mined at depths ranging from 1 791 m to 3 052 m below the surface.

In 2024, Mine A produced approximately 938 000 tonnes of rock, yielding a total gold production of 6 499 kg at an average grade of 8.03 g/t. The mine's energy distribution is illustrated in Figure 25, with refrigeration and pumping accounting for approximately 31% of the total energy usage. Mine A's refrigeration system has an installed electrical capacity of 6.3 MW and a pumping system electrical capacity of 22.8 MW.

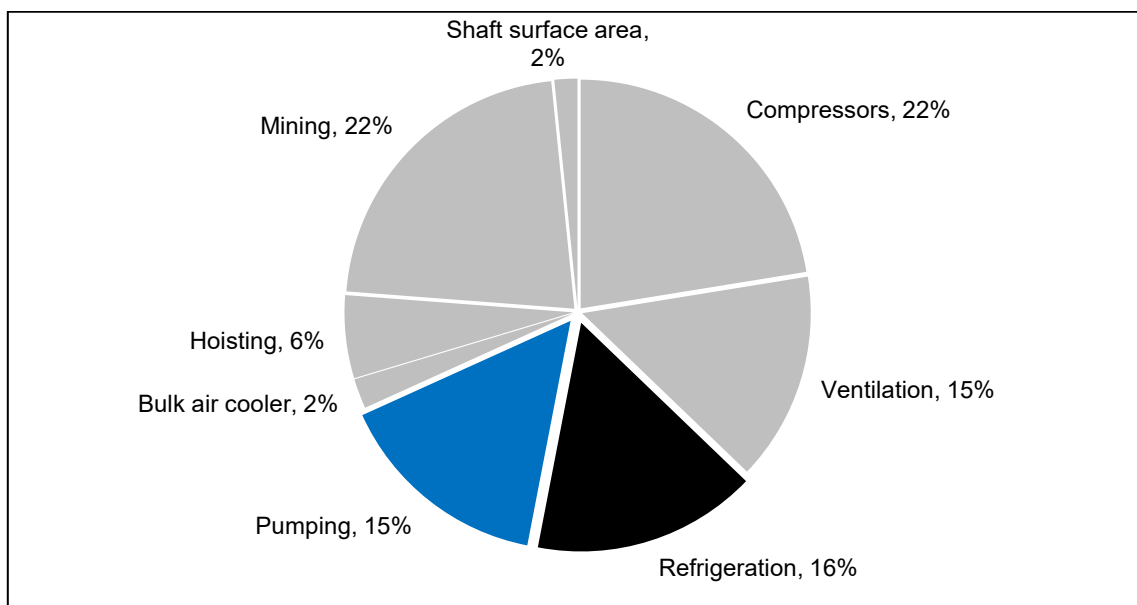


Figure 25: Mine A energy consumption distribution.

This chapter discusses all the steps of the developed method, as set out in Chapter 2, that were implemented on Mine A. The water layout of Mine A is shown in Figure 26.

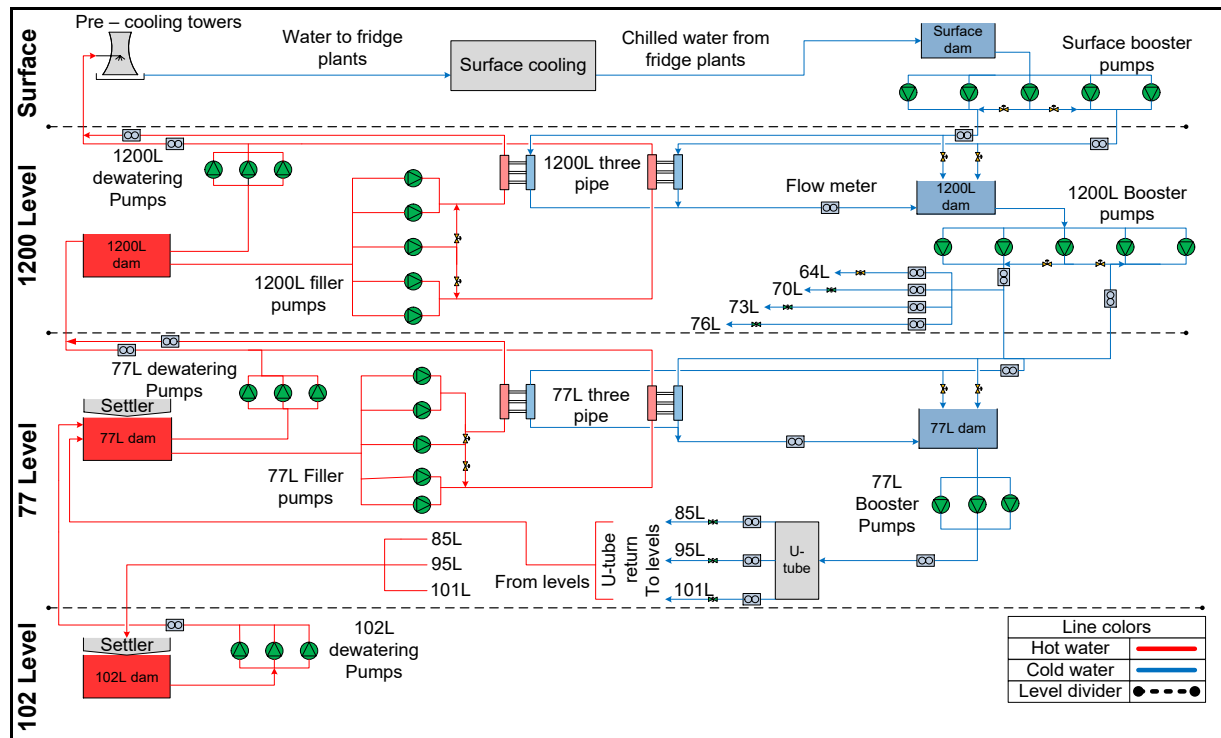


Figure 26: Mine A water layout.

3.2 Step 1: Initial identification

Initial identification was done by comparing the shaft water intensities from 2022 to 2024. Figure 27 depicts that the total shaft water intensity increased from 2022 to 2024. This is also significantly above the targeted water intensity (obtained from Mine A) as displayed. This means that more water is used by the operation without producing additional tonnes, indicating potential water wastage.

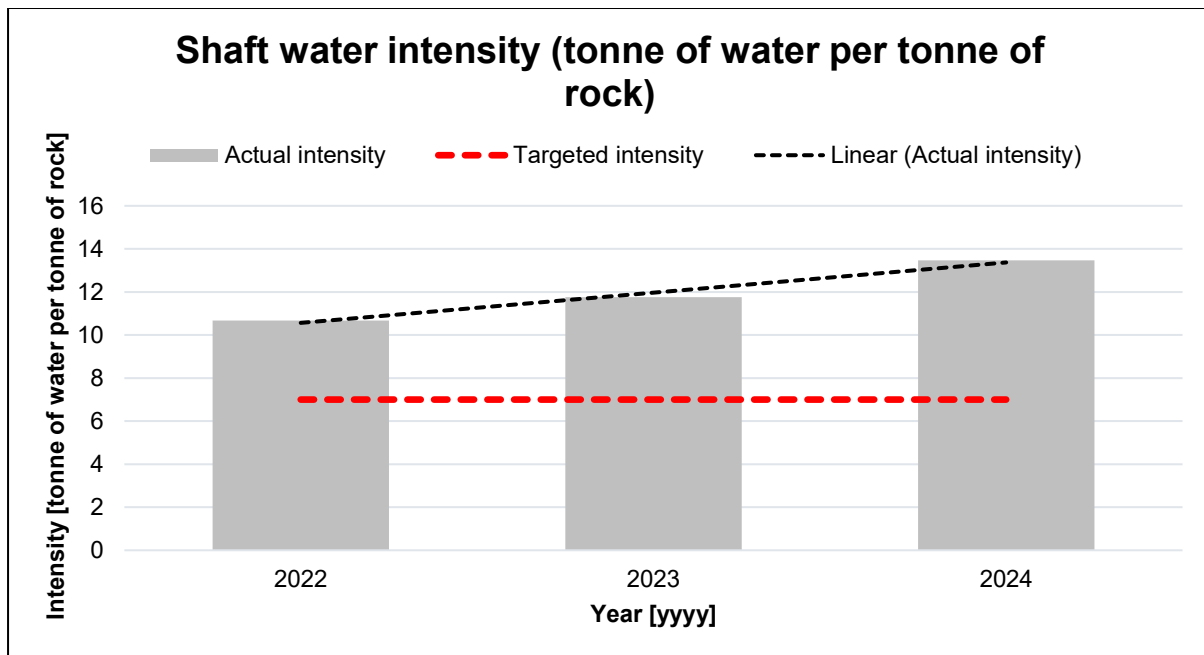


Figure 27: Mine A water intensity.

A detailed investigation was needed to confirm the potential scope identified and determine if the operation would benefit from the implementation of the proposed method.

3.3 Step 2: Detailed investigation

A detailed investigation was conducted to validate the potential scope identified in the previous section. This involved evaluating existing methods used in the case study to localise water leaks within working areas, assessing whether water leaks present a significant issue, and establishing a benchmark for comparison with the developed method. Based on the outcomes of this investigation, the developed method was deemed suitable for implementation. A comprehensive examination of the case study was carried out to gather all necessary information.

3.3.1 Scope identification

The current methods used on Mine A for localised detection within working areas include step-testing and underground audits.

Service water step testing, also referred to as drop testing, is a method used to identify water wastage when no personnel are working underground during non-entry periods as explained in Chapter 1. Here, the author applied this existing method to assess whether water wastage was a concern at the case study mine. A portable water flow meter was installed upstream of

the network being tested. The flow meter used was an ultrasonic water flow meter as seen in Figure 28. Here, the flow meter was installed per level and manual valves in the working areas were sequentially opened and closed to measure the water consumption of each area when no mining took place. During this time, theoretically no water should be used as no users are working underground. Any water consumption measured is attributed to wastage.



Figure 28: Ultrasonic water flow meter used.

Table 10 presents the drop test results for Mine A over a period of three months prior to applying the developed method, focusing on the top five working areas with the highest water wastage. It is important to note that the results are displayed as fixed values, as they are measured instantaneously and recorded monthly when tests are conducted. These tests are only performed once per month due to their resource and time-intensive nature, requiring the manual installation of a portable meter per level and the isolation of each working area.

The results shown in Table 10 were shared monthly with top management for mitigation, as recommended by the literature. However, water wastage was still present within three months when the tests were repeated, highlighting that issues are not being addressed. Recurring leaks are highlighted using colour coding in Table 10. This shows that no corrective actions have been taken over a period of three months, as some of the issues still persist. This approach highlights a key limitation: accountability cannot be effectively assigned based on instantaneously measured values, as success metrics remain unclear.

Considering the static and infrequent nature of these tests, the focus is placed solely on mitigating the most significant issues to provide better chances that they are addressed. However, this is not always the case, as seen in the results provided here. In practice, when a list of numerous leaks is provided, it is often ignored as accountability becomes difficult to enforce. Therefore, only the five most critical issues were highlighted.

Furthermore, to validate whether issues have been resolved, the test must be repeated, reinforcing this method's inefficiency in tracking sustained improvements. It's also important to note that, while some leaks reoccurred, others did not. However, this is largely due to the table only displaying the top five areas with the highest levels of wastage. Some problematic areas may have dropped out of the top five but still remain an issue. This is a result of the snapshot nature of the data. For instance, in Month 1, more inactive equipment might have been left open than in Months 2 or 3. This does not mean the problem was fixed, it just did not rank in the top five when the tests were conducted again. This again shows that the current methods are insufficient and do not provide accurate enough data to hold personnel accountable.

Table 10: Drop test results from Mine A (Top 5 areas with the highest water wastage).

Month 1			Month 2			Month 3		
Level	Working area	Wastage [l/s]	Level	Working area	Wastage [l/s]	Level	Working area	Wastage [l/s]
A	35	44	A	51	11	B	51	17
A	57	18	B*	36	10	A	62	11
A*	38	15	A	32	10	A*	36	11
B	33	15	A	63	8	B*	36	11
A*	36	14	A*	38	8	A	62	9

*Colour coding used to show recurring leaks. For instance, Level A working area 36 (coloured in red) is first noted in Month 1 and recurs in Month 3.

In addition, underground audits were conducted by the author to localise water wastage within working areas. This process required employees to physically walk through the entire network to identify issues. Similarly to step testing, water wastage identified by audits are only displayed instantaneously when tests are performed. However, issues are not quantified as done for step testing, only marked. Auditors typically relied on visual inspection, classifying issues as small, medium, or large.

Figure 29 shows a screenshot of a mining level on Mine A where service audits were conducted. One audit took two employees approximately 6.5 hours to cover a total distance of just over 22 km. This process is highly time intensive and physically demanding, which limits audit frequency to once per month.

Once an audit was completed, the results were given to top management for corrective action. Issues were marked on a layout, as seen in Figure 29, so personnel knew exactly where they occurred to ensure prompt mitigation. The figure clearly shows that most issues occur in working areas, confirming findings in the literature.

Employees reported that issues were fixed after a month of initial identification, but a follow-up audit on the same mining level identified recurring problems, highlighting that issues were not fixed. As seen in Figure 29, many of the same issues reappeared, proving that they were not properly addressed. After three months of using time-intensive methods to identify and mitigate issues, they still persist, showing that the current approach is ineffective. Employees are unaware of their roles and responsibilities regarding leak repairs, and no success metrics exist to hold them accountable.

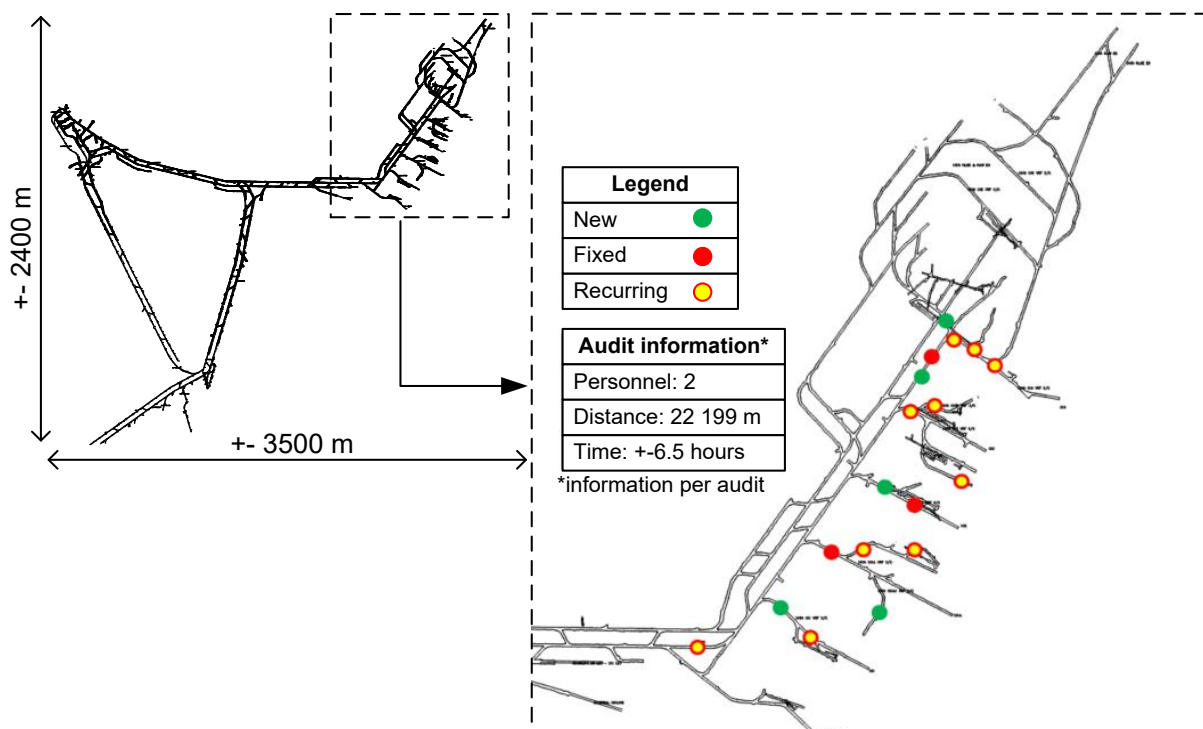


Figure 29: Service audit results on a mining level on Mine A.

The two methods currently used at Mine A demonstrate that water wastage identification is both time- and resource-intensive, with no mitigation or monitoring measures in place.

Furthermore, the infrequency of these audits, conducted only once per month, delays detection, resulting in recurring water wastage even after three months. This highlights the inefficiency of current approaches. The results obtained here were compared to those from the implementation of the verified method to assess its effectiveness in improving detection and mitigation.

3.3.2 Data collection

All necessary information and access were obtained from the Mine A personnel. This included water users, working schedules, production schedules and data, water flow data, access to employee tracking systems, hierarchical structures and underground layouts.

According to the production schedules, Mine A currently have approximately 75 operational working areas. Working areas consist of two or three panels, depending on the specific area.

Underground audits were conducted to identify all water-consuming equipment, the number of tools and their locations. Discussions with mining personnel confirmed this. The major intermittent water consumers identified on Mine A are displayed below, with a detailed summary available in Appendix B: Water users on Mine A.

- Orange hoses for water distribution to rock drills and washing down the rock face;
- Victoria rock drills to drill holes in the rock face for explosives and support (for heavy duty use);
- Conventional rock drills to drill holes in the rock face for explosives and support (for standard use);
- Omni props to inflate hydro plates used for support;
- Blue jackpots for roof support;
- Bazookas for washing the rock face – being phased out and replaced by waterjets; and
- Waterjets for washing the blasted rock into the strike gully.

Figure 30 displays pictures taken by the author of some of the tools identified during the audits conducted on Mine A.



Figure 30: Intermittent water-consuming tools identified on Mine A.

3.4 Step 3: Dynamic ZWB development

This section focuses on the development of the dynamic ZWBs, which consist of three steps, namely major water consumers, TOU calculations and additional metering installations. Each step is discussed in detail, ultimately forming the dynamic ZWBs.

3.4.1 Major water consumers

The first step was to identify the major intermittent water consumers to conduct tests for the actual water usage in the underground environment. The underground test bench is displayed in Figure 31. The test bench includes a pressure-regulating valve used to vary the pressure between 2 and 16 bar (the typical operating range of equipment).



Figure 31: Underground test bench to conduct water tests.

Here, a portable ultrasonic water flow meter as seen in Figure 28 and portable pressure logger displayed in Figure 32 were used to record the water pressure and corresponding water flow.



Figure 32: Portable pressure logger used.

The data obtained were used to develop scatter plots to establish water consumption equations. The equations of the corresponding water-consuming tools are shown in Table 11, with scatter plots and MAPE verification displayed in Appendix C: Intermittent scatter plots and MAPE verification. The data measured are deemed to be accurate, seeing that the flow meter has been calibrated. The calibration certificate is displayed in Appendix D: Portable ultrasonic water flow meter calibration certificate.

Here:

x – water consumption in l/s

y – water pressure in bar

All equations have an R^2 value close to 1, indicating that equations closely represent actual water consumption at corresponding pressures.

Table 11: Major intermittent water-consuming tools with developed equations.

Equipment name	Trendline equation	R^2 Value
10mm hose	$y = -0.0015(x)^2 + 0.0823(x) + 0.0127$	0.9986
25mm hose	$y = 1.7913 \ln(x) + 0.3892$	1.0000
Victoria rock drill	$y = 0.2441 \ln(x) - 0.0197$	0.9927

Conventional rock drill	$y = -0.0003(x)^3 + 0.0075(x)^2 - 0.0144(x) + 0.2681$	0.9904
Omni prop	$y = 0.0181(x) + 0.076$	0.9979
Blue jackpot	$y = 0.0001(x)^2 + 0.006(x) + 0.0062$	0.9821
Bazooka	$y = 1.5879 \ln(x) + 0.5216$	0.9953
Waterjet	No correlation function as a high-pressure pump is used to ensure the designed water flow—2.67 l/s.	

As suggested, the manufacturer specification sheet values were compared to the values obtained by using the verified equation to determine the discrepancies between the two. An example is shown for the Victoria rock drill as a specification sheet is available and this component is widely used. Figure 33 displays the comparison between the water flow calculated using the verified equation and the water flow obtained from the specification sheet of the Victoria rock drill. The difference between the values becomes more significant as pressure increases.

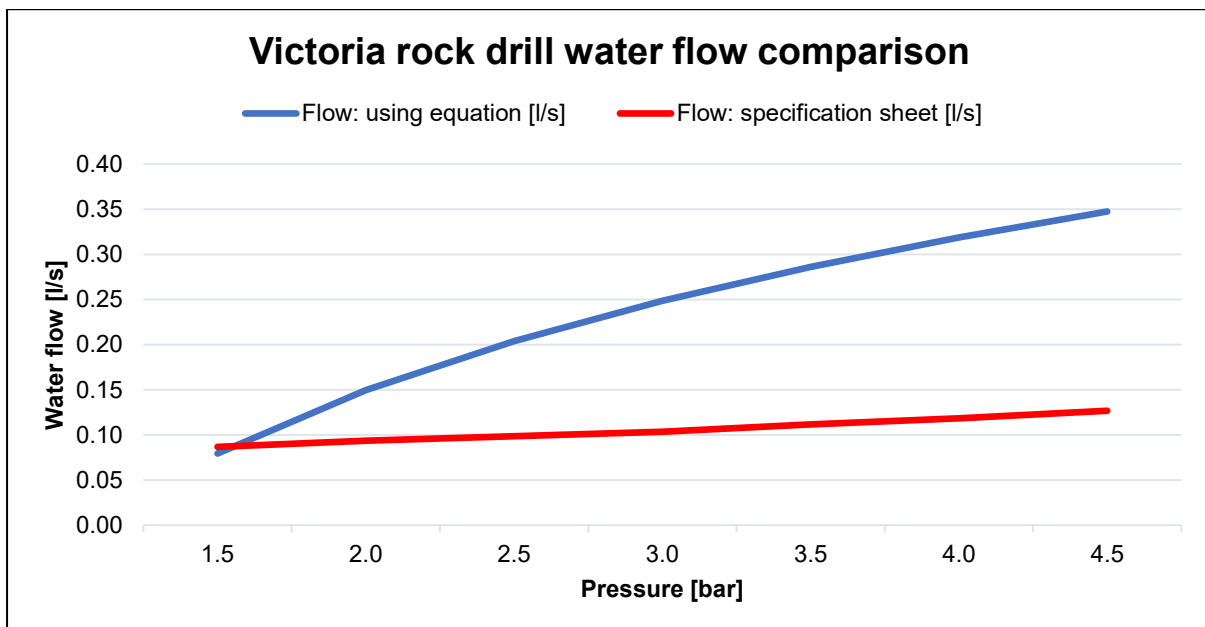


Figure 33: Flow comparison between the specification sheet and actual measured values represented by the verified equation for the Victoria rock drill.

Table 12 displays the MAPE calculation for the values portrayed in Figure 33. The MAPE for the analysis goes as high as 174%, clearly showing that the water flow shown on the specification sheets differs significantly from the actual measured values. This might result in inaccurate readings when relying on values from the specification sheets.

Table 12: MAPE calculation for Victoria rock drill.

Pressure [bar]	Flow: using equation [l/s]	Flow: specification sheet [l/s]	MAPE [%]
1.5	0.079	0.087	9%
2.0	0.149	0.093	60%
2.5	0.204	0.098	107%
3.0	0.248	0.103	140%
3.5	0.286	0.112	156%
4.0	0.319	0.118	169%
4.5	0.347	0.127	174%

The significant differences observed here are explained by the following paragraph quoted from the specification sheet: *“It must be appreciated that the figures shown do not in any way reflect drilling performance in run-of-mine conditions. They were derived from controlled drilling tests in a laboratory environment. The rockdrill was mounted on a free running cradle set horizontal. The test block used was Noritic granite of 300 mPa uniaxial compressive strength. Drill steel was 22 mm hexagon with a brand new 36 mm diameter button bit fitted. All variables of air pressure, water flushing pressure and thrust force were closely controlled and monitored. The rockdrill used was brand new and in-hole drill steel positioning was set in correct alignment throughout the test.”*

Therefore, using values from the specification sheets is not advised by the researcher as these values are obtained from tests conducted in controlled environments. In contrast, using the actual calculated values ensures that the correct water consumption is allocated to equipment based on the conditions experienced underground.

3.4.2 Time of use calculations

Mine A makes use of the Missing Persons Locator (MPL) system to track employees' locations. This system is commonly used in South African gold mines where data logged is stored within the mine's internal databases. The data stored are logged according to the time when employees passed RFID tag readers, as displayed in Figure 34. This includes the tracking information for every employee across all areas of the mine.

Chapter 3: Results & Evaluation

abc region	abc zone_name	abc direction	abc location	observed	observed_UTC	abc job_categories
083 Level	083SS201	Workings	Underground	2024-06-16 17:34:54.000	2024-06-16 15:34:54.000	(004E058) Shaft Assistant
120 Level	120SS202	Workings	Underground	2024-06-16 17:34:49.000	2024-06-16 15:34:49.000	(004E092) Engineering Assistant
120 Level	120SS202	Workings	Underground	2024-06-16 17:34:44.000	2024-06-16 15:34:44.000	(004E092) Engineering Assistant
120 Level	120SS202	Workings	Underground	2024-06-16 17:34:34.000	2024-06-16 15:34:34.000	(004E092) Engineering Assistant
120 Level	120SS201	Shaft	Underground	2024-06-16 17:33:54.000	2024-06-16 15:33:54.000	(004E063) Asst-Conveyance Operation
Decline 4	D4CXC701	126L	Underground	2024-06-16 17:33:36.000	2024-06-16 15:33:36.000	(004E002) Chairlift Operator
Decline 4	D4CXC701	126L	Underground	2024-06-16 17:33:36.000	2024-06-16 15:33:36.000	(004E002) Chairlift Operator
083 Level	083CPV01	Mid	Underground	2024-06-16 17:33:33.000	2024-06-16 15:33:33.000	(004E058) Shaft Assistant

Figure 34: MPL system data entries of employee movements.

For the purpose of this study, employees were filtered based on crew names and job descriptions corresponding to their designated working areas. Job descriptions were specifically filtered to include employees who operate water-consuming tools, as outlined in Table 11. The filtering process was performed using Python 3.12. However, the Python script is not included due to the presence of confidential information. The following water users have been identified:

- Night shift cleaner;
- Rock drill operator;
- Waterjet operator; and
- General miner.

The Python script accesses the mine's internal MPL database. Thereafter, the script filters the data for water users and allocates them to specific working areas by considering the crew names working within the working area. Figure 35 displays the employee movements filtered according to water users for a working area on a random day. The total employee movement is also included to highlight the difference between the two profiles.

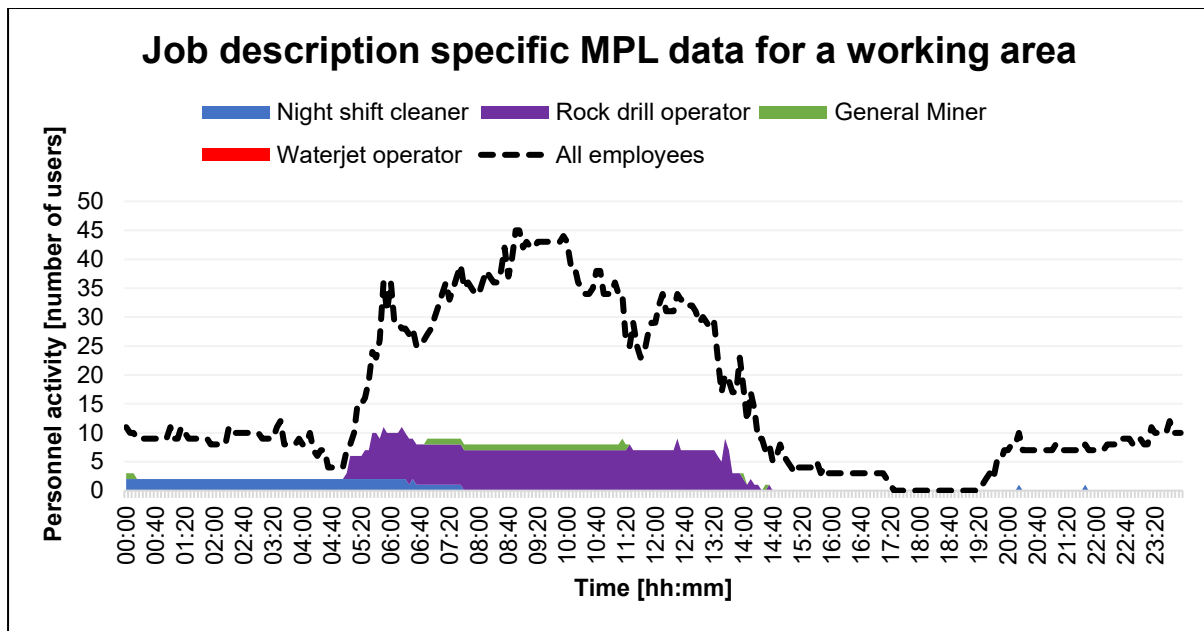


Figure 35: MPL database filtering for water users.

By having knowledge of employee movements, accurate TOU allocation for water consumption was done based on the equipment used by the corresponding water users.

The data obtained from the MPL system were verified to ensure accurate personnel tracking and system functionality. Verification was conducted through an underground audit on a mining level, during which RFID tag reader locations were identified, and manual recordings were taken when the readers were passed. The manually recorded data were compared with the MPL system data to confirm accuracy, as shown in Table 13. The discrepancies between the two values remain relatively constant and were attributed to two factors:

- Time differences between the manual recording device (normal wristwatch in this case) and the MPL system; and
- RFID tag readers detect employees before they are visually identified, as their visibility is obstructed by infrastructure.

Despite these insignificant discrepancies, the system was deemed accurate and was verified for further use.

Table 13: MPL system verification.

RFID tag reader ID	RFID tag reader time	Measured time	Difference
Box 2 Station Area	10:16:30	10:20:49	00:04:19
Station Area Box 5	10:14:21	10:17:35	00:03:14
Box 6 Multisplit HLGE	10:12:26	10:15:31	00:03:05

ZP2 Box 2	10:01:30	10:04:45	00:03:15
ZP2 Box 3	09:59:38	10:03:43	00:04:05
ZP2 Box 4	09:56:47	09:59:57	00:03:10
ZP2 Box 5	09:55:11	09:58:22	00:03:11
ZP2 Box 6	09:51:52	09:55:18	00:03:26
ZP2 Box 6	08:04:32	08:07:45	00:03:13
ZP2 Box 5	07:59:24	08:02:25	00:03:01
ZP2 Box 4	07:53:21	07:57:48	00:04:27
ZP2 Box 3	07:50:53	07:53:58	00:03:05
ZP2 Box 2	07:48:42	07:52:06	00:03:24
ZP2 Box 1	07:46:41	07:49:56	00:03:15
100 XC	07:36:45	07:40:11	00:03:26
101 XC	07:33:22	07:37:39	00:04:17
101 A XC	07:31:12	07:34:35	00:03:23
101 A XC	07:00:27	07:03:51	00:03:24
101 XC	06:48:09	06:51:58	00:03:49
100 XC	06:41:27	06:44:55	00:03:28
ZP2 Box 1	06:30:28	06:33:45	00:03:17
ZP2 Box 2	06:28:27	06:31:45	00:03:18
Box 6 Multisplit HLGE	06:14:02	06:17:20	00:03:18
Box 2 Station Area	06:11:08	06:14:47	00:03:39
RV Shaft	06:08:18	06:11:43	00:03:25

3.4.3 Additional metering installation

Three different flow meters were compared and tested on a test bench as seen in Figure 36. These flow meters included:

- Ultrasonic flow meter;
- Magnetic flow meter; and
- Differential pressure flow meter.

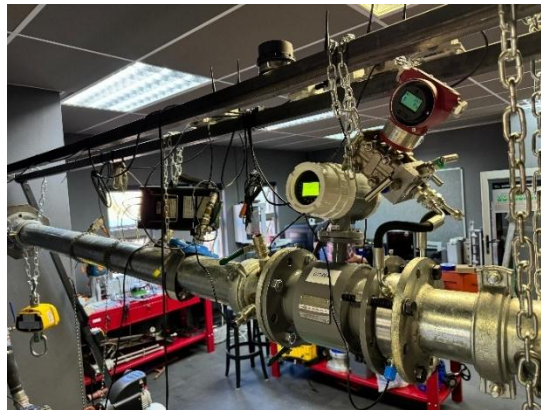


Figure 36: Test bench – picture used with permission.

A magnetic flow meter was selected for this application due to its high accuracy and proven success at Mine A. While ultrasonic flow meters could also be used for this application, the choice of meter depends on the specific requirements of each scenario. Together with this, a gauge pressure transmitter was selected for the application. The cost of these included:

- DN100 PN40 Magnetic inductive flow meter setup: R63 982.67 including VAT;
- Gauge pressure transmitter with range 0-30 bar: R5 343.28 including VAT; and
- Total cost for one working area: R69 325.95 including VAT.

The proposed installation at Mine A for two typical working areas is shown in Figure 37. The instruments were installed at the beginning of the working area, just after the continuous water users, ensuring that only water supplied to the working areas was monitored. This decision is further supported by the presence of isolation valves installed after the continuous water users, which are used to isolate the working area when the crew leaves.

The water supply to the continuous water user remains uninterrupted to ensure that working area conditions stay within legal limits when miners return. Water entering the working area first passes through the continuous water user before being supplied to mining activities. Any excess water that is not used by mining operations is returned via the high-pressure return line, preventing wastage. This operating principle is illustrated in Figure 17, Section 2.4.3.

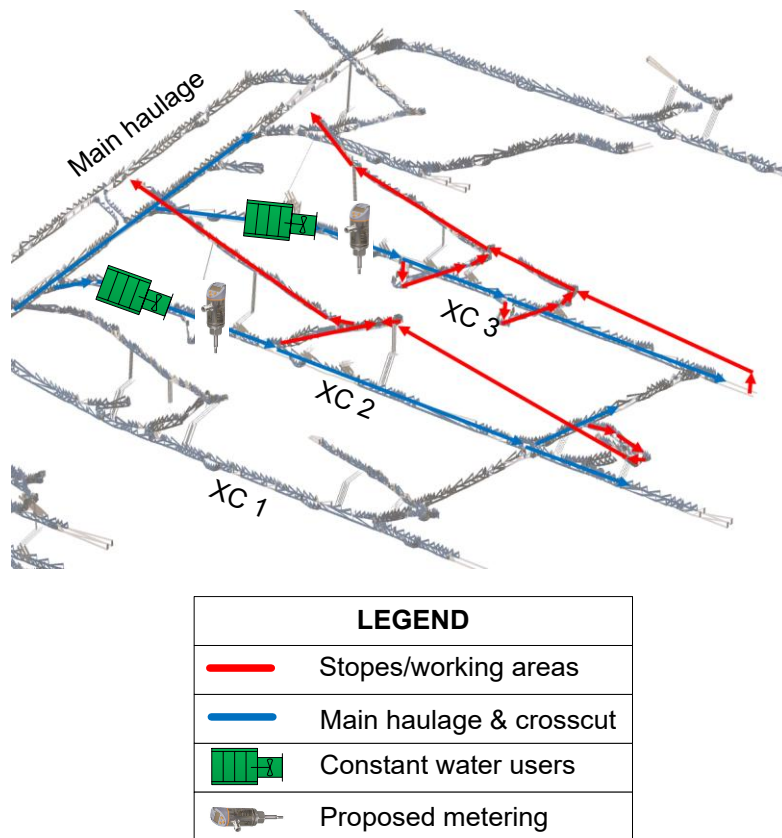


Figure 37: Location of flow- and pressure meters installed in the working areas.

The installation locations were determined based on production plans. Metering was installed in all currently active working areas, as well as those scheduled to start soon, provided they have an LOM exceeding one year. This resulted in a total of 22 working areas (of the total of 75 working areas), which, along with their planned tonnage, are summarised in Table 14.

For analysis, results are presented for a single working area, as the underlying principles remain the same across all sites. Working area 98 Level (L) XC 113 (highlighted in grey in Table 14) has been selected as a case study to prove the concept. This working area was selected as it has an LOM of over 1 year and was suggested by the mining operation due to the good gold grade in the area.

Table 14: Active working areas' information to determine metering locations.

Working area	Total operational days	Total planned tonnes
101L XC 88	3 468	87 625
101L XC 89A	3 304	61 542
98L XC 113	3 081	101 307
101L XC 80	1 966	205 964
101L XC 79	1 899	203 784
101L XC 77	1 722	193 701
101L XC 81	1 579	221 226
101L XC 82	1 474	150 141
101L XC 78	1 325	203 168
101L XC 89	1 179	23 912
98L XC 114	1 166	35 277
98L XC 112B	1 090	35 652
101L XC 90A	1 074	31 290
88L XC 113	897	25 711
98L XC 114B	881	24 428
101L XC 90	702	17 157
88L XC 111	686	20 803
92L XC 106(1)	627	21 015
92L XC 105A	627	19 710
88L XC 100	550	15 542
92L XC 113 Rse5	450	14 237
95L XC 105	431	9 817

Following the installation of the metering equipment, the values logged by the installed sensor were verified using the calibrated ultrasonic water flow meter shown in Figure 28. The measurement setup underground is presented in Figure 38, with the verification results displayed in Figure 39 and Table 15. The measurement values were averaged over 30-minute intervals to align with logged data.



Figure 38: Pictures of portable ultrasonic flow meter setup (picture taken by author).

While some differences have been observed between the readings of the installed and portable meters, several factors could contribute to these variations:

- Temporary flow disturbances: turbulence or short-term pressure variations can affect sensor readings;
- Sensor sensitivity differences: portable sensors may react faster to changes, while installed sensors might have averaging effects;
- Installation or positioning issues: misalignment, vibration, temperature changes, or external interference can impact accuracy;
- Air pockets or entrained solids: air bubbles or suspended particles can influence sensor readings, especially if the sensors are positioned differently; or
- Flow profile variations: pipeline bends, restrictions, or fluctuating demand can cause velocity profile changes affecting readings.

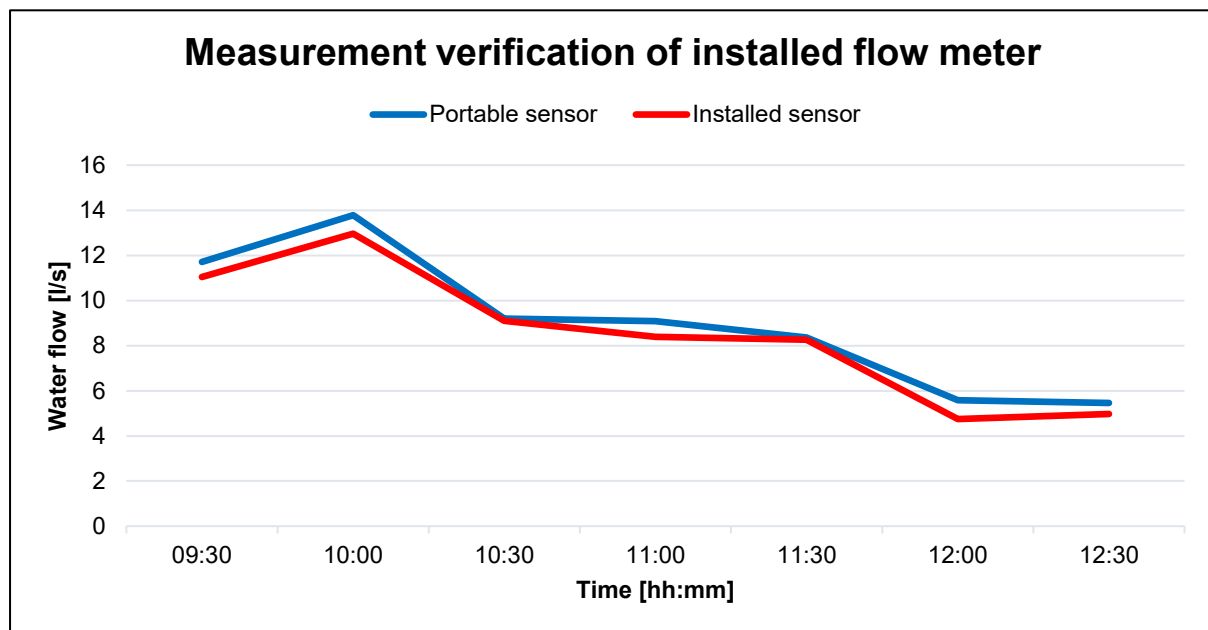


Figure 39: Comparison between the installed water flow meter and the portable water flow meter.

Table 15 summarises the MAPE between the two sets of readings. The MAPE remains below 10% with one entry exceeding 17%. While the discrepancies observed can be attributed to the factors listed above, the overall differences still fall within an acceptable range, confirming the validity of the verification process.

Table 15: MAPE calculation between installed and portable flow meters.

Time	Portable sensor [l/s]	Installed sensor [l/s]	MAPE [%]
09:30	11.72	11.04	6.1%
10:00	13.78	12.96	6.3%
10:30	9.20	9.10	1.2%
11:00	9.08	8.40	8.1%
11:30	8.36	8.27	1.1%
12:00	5.58	4.75	17.4%
12:30	5.46	4.97	9.8%

3.4.4 Dynamic ZWB establishment

All preceding elements were integrated to form distinctive baselines for each day based on employee movement and operating conditions. Therefore, these baselines dynamically adjust to ensure production is prioritised without wasting any water. It is important to note that these baselines do not intend to reduce the water needed for mining activities, but rather just make sure that water is not wasted.

First, each job description was linked to the corresponding water-consuming tool as displayed in Table 16.

Table 16: Equipment allocation to water users.

Job description	Task	Water-consuming tool
Night shift cleaner	Performs post-blast cleaning of the rock face	Rubber hoses and Bazooka
Rock drill operator	Drills holes in the rock face	Rock drill
Waterjet operator	Performs post-blast cleaning of the rock face	Waterjet
General miner	Assists with support and rock formations	Omni prop and jackpot

Next, the type and number of water-consuming tools on 98L XC 113 were obtained and are displayed below in Table 17. Each user entering the specific working area is allocated their corresponding water-consuming tool, with the data presented in Table 17 used as a secondary verification method. This means that if only 3 waterjets are allocated to the working area in question, water is only assigned for the first three waterjet operators entering the area.

Table 17: 98L XC 113 equipment census.

Equipment name	Quantity
Rock drills	16
Waterjets	3
10mm rubber hoses	8
25mm rubber hoses	2
Omni props	3
Jackpots	2

As mentioned, each day has a unique baseline. Figure 40 shows the dynamic ZWBs for three days, clearly illustrating these daily differences.

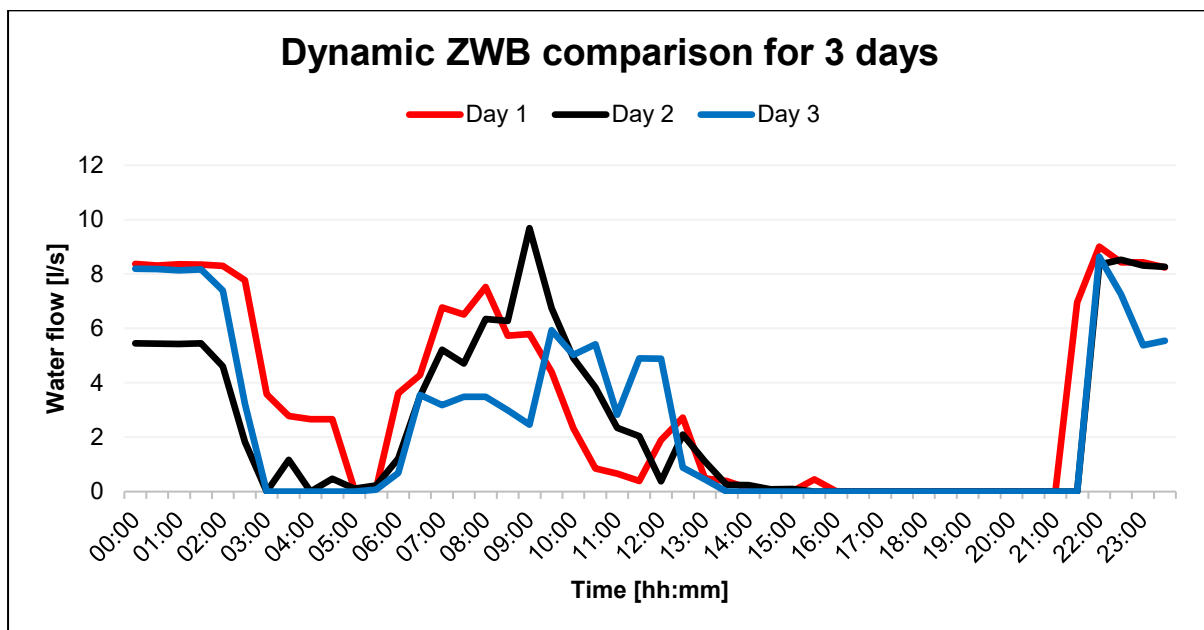


Figure 40: Dynamic ZWBs for three different days for 98L XC 113.

Figure 41 compares the dynamic ZWB to actual water usage in the working area. It also shows personnel activity, separated into total and water users. Here, the total water wastage equates to 0.32 MI per day.

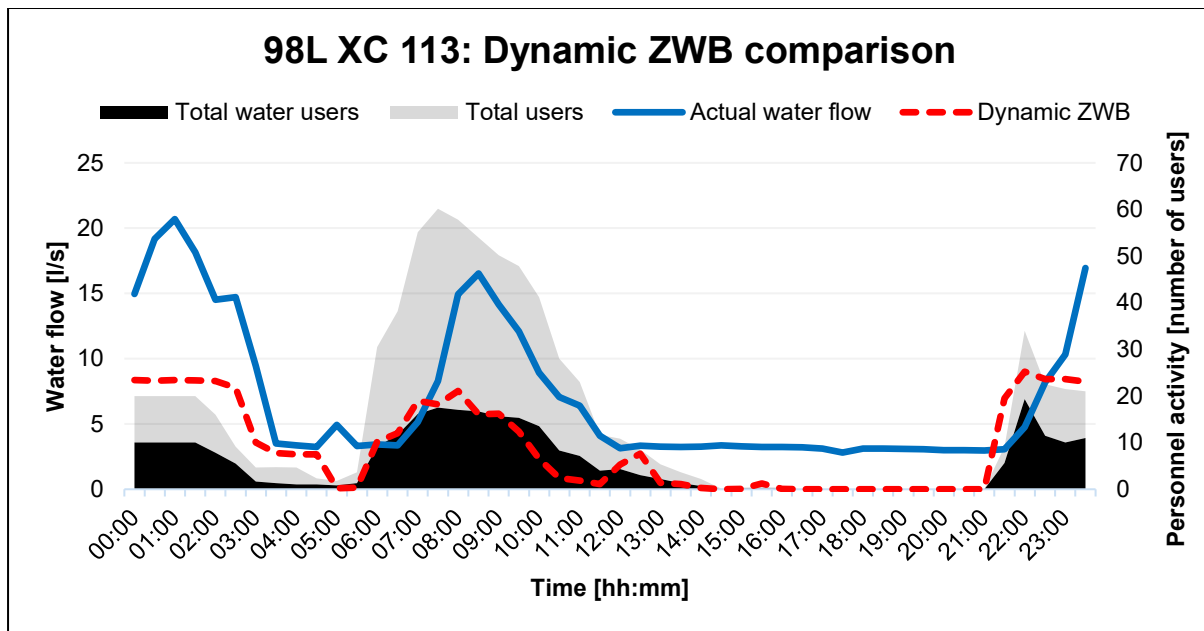


Figure 41: 98L XC 113 water flow comparison.

Figure 41 clearly shows significant water wastage in the working area, as indicated by the large gap between the ZWB and actual water consumption. However, before using these baselines for accountability, their accuracy and the accuracy of the identified wastage were first verified.

This verification was conducted by first calculating upper and lower limits of expected water wastage based on literature values, which suggest that typically 22% to 84% of water is wasted. Using the actual water usage data, these percentages were applied to establish a range of expected wastage volumes. The wastage detected by the ZWB was then compared against this calculated range to assess whether the detected values fell within the expected limits, thereby confirming the accuracy of the method. Figure 42 illustrates the identified wastage against the specified range. The wastage profile mostly falls within this range, except for two periods (06:00 – 07:30 and 21:30 – 23:00), where actual water usage was lower than the ZWB. This indicates no wastage during these times, meaning personnel adhered to the ZWB. Here, the actual water consumption remained below the ZWB, indicating that the water usage during that period was well below the allowable usage based on the equipment used.

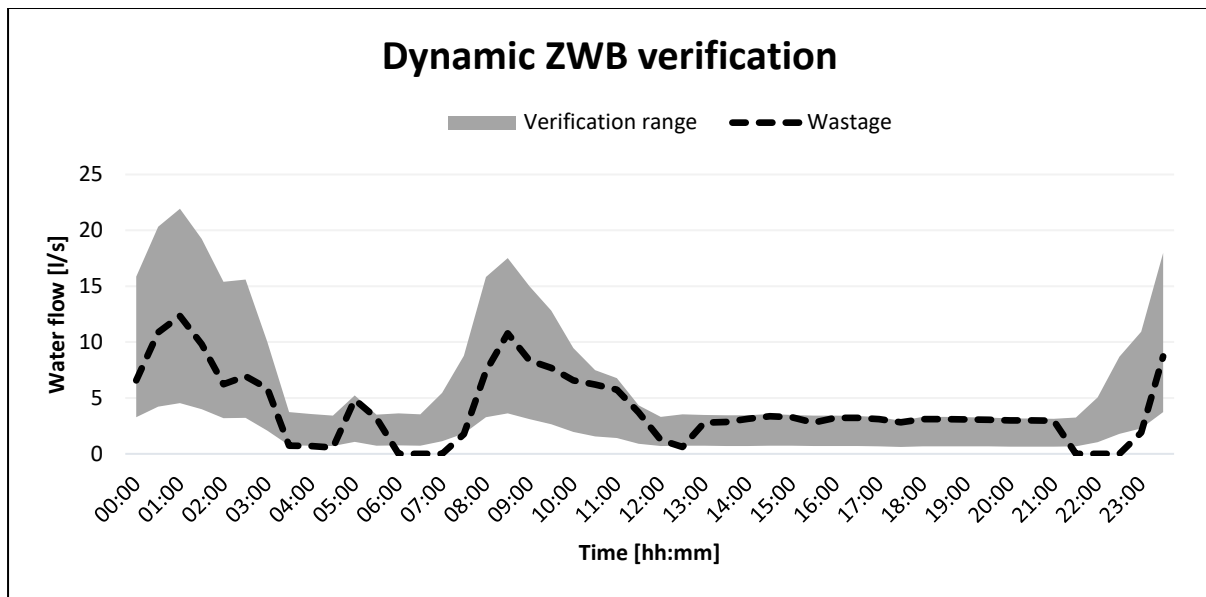


Figure 42: ZWB verification range.

In addition, Figure 41, reveals that water wastage occurs throughout the day, even when no personnel are underground in the working area. An underground inspection confirmed the presence of multiple water leaks, as shown in Figure 43.

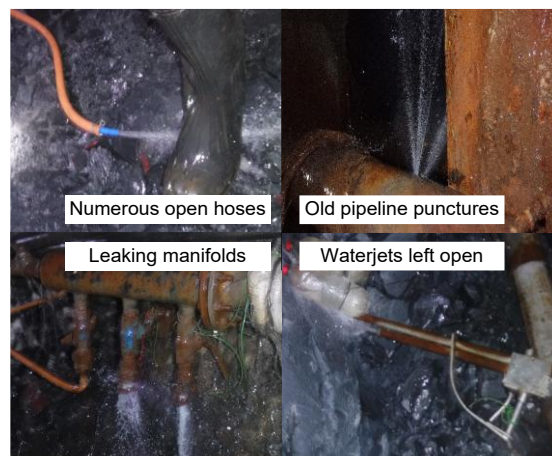


Figure 43: Issues identified in the working area contributing to water wastage.

Therefore, the baselines are deemed accurate and can be used to keep personnel accountable for water wastage within working areas.

3.5 Step 4: Accountability incorporation

Before accountability integration is done, all tools and processes are put in place to ensure all components and drivers of accountability are met as suggested by literature. These are discussed below, whereafter the integration and practical example on the case study follows.

3.5.1 Define

Success metrics are defined by the developed dynamic ZWBs, which adjust based on underground operating conditions and employee movements. These baselines set practical targets that align with full production efficiency while eliminating waste, ensuring that employees have a clear understanding of performance expectations.

Additionally, hierarchical structures were used so that employees knew to whom they were accountable when expectations were not met. The system was designed to avoid financial incentives that could lead to labour disputes. Existing hierarchical structures within the mining operations were used. As shown in Figure 44, mine captains reported to engineering and mining managers regarding performance across multiple working areas. They, in turn, held their shift bosses accountable, who ensured that their crew members took responsibility for fixing the identified issues.

This allowed for a bottom-up approach, where personnel at lower levels of the hierarchy had the opportunity to address identified inefficiencies. This thesis focuses on accountability up to the mine captain level, as shown by the red dotted lines in Figure 44.

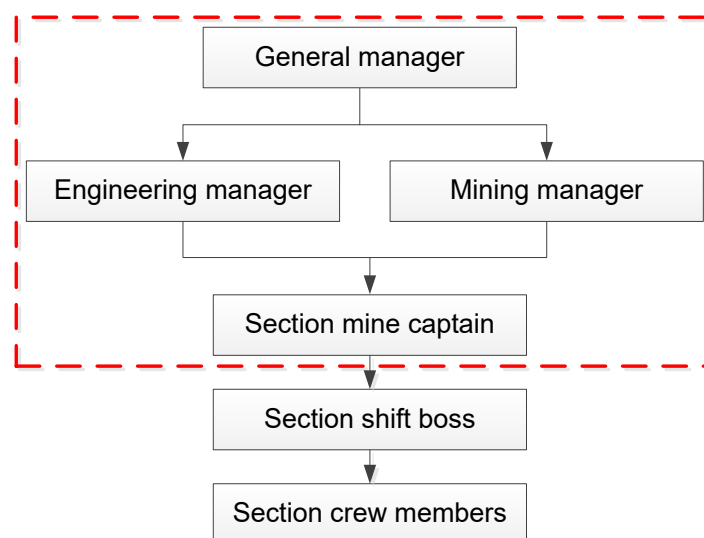


Figure 44: Mine A hierarchical structure.

3.5.2 Assess

Literature refers to the importance of performance monitoring. An EMIS was used to create user-specific dashboards where performance is viewed. The physical development of the EMIS falls outside the scope of the thesis and is not discussed but merely used. The layout of 98L XC 113, together with the locations of the installed instrumentation, is developed using Process Toolbox (PTB) as seen in Figure 45.

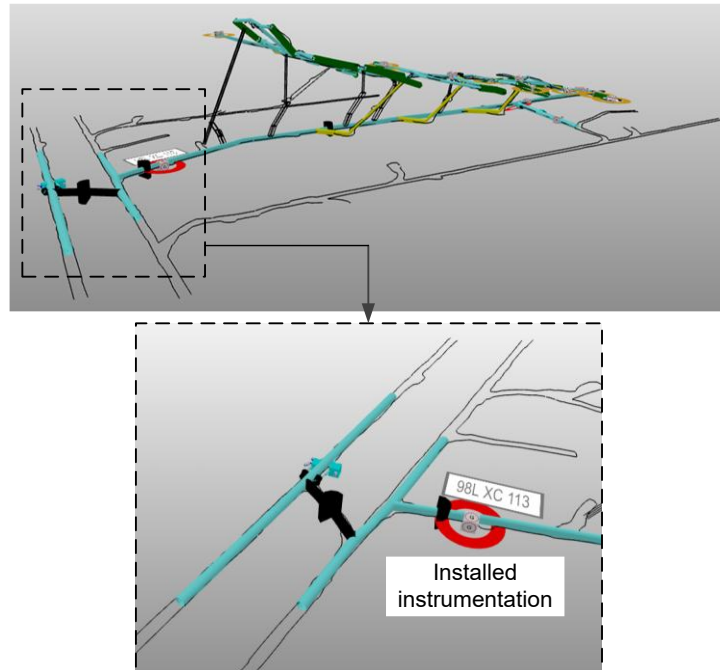


Figure 45: 98L XC 113 layout on dashboard.

When the user clicks on the instrumentation icon, the dashboard as displayed in Figure 46 appears. This dashboard compares actual water consumption with the dynamic ZWB, allowing users to identify when and where wastage occurs within the area. Additionally, the wastage is quantified, highlighting the magnitude of the issue to ensure proper attention is given to the severity of the problem. The profiles shown in this figure are purely for demonstrative purposes.

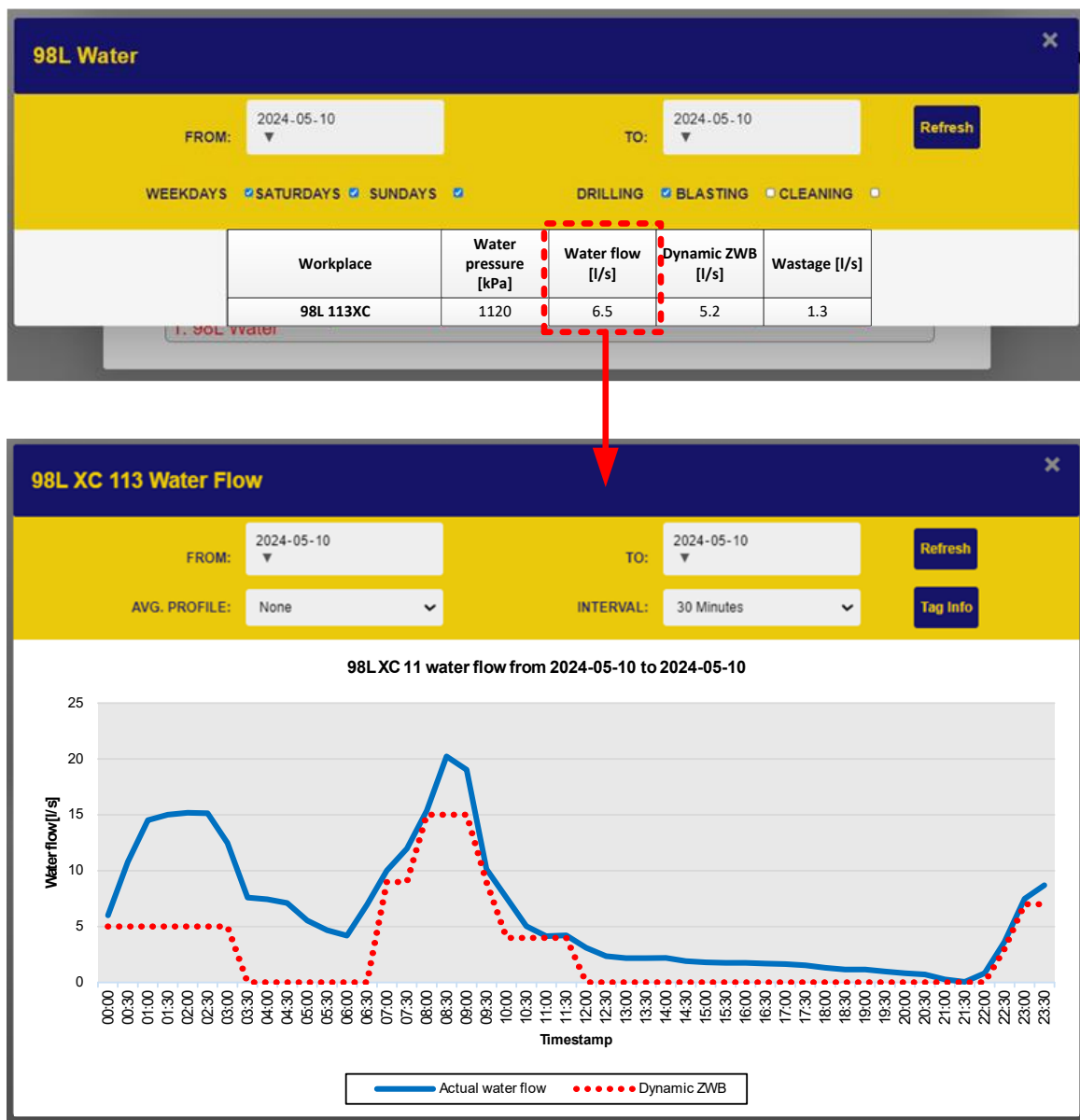


Figure 46: 98L XC 113 performance monitoring dashboard.

This system/program also automatically calculates the ZWBs and compares them to the actual water consumption as seen in Figure 46. This is done in real time, allowing performance to be viewed as data become available. However, in practice, the data from the previous day is typically used to ensure that wastage per working area is identified within a day, enabling identification the following day based on the previous day's performance.

3.5.3 Execute

Execution involves both consequences for not meeting expectations and recognition for employees who exceed them.

Employees who fail to meet expectations must answer to higher authorities within the mine's hierarchy. Holding employees accountable to senior personnel has been shown to positively impact performance. After discussions with personnel at Mine A, it was decided to implement a three-strike system. Each time an inefficiency is identified, it is added to an action list. Mine captains are given a specific timeframe to resolve the issue, which is clearly communicated. If the issue is not mitigated within the given timeframe, the mine captain receives a strike. After accumulating three strikes, the mine captain must report to the general manager of the operation.

Conversely, high-performing teams and mine captains receive recognition when expectations are met. Their names are displayed on a notice board at the mine's entrance, ensuring visibility for all employees, as shown in Figure 47. This recognition serves as motivation, as employees strive to have their names featured on the board.



Figure 47: Notice board for good performance.

3.5.4 Communication

Communication has been highlighted as a crucial step. Open lines of communication were established on Mine A by incorporating performance discussions into existing meetings. Mine A has daily meetings to discuss all important matters on the operation and a slot has been allocated to discuss the water usage performance as measured by the developed baselines. During these meetings, all relevant stakeholders are present as action plans are discussed. The general manager is included in the monthly meetings to bring them up to speed and obtain their input on unresolved issues. WhatsApp groups have also been established where the performance of the previous day is shared and mine captains are given the opportunity to gather all information before the daily meetings with higher authorities.

3.5.5 Method integration

Once all aspects of accountability have been successfully developed and put in place, it can be rolled out to site personnel.

Water wastage has been identified on 98L XC 113 as shown in Figure 41. Here, water is not only wasted throughout the day while mining activities are taking place, but also during periods when no personnel are working within the area.

As mentioned, the accountability approach was implemented using a phased approach to ensure a smooth transition and assist with the change management process. For this thesis, a two-phase approach was used:

- Phase 1: Reduce water wastage when no personnel are working underground. This entailed users closing down the water to the working area when leaving. This is considered a relatively easy task; and
- Phase 2: The phase entailed reducing wastage throughout the day (24-hour period).

These commitments were discussed with all relevant stakeholders during the daily meetings. Together with this, the mine captain for 98L XC 113, referred to as Mine Captain A, was notified of the water wastage identified within his area. Mine Captain A was also allowed access to the dashboard to view his team's performance. For Phase 1, the water isolation valve at the entrance of 98L XC 113 needs to be closed by the last employee leaving the area. Doing so shuts off the water supply to the area and ensures that no water is consumed by leaks within the area during periods when no personnel are underground. The hierarchical structures were used to keep Mine Captain A accountable, where he in turn kept his team accountable to close this valve. Figure 48 displays the results from this initiative. Here, Mine Captain A effectively led his team to ensure that water is closed during periods when no personnel are underground, resulting in no wastage during this time (between 15:00 – 22:00). This was achieved within a week of notification.

It is important to note that for certain periods of time in Figure 48, the ZWB exceeds the actual water usage (09:00 and between 22:00 – 23:30). This happens as a water user is detected within the working area and water is allocated to them. However, in some rare cases, users are within the working area without consuming any water. Nevertheless, the main goal is to ensure that the actual water consumption remains below the ZWB as this represents the total allowable water usage for the working area. Between 00:00 and 06:00, a significant amount of water wastage is evident, as indicated by the deviation between the actual water

consumption profile and the ZWB. Specifically, between 00:00 and 03:00, the wastage is likely attributed to cleaning equipment that may have been modified to simplify operation, resulting in excessive water use, or operated by unauthorised personnel. From 03:00 to 06:00, the continued wastage is likely due to water not being isolated from the area during the shift change, indicating a combination of operational oversight and poor control measures.

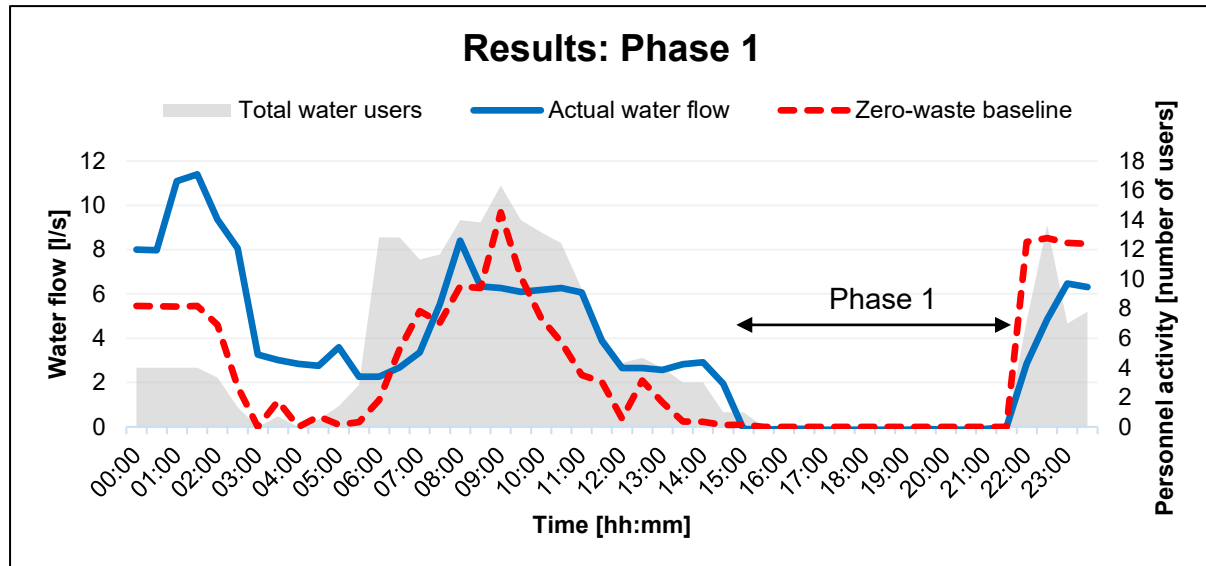


Figure 48: Phase 1 results.

After successful adherence to Phase 1, Phase 2 was introduced. Again, Mine Captain A was informed about wastage occurring during normal working periods. The way forward was discussed, and Mine Captain A was tasked to identify the points where water was wasted and present an action plan.

After investigation and discussion with his team, it was found that workers opened rubber hoses to relieve the water pressure within the line as the pressure exceeded the norm. This was due to a faulty PRV which failed to relieve the water pressure before being transferred to the working area. Furthermore, it has been found that a broken manifold resulted in excessive wastage and needed to be replaced.

During the daily meeting, Mine Captain A presented his action plan and timelines which were approved by the engineering and mining manager. The action plan is displayed in Table 18.

Table 18: 98L XC 113 action plan.

Identified issue	Action	Timeline	Responsible person

Faulty PRV	Fix/replace PRV	7 days	Engineering Foreman A
Broken manifold	Fix/replace the manifold	5 days	Fitter A

The action plan was executed within the required timelines and resulted in a water reduction. Figure 49 displays the results obtained. Here, the actual water usage profile closely follows that of the dynamic ZWB, meaning that water wastage throughout the day is reduced. Although some wastage still occurs during certain periods, these results demonstrate that incorporating accountability effectively reduces water wastage throughout the day.

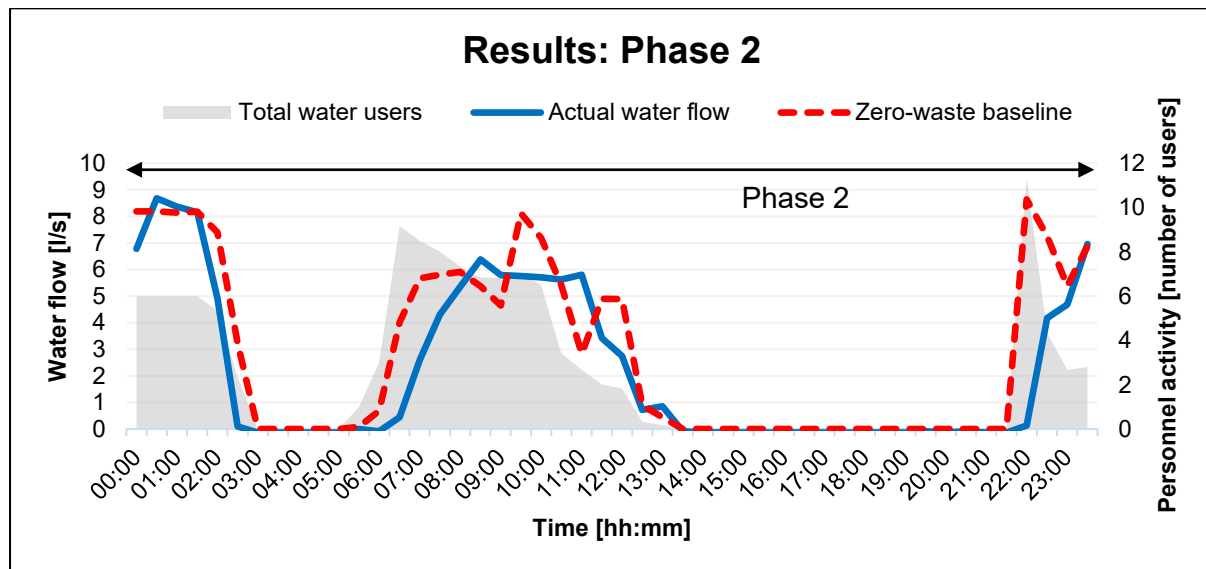


Figure 49: Phase 2 results.

The implementation resulted in a water wastage reduction from 0.34 MI per day to 0.03 MI per day for 98L XC 113. This resulted in a monthly cost benefit of approximately R235 000 for 98L XC 113. With a total capital cost of R69 325.95 per working area, the payback period was calculated as 0.31 months (9 days). The savings displayed here were calculated by measuring the reduction in energy usage of the dewatering pumps and refrigeration system, which no longer need to pump and cool the wasted water. This energy reduction was multiplied by the relevant electricity tariff to determine the cost benefit. This calculation is displayed in Appendix E: 98L XC 113 cost saving calculation.

The capital spent is recovered within 9 days from when the equipment is installed and working. This means that the investment is highly justified and extremely profitable.

Furthermore, the fact that the actual water profile now closely aligns with the dynamic ZWB after addressing wastage highlights the accuracy and effectiveness of these baselines.

From the results, a general checklist was developed for all working areas. This includes:

1. Checking the PRV status by confirming the water pressure before and after the PRV to ensure that the water pressure is reduced to the correct amount. If the PRV is not working as intended, the relevant engineering foreman is notified.
2. If the PRV is in working condition, the working area is investigated for wastages such as bad housekeeping (open hoses, waterjet guns left open, etc.)
3. The last check is to ensure that the working area is operated according to the correct working area standards. This entails checking the manifold locations, equipment conditions, pipe sizes, etc.

Figure 50 compares the actual water usage before implementation, during Phase 1 and during Phase 2.

Phase 1 targeted the reduction of water wastage during times when no personnel were underground in the working area (between 15:00 – 21:00). A noticeable daily reduction in water usage was observed during this phase, largely because employees became aware that their usage was being monitored and that they would be held accountable for any wastage. Although Phase 1 only targeted wastage reduction during non-working hours, personnel naturally began conserving water throughout the day as they adopted a more mindful approach to saving.

Once Phase 1 was successfully implemented, the focus shifted to Phase 2, where the emphasis was placed on reducing water wastage throughout the entire day. This improvement ensured that water consumption in the working area was efficient, allowing production to continue without unnecessary wastage, directly improving profitability.

Employees played a key role in this shift, as reducing water wastage also made their jobs easier. Excessive water wastage leads to the accumulation of mud in the working area, which must then be cleared by personnel. By minimising water wastage, less mud forms, reducing the workload, and ultimately boosting morale.

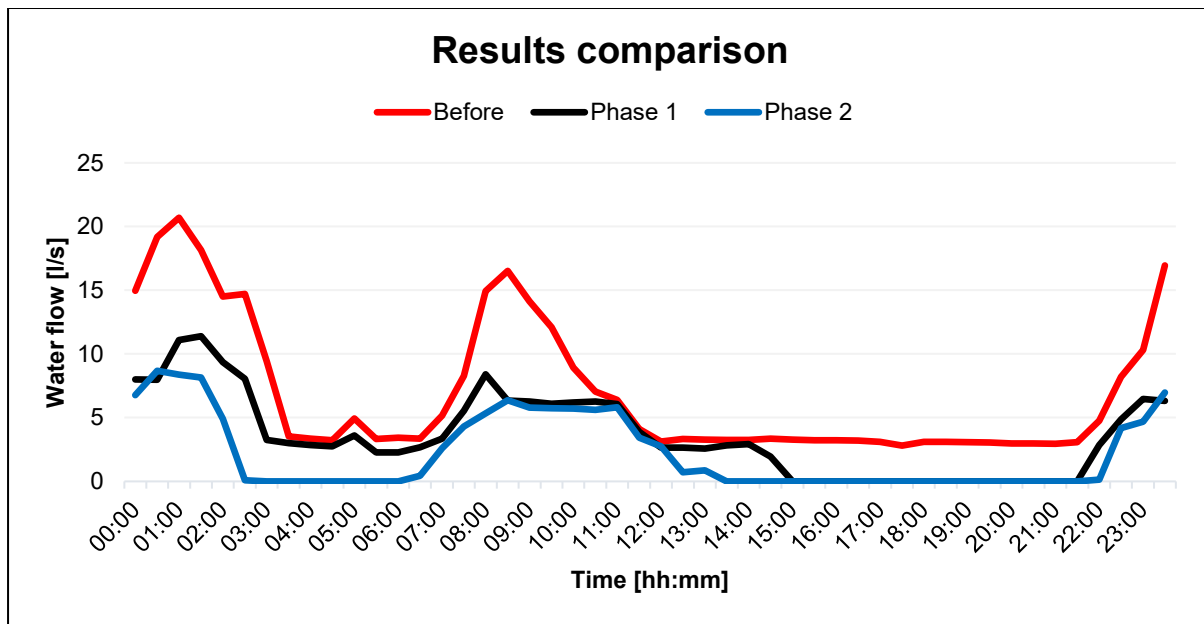


Figure 50: Results comparison (flow profiles).

Table 19 displays the comparison for the total water usage, ZWB and wastage for the three scenarios.

Table 19: Results comparison (totals).

Daily totals	Before implementation [MI]	Phase 1 [MI]	Phase 2 [MI]
Actual usage	0.61	0.31	0.19
ZWB	0.28	0.22	0.25
Wastage*	0.32	0.12	0.01

*wastage is only calculated during times when actuals are above the ZWB

Figure 51 illustrates the sustainability monitoring for 98L XC 113, showing the actual daily water consumption over 29 days (excluding weekends). Inefficiencies were identified and discussed on Day 1. Following this, a significant reduction in total water usage was observed after seven days. On Day 20, an increase in water consumption was noticed and addressed within the same working shift, even before it needed to be formally addressed. This spike was due to a burst hose, which was promptly replaced. This highlights the positive impact of accountability on personnel. They were aware that they would be held responsible for any wastage and took the initiative to resolve the issue before it became a problem. The results presented here correlate with the literature study that mentioned that, when formal accountability mechanisms are implemented, informal accountability mechanisms will follow in the form of self-accountability and peer-to-peer accountability. Employees knew that they

would need to answer for issues, so they fixed them by themselves, keeping themselves and others accountable.

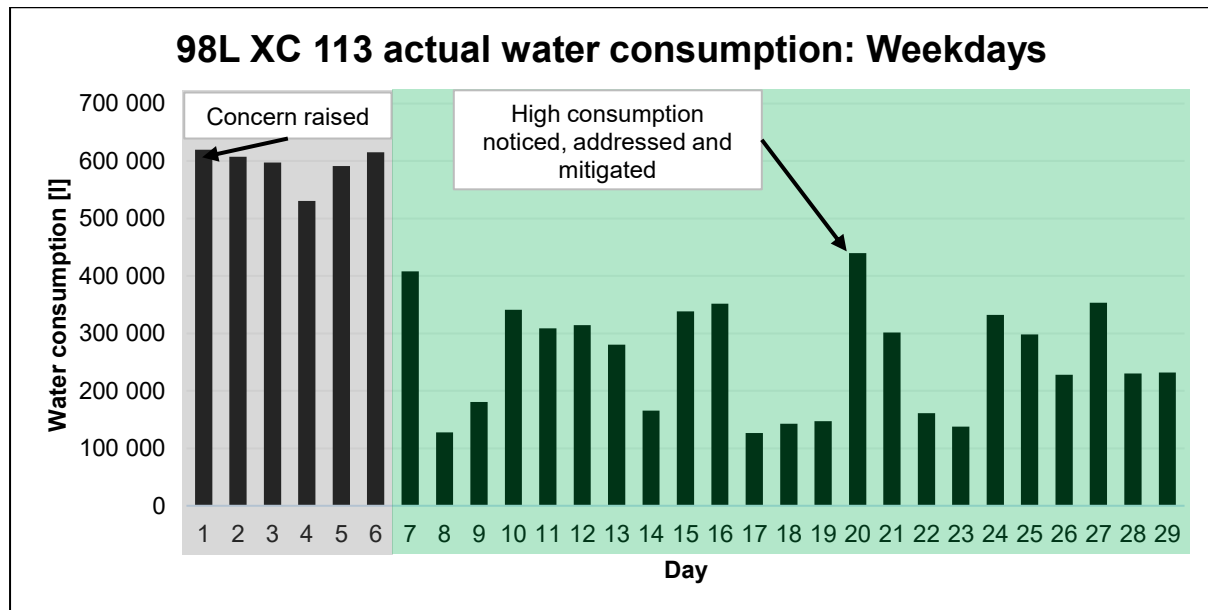


Figure 51: 98L XC 113 sustainability monitoring.

Walk-through audits and step testing were initially implemented on Mine A to identify water wastage, with the identified issues handed over to management for attention. However, after three months, no mitigation was carried out. The proposed method was introduced, where water wastage within the working area was identified, and responsible personnel were assigned to address the issues. Within just seven days, a significant reduction in water usage was observed.

Sustainability monitoring was carried out to ensure that the water wastage remained mitigated. After a few days, a hose burst occurred, and personnel promptly addressed the issue. This response demonstrates that the proposed method was successful in identifying water wastage faster than current methods, while also ensuring that issues were resolved, leading to cost savings and the ongoing mitigation of water wastage.

3.6 Total benefit

Significant benefits were achieved in the selected working area, 98L XC 113. However, walk-through audits were also conducted throughout Mine A to demonstrate that water wastage remains a widespread issue and that 98L XC 113 was not selectively chosen as a “best-case” scenario with unusually high water wastage to produce favourable results. Figure 52 and Figure 53 present the outcomes of walk-through audits on two mining levels at Mine A, clearly

illustrating that water wastage is prevalent across the mine, not just in the selected working area. It should be noted that water pipes to the closed-down areas have been blanked off.

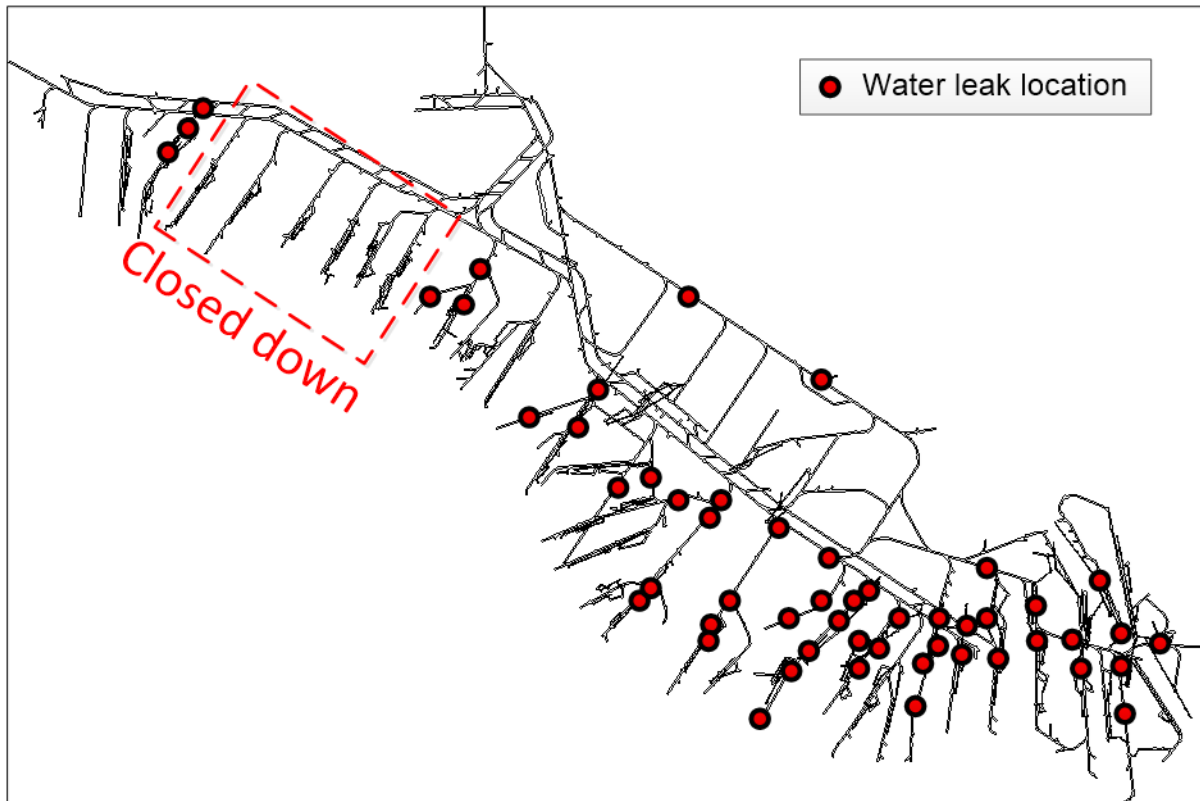


Figure 52: Mine A 92L.

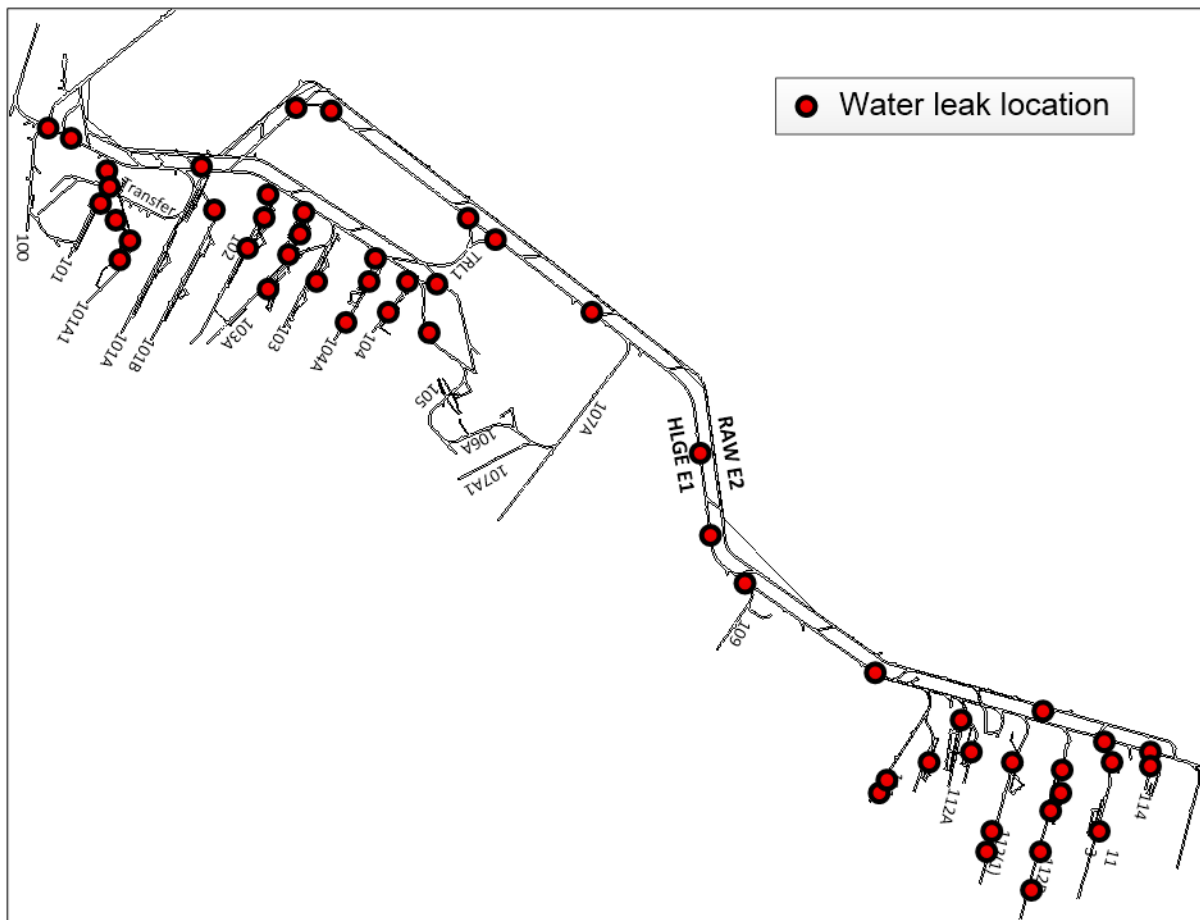


Figure 53: Mine A 98L.

Therefore, seeing that water wastage remains an issue throughout the operation as displayed in Figure 52 and Figure 53, the implementation of this method on all working areas of Mine A translates to an annual energy cost saving of approximately R28.7 million (assuming that all 22 working areas' water wastage is the same as calculated for 98L XC 113). This significant saving comes from eliminating the need to pump wasted water a total distance of 3 109 m using the 22.8 MW pumping system and subsequently cooling it down with the 6.3 MW refrigeration system.

Furthermore, similar audits were conducted at another deep-level gold mine in South Africa (Mine B), reinforcing that water wastage is a persistent issue across the gold mining industry. The results from Mine B are included in Appendix F: Walk-through audit results from Mine B, supporting the broader applicability of the proposed method. These findings correlate with existing literature, which indicates that water wastage can account for up to 50% of the total water supply in such operations.

To demonstrate the significant benefits achievable by the mining industry, five mining operations were considered. The total number of active working areas with a LOM exceeding one year was considered to estimate the potential savings attainable through reduced water wastage. Underground audits conducted at Mines A and B confirmed that water wastage in the working areas remains a persistent issue. Therefore, for the purpose of this analysis, it was assumed that the savings potential of each active working area is equivalent to that observed at 98L XC 113. Table 20 displays the significant savings potential if water wastage in all working areas with a LOM of longer than 1 year is rectified for the five mining operations considered. This calculation was based on the assumption that the wastage percentage determined for the case study working area is representative of all other operations, supported by audits that confirmed similar issues across sites as detailed in the thesis. The wastage for the case study area was therefore multiplied by the total number of active working areas to estimate the overall wastage.

Table 20: Achievable benefits in the mining industry.

Operation	Total active working areas (LOM > 1 year)	Expected annual benefit [R - million]
Mine A*	22	R28.7
Mine B	26	R33.9
Mine C	17	R22.2
Mine D	33	R43.1
Mine E	34	R44.4
Total		R172.3

*Case study mine

3.7 Validation

This section discusses the validation of the proposed method developed in Chapter 2, focusing on assessing its validity and accuracy. The validation process involves comparing the outcomes achieved through the actual implementation of the method at Mine A with the study objectives outlined in Chapter 1. Table 21 presents a comparison between the study objectives and the outcomes achieved.

Table 21: Method validation.

Objective	Outcome	Section	Step
To install monitoring equipment in closer proximity	Water flow and pressure metering were strategically installed in the working area by ensuring a LOM of 1 year. This entailed	3.4.3	3

Chapter 3: Results & Evaluation

to working areas to improve sustainability monitoring.	continuous monitoring of the water consumption in the working area. Furthermore, literature revealed that flow meters are typically installed up to half-level splits, with approximately 10 work areas monitored by these meters. In contrast, the study employed a more detailed approach, where each work area was equipped with its own dedicated meter.		
To develop and implement dynamic ZWBs to localise water leaks in working areas and enable continuous detection.	Dynamic ZWBs were developed using derived equations for all water-consuming tools using actual measured data and incorporating the MPL system to identify and allocate water consumption to water users. Comparison between dynamic ZWBs and actual consumption measured by installed metering allowed for continuous and localised detection within working areas.	3.4 and 3.5.5	3
To develop and implement an accountability method for mining operations.	Accountability was successfully incorporated within Mine A by ensuring that all drivers and components of accountability, as identified by literature, were addressed.	3.5	4
To detect and mitigate inefficiencies faster than with previous methods.	Previous identification methods were conducted on Mine A where issues were given to management to fix. However, after 3 months, no mitigation was done. Also, detection was time- and resource-intensive, limiting the frequency of detection. In contrast, the developed method allowed for continuous detection and mitigation of issues within one week. Thereafter, issues were mitigated within the same working shift.	3.3.1 and 3.5.5	3 and 4
To obtain cost savings by mitigating water leaks.	The implementation of the developed method led to a monthly cost saving of R235 000 for 98L XC 113. This equates to a total annual cost saving of R28.7 million for Mine A.	3.5.5	4

To ensure sustainable water leak mitigation.	Sustainability monitoring was done to ensure that mitigation issues remained resolved. Subsequently, new issues were fixed almost immediately to ensure sustainability. Moreover, leaks were found to remain unfixed after three months using old/current methods, whereas the approach developed in this thesis ensured that issues were addressed within just 7 days.	3.5.5	3 and 4
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The outcomes demonstrated that all study objectives are successfully met, deeming the method successful and validated.

3.8 Conclusion

Chapter 3 presents the results obtained through the implementation of the developed method. Dynamic ZWBs were created by successfully deriving water consumption equations for all identified water-consuming equipment, displaying the significant discrepancies between specification sheets used by previous researchers and actual measured values. These equations were verified using the MAPE function.

Next, TOU calculations were conducted using the MPL system to identify water users within the working area and assign the corresponding water-consuming tools to them. The accuracy of the MPL system was verified through underground audits, where manual readings were compared to system data.

Water flow and pressure metering equipment was installed in each working area to detect water wastage by comparing the readings to the dynamic ZWBs. The installation of metering equipment was strategically planned based on the mine production plan, ensuring that it was only placed in areas with an LOM exceeding one year.

Accountability was integrated by addressing all key drivers and components identified in the literature. This included:

- Defining clear expectations of what success would look like and identifying to whom accountability was assigned. Success was defined by the developed ZWB, with existing hierarchical structures used to establish accountability;

- Accurate performance assessments using monitoring dashboards that displayed actual water consumption compared to the ZWB for each working area were developed;
- Execution was employed, where employees who failed to meet targets were required to answer to higher authorities, while those exceeding expectations received public recognition. Financial incentives were avoided, in line with the literature; and
- Active and continuous communication was done through recurring daily meetings with all stakeholders and WhatsApp groups to discuss performance.

The method was successfully validated as all study objectives were achieved through the implementation of the developed method.

Moreover, walk-through audits were conducted on several mining levels at Mine A, as well as at another mining operation, Mine B. These clearly show that water wastage remains an ongoing issue within the South African mining industry and that simply sharing results with top management is not enough to drive meaningful change.

As discussed in the accountability literature in Section 1.4, performance can be improved through the proper implementation of accountability frameworks, something that is supported by the results obtained here. It also highlights the importance of addressing all key components of accountability to ensure successful integration and long-term impact.

The development of a more accurate and dynamic ZWB model played a major role in the success of this method. Once again, this reinforces the fact that many mining operations are not fully aware of the benefits that can be unlocked through additional instrumentation and digital solutions. By installing additional monitoring instrumentation closer to working areas, issues can be detected faster in comparison to current methods and therefore mitigated much faster. This further proves that enhanced instrumentation is not only effective in non-mining industries as seen in Section 1.3.2, but also holds significant potential within the mining sector.

CHAPTER 4: CONCLUSION & RECOMMENDATIONS

"In the middle of every difficulty lies opportunity." – Albert Einstein



⁴ Personal photo taken by the author.

4 Conclusion & Recommendations

Chapter 4 concludes the thesis through the executive summary which includes the problem statement, discussion on how study objectives have been met through implementation, addressing novel contributions, reflecting on the developed method and recommendations for future research. The objectives of the thesis are summarised below, which have all been met through the implementation of the developed method:

1. To install of monitoring equipment in closer proximity to working areas to improve sustainability monitoring.
2. To develop and implement dynamic ZWBs to localise water leaks in working areas and enable continuous detection.
3. To develop and implement an accountability method for mining operations.
4. To detect and mitigate inefficiencies faster than with previous methods.
5. To quantify cost savings by mitigating water leaks.
6. To ensure sustainable water leak mitigation through continuous monitoring.

4.1 Executive summary

Operating costs in gold mining continue to rise due to increasing electricity tariffs, declining gold grades, unstable gold prices, and inefficient operations. The only controllable factor within mining operations is inefficient operations, with water wastage being a significant contributor, accounting for approximately 50% of the total water supply. Addressing these inefficiencies is crucial, but identifying them remains challenging due to the complex and dynamic nature of underground mining operations.

This research investigated current methods used for localised inefficiency detection within working areas (as this is where the majority of issues occur), with a focus on the mitigation of identified issues. ZWBs were identified as the best approach to detect wastage, but existing methods have limitations. From the literature, it was determined that current methods are not well suited for quick and accurate identification in these environments, often lacking continuous, automated detection. Mitigation efforts also tend to focus on short-term fixes rather than sustainable solutions.

A key issue is the lack of accountability, which plays a critical role in improving water wastage. Research has shown that accountability drives performance, yet mining operations typically report inefficiencies to top management without ensuring ownership at the operational level.

This research addressed this gap by integrating accountability with better detection methods to drive sustainable improvements.

The developed method introduced dynamic ZWBs for each working area, representing the optimal water consumption under actual working conditions. Instead of using manufacturer specifications, equations were derived based on actual measured values to account for variations in water pressure as seen in Appendix C: Intermittent scatter plots and MAPE verification. The MPL system was used to track water-consuming users and assign corresponding equipment, ensuring that ZWBs dynamically adjusted based on employee movements, working conditions, and equipment usage.

Water wastage was identified by comparing the dynamic ZWB to the actual water consumption, measured through additional flow and pressure metering installed in working areas with a LOM over one year. Accountability was incorporated based on key drivers identified in the literature:

- **Define:** Success metrics were clearly established using dynamic ZWBs so employees understood what success looks like. Existing hierarchical structures ensured clear accountability;
- **Assess:** Performance was continuously monitored through a dashboard displaying actual water usage and ZWBs for transparency;
- **Execute:** Employees failing to meet expectations had to answer to higher authorities, while those exceeding expectations received public recognition. Financial incentives were avoided, as research suggests they can be counterproductive; and
- **Communicate:** A structured communication strategy was implemented, including daily meetings with stakeholders to discuss performance and action plans, as well as a WhatsApp group for real-time updates.

Accountability was introduced in a phased approach to assist with the change management process. Before implementation, water wastage in the case study working area was 0.32 MI per day. Phase 1 targeted wastage during non-working hours, already leading to a noticeable reduction. Phase 2 extended mitigation efforts throughout the workday. Within seven days, water wastage dropped to 0.01 MI per day, resulting in a monthly cost saving of R235 000 for 98L XC 113, with a payback period of only 9 days for the installed equipment. This equates to an annual cost saving of R28.7 million for Mine A. Sustainability monitoring was incorporated to ensure that resolved inefficiencies remained under control and that new issues were quickly

identified and mitigated. A mining industry analysis highlights the significance of implementing this method on other deep-level gold mining operations following audits that confirmed that water wastage remains an issue throughout the industry, supporting literature findings in Section 1.1.2. The analysis highlights that the implementation of this method on five mining operations can have a significant annual cost benefit of R172.3 million.

The developed method significantly outperformed traditional detection methods, which, even after three months, failed to show measurable mitigation. In contrast, this method mitigated initial inefficiencies within seven days and continued to address new inefficiencies without requiring top management intervention.

All research objectives were successfully met through the implementation of the developed method on Mine A, validating its effectiveness in identifying and mitigating inefficiencies. This research demonstrates how dynamic ZWBs, combined with accountability, can improve efficiency, reduce costs, and support the long-term sustainability of deep-level mining operations.

4.2 Revisiting the novel contributions

The next section discusses how the novel contributions of the thesis have been addressed through the implementation of the developed method.

Novel contribution 1:

Development of a localised inefficiency detection method using dynamic ZWBs to continuously identify water leaks in mine working areas.

The study developed dynamic ZWBs capable of localised and continuous water wastage detection. This was achieved by deriving water consumption equations for all water-consuming tools based on their actual usage within the underground environment, rather than relying on manufacturer specification sheets, which provide consumption values from controlled tests that do not reflect real mining conditions. The MPL system was utilised to determine the TOU water allocation for equipment, linking it to corresponding water users tracked through the MPL system. Finally, the dynamic ZWBs were compared to the actual water usage in the working area, measured using additional flow and pressure meters installed in areas with LOM exceeding one year.

Novel contribution 2:

Incorporation of accountability to ensure that identified leaks are mitigated and operational costs decreased.

Accountability was successfully implemented by aligning with key drivers and components identified in the research. Expectations were clearly defined using the developed dynamic ZWBs, with accountability enforced through the existing hierarchical structure. Performance monitoring was facilitated through dashboards accessible to all stakeholders, ensuring transparency. Daily recurring meetings provided a platform for discussing performance, while WhatsApp communication enabled real-time updates. Execution was reinforced by requiring employees who failed to meet expectations to answer to higher authorities, while those exceeding expectations were publicly recognised. Through a phased rollout approach, water usage and wastage were significantly reduced, leading to substantial cost savings of R235 000 per month for the case study working area, amounting to an impressive annual cost savings of R28.7 million.

Novel contribution 3:

Integrated sustainability monitoring for deep-level mine working areas.

Sustainability monitoring was carried out through the developed dashboards and installed equipment. Within seven days, water consumption on 98L XC 113 decreased as a result of mitigating identified inefficiencies. On Day 20, an increase in water consumption was detected; however, personnel promptly addressed the issue before further intervention was needed. For the remainder of the monitoring period, water usage remained low and is now continuously tracked to ensure sustained efficiency, promptly identifying and mitigating any new inefficiencies as they arise.

4.3 Method reflection

This section provides a reflection on the developed method shown in Figure 24. It discusses the effectiveness of the method in meeting the study's objectives and provides a critical assessment of its performance in practice, particularly in addressing the challenges identified in the literature. The focus is placed on evaluating the method's ability to dynamically detect inefficiencies, incorporate accountability, and support sustainable water wastage mitigation

within working areas. This reflection offers insights into the method's practical value and its potential for broader application in deep-level mining operations.

The developed method successfully met all the objectives of this thesis. It enabled dynamic, localised and continuous water wastage detection within a deep-level mine's working areas by developing dynamic ZWBs for each working area. The dynamic aspect of the ZWBs lies in their use of actual measured values from water-consuming equipment, rather than relying on fixed manufacturer specifications. Additionally, the ZWBs automatically adapt to changes in employee movements and equipment usage, ensuring they remain accurate under varying operational conditions. The dynamic ZWB is compared to the actual water consumption of the working areas, enabled through the installation of measuring equipment on active working areas. This ensured faster and more accurate identification of water inefficiencies, addressing the gaps identified in literature.

Another key shortcoming highlighted in this thesis was the lack of accountability to mitigate costly water wastage. This method allowed for the successful implementation of accountability in day-to-day operations. Costly water wastage was not only detected, but also mitigated and monitored for sustained improvements. The method ensured that the main components of accountability, as seen in Table 4 was included. This included setting clear performance targets, monitoring actual performance, providing feedback on performance and taking action where needed, and establishing open lines of communication. This ensured that accountability was not just a management function but rather built into day-to-day operations underground.

The results obtained through the implementation and validation of this method clearly show the method's success. Before implementation, wastage was identified using static and resource-intensive measures, without any mitigation seen after 3 months of identification. Moreover, the water wastage before implementation of the method on the case study working area, 98L XC 113, was quantified as 0.32 MI per day. After the implementation of the developed method, using a phased approach, the water wastage within working area 98L XC 113 was significantly reduced to 0.01 MI per day within only 7 days. This resulted in a monthly cost benefit of R235 000 for this working area, with a payback period of only 9 days for the measuring equipment installed. An underground audit on the remaining working areas of Mine A was conducted, showcasing that the water wastage remains an issue throughout the operation. Therefore, seeing that water wastage remains an issue throughout the mine, roll out of this method across Mine A would yield an annual cost benefit of R28.7 million (assuming the wastage is the same throughout the mine as obtained for 98L XC 113).

Moreover, another key aspect addressed by the developed method is the sustainable monitoring of improvements to ensure the long-term sustainability and profitability of the mining operation, a major concern identified during the literature review. After initial issues were resolved on Mine A, an increase in water consumption was observed, as shown in Figure 51. This high consumption was mitigated by the crew without any involvement from top management, demonstrating the impact of accountability. Employees now clearly understand what is expected of them and proactively address issues they know they will be held accountable for.

In summary, the developed method fulfilled all the objectives of this study. It provides a proven, practical, and sustainable approach to detecting and mitigating water wastage in deep-level gold mining. Its success at Mine A highlights its potential for widespread implementation across the industry, showcased by the potential of implementation on 5 different gold mines in South Africa (Table 20), supporting both cost reduction and long-term operational sustainability.

4.4 Recommendations for future work

The following section outlines recommendations for future work that emerged from the implementation and outcomes of this study.

The current method identifies wastage effectively; however, it still relies on human interpretation to determine the root cause. It merely shows that the actual water consumption is above the ZWB, without explicitly stating the likely cause of water wastage. Therefore, with the data available within the working areas, logic or algorithms can be developed to automatically suggest the type of water wastage to improve root cause analysis. Considering the rise in machine learning and AI, the incorporation and use of it can be beneficial.

The second level of assurance used in the thesis is the number and type of water-consuming equipment in the specific working area. This information is obtained through sessions with the crew or manual audits; however, this can be improved by incorporating a system that can determine or track the amount and type of water-consuming equipment on a specific working area more accurately. This will assist greatly in ensuring that the correct type and amount of equipment is assigned.

Considering the significant benefits obtained through the implementation of this method on the water system of a deep-level mine, it is suggested that a similar framework is applied to other systems such as compressed air, electricity or diesel use in deep-level mines. Each of

these systems has inefficiency potential and would benefit from a similar dynamic, localised, and accountable approach. In addition, an analysis has shown the significant benefits achievable through roll out of the method throughout the industry.

From the results presented in this thesis, it was found that employee behaviour changed, where after the implementation and mitigation of initially identified issues, increased water consumption was noted and fixed before any intervention by top management. Therefore, a study can be conducted on how employees' attitudes and behaviours can change over several months or years, where leak fixing will become something that's being done automatically by employees. This would give insight into the long-term sustainability of accountability-based systems and determine where reinforcements are needed.

Improving the user interface and dashboard experience could increase adoption and daily use. More visual aids (trend lines, alerts, rankings) and mobile compatibility could help operational teams take quicker action. Together with this, accountability is currently tracked daily, but mining operations work on different shifts, as discussed in Chapter 1. Introducing shift-based tracking and performance feedback could allow even faster mitigation and improve ownership among smaller teams.

The effects of lead and lag periods can be considered when developing the ZWB. These periods account for the time required to start up and shut down activities, during which water consumption may not align perfectly with the actual productive work period. Incorporating lead and lag adjustments into the ZWB will improve its accuracy by better reflecting realistic operational conditions and preventing the misclassification of legitimate consumption as wastage. This approach ensures a more precise distinction between unavoidable consumption during transitional periods and true inefficiencies.

In this study, new equipment was used during testing to obtain accurate and reliable water consumption data in the underground environment. However, it is acknowledged that as equipment ages, water consumption patterns are likely to change due to factors such as wear, inefficiencies, and possible leaks associated with ageing infrastructure. Therefore, it is recommended that future research focus on incorporating the effects of equipment ageing into water consumption models. This will allow better reflection of long-term operational conditions and ensure that inefficiencies related to ageing equipment are accurately captured and addressed.

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Appendix A: Journal Article



Article

New Accountability Approach: Utilising Dynamic Zero-Waste Baselines to Mitigate Water Wastage in Gold Mines

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Abstract: The South African gold mining industry requires complex water reticulation systems to deliver chilled water to underground production areas. However, chilled- and service-water wastage, including leaks and misuse, contribute to approximately 50% of the total chilled-water demand. The current inefficiency detection methods rely on broad, infrequent, and labour-intensive work, focusing only on identifying and quantifying wastages without comprehensive mitigation strategies. This study aimed to develop a novel accountability framework employing dynamic zero-waste baselines to identify and address inefficiencies closer to active working areas. The proposed method incorporates four key components—*define, assess, execute, and communicate*—into an accountability system to monitor performance and ensure sustainable improvements. The integration of dynamic zero-waste baselines within this accountability framework will ensure faster and more accurate inefficiency detection and, more importantly, the mitigation thereof, significantly reducing water wastage. This study successfully reduced the daily water wastage, with an annual energy cost benefit of approximately USD 1.6 million (ZAR 28.7 million). The successful implementation of this method met all the research objectives, confirming its effectiveness.

Keywords: gold mine; zero-waste baseline; accountability; water wastage; dynamic baselines; efficiency



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1. Introduction

1.1. Background

Chilled water plays a vital role in South African gold mines. Its utility extends to underground air cooling and various mining activities, including the cooling of rock drills, cleaning/sweeping, and dust suppression [1,2]. Chilled-water pipelines are highly intricate and complex, supplying the end users with chilled water 4 km below the earth's surface, with these pipelines reaching lengths of over 15 km [3–5]. Presently, the water reticulation system, inclusive of pumping and refrigeration, constitutes approximately 39% of the overall energy consumption of a typical South African gold mine [6].

As mining operations progressively extend to greater depths in pursuit of new gold reefs, operational costs increase, further intensified by escalating electricity tariffs [7]. Consequently, there is an ongoing need to curtail the operational costs of South African gold mining operations [8].

Considering the complex nature of water reticulation systems, together with the harsh underground conditions, inefficiencies in the form of leaks and misuse are prone to occur [9]. Previous studies have shown that up to 50% of the total water used can be attributed to wastages [10].

Due to the intricate nature and scale of water reticulation systems, the ongoing challenge lies in the identification and quantification of the inefficiencies [6]. Addressing the inefficiencies is essential for reducing operational costs and extending the life-of-mine (LOM) of gold mining operations. However, before the inefficiencies can be mitigated, they need to be identified.

The current inefficiency detection methods include intensive underground audits, step testing, zero-waste baselines, hardware and software methods, benchmarking, historic baselines, and control valves [9,11–17]. These methods can identify the inefficiencies per mining level, still requiring labour-intensive measures to localise the issues.

A recent paper published by Le Roux [18] compared several wastage identification techniques to determine the effectiveness of each. Le Roux [18] considered techniques such as benchmarking, historic baselines, zero-waste baselines, leak detection, and control valves. Each technique was applied to a single mutual case study to provide a comparative platform. The paper concluded that the most accurate representation of wastages is the zero-waste baseline method, as all other techniques neglect some elements of wastage.

1.2. Zero-Waste Baseline Methods

A zero-waste baseline is described as the theoretical minimum consumption considering an idealised scenario, devoid of any wastages in a system [6,11]. This minimum consumption signifies the operational requirements achievable at 100% efficiency [19]. The utilisation of a zero-waste baseline is commonly employed to systematically identify and quantify wastages within a given system [14,20].

As mentioned, research has been conducted regarding the utilisation of zero-waste baselines, with a specific focus on mining operations [6,11,12,21–23]. The current zero-waste baselines have been developed per mining level. This means that inefficiencies can only be identified per mining level, still requiring labour-intensive underground audits to pinpoint the inefficiencies. Furthermore, the current zero-waste baselines have been developed using fixed timetables and fixed demands for mining equipment obtained from their specification sheets (using design specifications).

One study's unique approach included the localisation of inefficiencies in closer proximity to the working areas, namely that of Jordaan et al. [6].

Jordaan [6] made use of dynamic zero-waste baselines to effectively identify inefficiencies. Jordaan showed that most inefficiencies tend to occur closer to the stopes/working areas where the gold-bearing ore is mined. However, service water monitoring is currently only performed up to the half-level splits (measuring all the crosscuts on a half level together), which is not sufficient when considering the complex layout of underground mining operations. Jordaan installed flow and pressure meters in each working area to closely monitor the service water consumption in closer proximity to the working areas. Once the actual flow profiles for each working area were established, Jordaan developed a dynamic zero-waste baseline using the Missing Persons Locator (MPL) system's data, mining schedules, and correlation models, derived for each water user to introduce variability based on the underground pressures of specific areas. This approach ensured the quicker and more precise identification of inefficiencies, allowing for them to be pinpointed to specific working areas. These inefficiencies could then be addressed and continuously monitored to ensure sustainability.

The use of zero-waste baselines to identify inefficiencies in the mining industry is not a new concept. However, no studies could be found where a method was developed to actively ensure that the identified inefficiencies were mitigated and monitored for sustainability. Although it remains important to identify inefficiencies, it is meaningless if they are not addressed and managed. Responsibility allocation should be incorporated to assign the identified inefficiencies to certain personnel who will be held accountable for their mitigation [6].

1.3. Accountability Review

The term accountability is often regarded as a multifaceted and evolving concept with multiple definitions [24,25]. The literature on accountability confirms that it is rather disconnected, as authors have set out to produce their own definition depending on the context and purpose for which it is sought [26,27]. It has been used as a synonym for good governance, transparency, equity, democracy, efficiency, responsiveness, responsibility, and

integrity [26]. However, the concept of accountability can be simply defined as the process of being held responsible for one's actions [28–31]. Individuals and/or organisations are held accountable by reporting to a recognised authority (or authorities) [30,31].

Accountability has been described as the root of a viable social system, as the need for employees to be held accountable for good performance is widely accepted [32]. It has been found that there is a strong link between performance, behaviour, and accountability [33,34]. Consequently, accountability systems play a vital role in organisations by ensuring responsibility for actions, decisions, and performance. The main components of accountability, as identified in the literature, are shown in Table 1.

Table 1. Accountability components summarised from conducted research.

Component	Description
Clarified expectations	Mero et al. mentioned that outcomes are achieved when expectations are clear [33]. No accountability can be implemented if personnel do not understand what is expected from them. Expectations regarding roles, responsibilities, and performance standards should be clarified together with rewards and penalties [33,35,36].
Improved performance	Brandling et al. found that accountability measures improve employee performance and, by doing so, operational performance [36]. Performance appraisal systems should be implemented to track and monitor performance [37]. These include regular feedback, performance reviews, and goal tracking to allow individuals to identify areas for improvement. This promotes continuous learning and development of organisations.
Transparency and fairness	All actions and information should be made accessible to all employees to ensure transparency [30]. Furthermore, a culture of fairness should be fostered whereby all employees are held to the same standards [38].
Risk management	Assistance with risk mitigation by identifying certain risks and taking proactive measures to prevent them. By establishing accountability towards compliance with regulations, ethical standards, and best practice, organisations can reduce the likelihood of costly mistakes, legal liabilities, and reputational damage [30,36].
Goal alignment	Organisational and individual goals are aligned to ensure that everyone is working towards common objectives [33,39]. Organisations can maximise their efficiency by linking individual performance to their priorities and strategies [37].
Employee engagement and motivation	Employees are motivated as they are assigned responsibilities and receive recognition for their contributions [33,35]. When an accountability culture is fostered, employees hold each other and themselves accountable as improvement efforts are duly recognised, leading to engagement, motivation, and commitment to reaching organisational targets [36].

The research has highlighted four main methods of accountability, which are as follows [35,36]:

- **Self-accountability:** This refers to individuals taking responsibility for themselves. This overlaps with components of self-criticism, self-monitoring, and self-management. This is coupled with one's upbringing, values, and motivation to have a desire for achievement and inner satisfaction (an individual's sense of responsibility) [36].
- **Peer-to-peer accountability:** This form of accountability occurs between individuals at the same hierarchical level within an organisation. It involves reciprocal relationships and a sense of accountability towards one another, where individuals hold each other responsible for their actions and decisions. This type of accountability relies on peer interactions and mutual trust rather than hierarchical oversight. However, individuals may prioritise their personal reputation when being held accountable. Overall, while peer-to-peer accountability promotes collaboration and empowerment, it may also introduce ambiguity, bias, and conflicts in accountability assessments and decision-making processes.

- **Managerial accountability:** Managerial accountability involves individuals facing higher authorities to account for their performance, with hierarchical systems granting managers the power in this process. The research stresses that this mechanism is most effective when employees must face their managers in person to account for their performance. The negative aspects of managerial accountability include stress, when only failures are recognised, and perceptions of excessive control. The positive aspects include the recognition of good performance and showing compassion towards employees, leading to a positive association with accountability.
- **Systems accountability:** Systems accountability refers to the mechanisms and processes implemented within organisations to monitor, regulate, and ensure accountability for individual actions and performance. These mechanisms often include formal procedures, policies, and systems, such as performance appraisal systems, accounting systems, surveillance mechanisms, and computer monitoring. The goal of systems accountability is to establish clear standards, track performance, and enforce accountability to promote organisational effectiveness and compliance with the goals and objectives. While the significant impact of systems accountability is indisputable, it is essential that performance measurement and monitoring are performed accurately.

Accountability is a well-researched topic and has proven to be a powerful tool to use within organisations. However, accountability in the mining industry remains an unexplored topic. One relevant recent paper by Brandling et al. [36] examined accountability across different organisational levels within a mining company, revealing that the workers, supervisors, and managers perceived accountability differently, and focused on the rules, performance standards, and decision-making authority, respectively. Their study highlighted the importance of communication, role clarification, trust, discipline, and safety, especially in high-risk environments. However, it did not implement a specific accountability method, instead showing how different levels view it.

Pearson et al. [35] addressed this gap by developing a “System of Accountability” model based on interviews with 20 leaders, identifying five key factors: organisational systems, culture, role clarity, leadership, and individual attributes. These factors are critical for enhancing accountability and improving organisational performance. While accountability leads to better performance, mining companies often lack clear success metrics, according to Isacowitz [40], making it harder to measure outcomes effectively.

Developed systems play a crucial part in the development of successful accountability methods. It involves clear communication, role clarification, and transparency, which have all been identified as critical by researchers. While self-accountability and organisational culture are vital, managerial accountability provides the foundation that will ultimately determine the success of the subsequently described accountability types. A hierarchical approach ensures a holistic goal alignment, disciplined decision making, and unifies the actions that contribute to organisational success.

Accountability is a key element to reduce wastages [41]. However, the application of the outlined methods without their coherent adaptation to the economic, social, and demographic limitations associated with the mining industry can be detrimental to workforce morale and organisational profitability [42]. References to an incentive or sanction structure can produce various union-related complications, such as strike actions. The research further highlights that the consequences do not only include incentives or sanctions, but can also include social pressure, where others will know if an expectation has been met, praise or critique, to even having an impact on one’s career or having to answer to a higher authority [43]. It is, therefore, crucial to evaluate the influential parameters to reconstruct existing accountability methods to conform to the mining industry.

1.4. Research Aim and Objectives

The research highlights the need to develop a framework that will ensure that identified inefficiencies are addressed. By establishing clear lines of responsibility and fostering a

culture of accountability, mining operations can sustainably avoid unnecessary expenses and optimise resource utilisation.

This aligns with a significant limitation identified in the prior research regarding the absence of a well-defined post-identification method for addressing inefficiencies. While certain studies have incorporated feedback sessions, a substantive gap remains toward establishing a robust method for holding individuals accountable for issues within their designated areas.

Therefore, this paper includes a novel approach where zero-waste baselines will be integrated with an accountability method for mining operations. This combined approach seeks to ensure personnel accountability for wastage within their designated areas, thereby contributing to a reduction in the operational expenditures.

Therefore, the objectives of this paper are as follows:

1. The development of an accountability method for mining operations to address costly inefficiencies.
2. The incorporation of zero-waste baselines into the method as an accurate performance benchmarking metric.
3. Expedient inefficiency detection and mitigation in comparison to previous methods.
4. Ensuring that the developed method avoids labour-related concerns by steering clear of financial incentives.

The method used to address the objectives of this paper is discussed in the following section. The newly proposed method develops dynamic zero-waste baselines for each working area to enable inefficiency detection throughout the day and in closer proximity to working areas where the majority of inefficiencies are found. Due to the localisation of inefficiencies, responsibility allocation is implemented to ensure that the identified issues are mitigated. The continuous monitoring of each working area is implemented, which leads to decreased water wastage and ensures the sustainability of the mitigated inefficiencies.

2. Method

Four key steps are highlighted that should be included in a bespoke accountability model, namely *define*, *assess*, *execute*, and *communicate* [44]. These four steps are used as the basis of this method. The components described in Table 1 will be incorporated into and addressed with the implementation of the method. The proposed method is displayed in Figure 1.

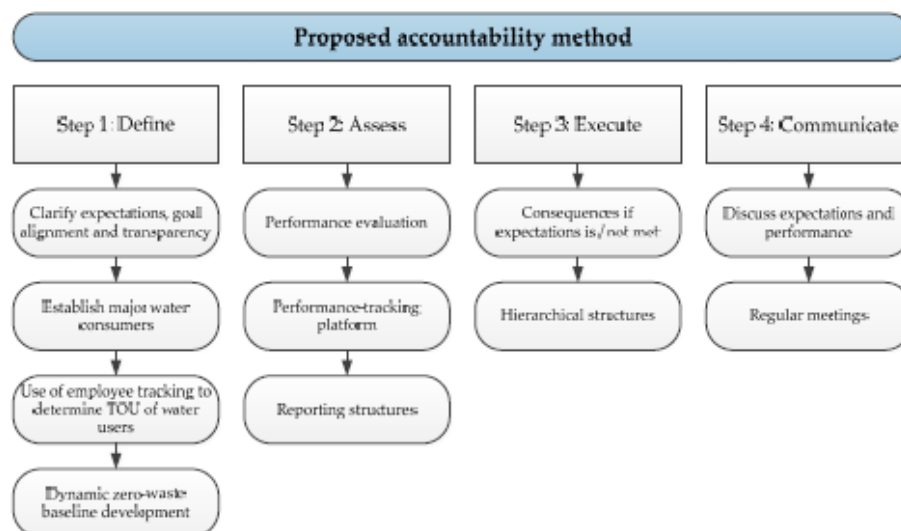


Figure 1. Proposed accountability method for inefficiency mitigation.

2.1. Step 1: Define

2.1.1. Clarify Expectations, Goal Alignment, and Transparency

Table 1 addresses the importance of clarified expectations, goal alignment, and transparency within an accountability method. Clear expectations should be established so that employees have a thorough understanding of the success criteria. In this context, success will be represented by the dynamic zero-waste baselines, which will be developed for each individual working area. These baselines will display the best practices for water consumption, serving as the operational standard. The success metrics will dynamically adjust based on the operational conditions and employee activity in each working area. Ensuring that all personnel are aware of the expectations not only promotes transparency, but also aligns with organisational and individual goals [30].

2.1.2. Major Water Consumers

The service water distribution in deep-level gold mines is divided between continuous and intermittent water users [1]. Continuous users, including air-cooling units such as bulk air coolers and mobile cooling units, receive a continuous water supply to maintain underground conditions in compliance with the Health and Safety Act of 1996 [45]. The focus here lies on the intermittent water users, who are the non-continuous water consumers in gold mining operations. The primary intermittent water consumers in gold mining operations include [46] the following:

- Rubber hoses;
- Rockdrills;
- Waterjets;
- Sweeping tools;
- Support tools.

To uphold accountability, it is essential to ensure that performance measurements are accurate, promoting fairness across the board. Conversely, previous researchers have tended to assume a fixed water consumption rate for water-consuming equipment obtained from specification sheets [11,23]. However, this approach overlooks the fact that some equipment, especially those manufactured in-house, may lack specification sheets. Furthermore, the data on equipment specification sheets typically represent the optimal operating conditions, which are determined within controlled environments and may neglect the performance in a deep-level gold mine. Therefore, to address this gap, tests should be conducted on identified water-consuming equipment to accurately determine their actual water consumption for specific operations. By doing this, all the water-consuming equipment will be considered, and their usage accurately accounted for. The tests should involve an underground test bench where water consumption can be evaluated by adjusting the water pressure. Measurements should be taken at different pressure levels using a portable flowmeter and pressure gauge.

The test data should be represented on a scatter plot, and the trendline that best fits the data should be chosen based on the R^2 value closest to 1 [6]. This trendline equation will be used to represent the water consumption at various pressures.

2.1.3. Employee Tracking Incorporation

The water consumption of all users has now been determined; however, the allocation throughout the day should be established. The literature indicates that water allocation for zero-waste baselines is performed for fixed periods corresponding to the working shifts of gold mines [6]. This approach may not provide an accurate depiction of water usage. This is due to the fact that water consumption by users may vary throughout shifts, leading to potential inaccuracies in its allocation [11,12,19]. Most of the intermittent water-consuming equipment consists of handheld, manually operated tools used by mining personnel. These tools only consume water when actively used by employees. Therefore, if there are no employees present in a working area, these handheld tools should not consume water.

Water usage during times when employees are not present will be classified as a misuse or inefficiency. Moreover, the operation of these tools requires specialised training to ensure their safe and optimal use. Consequently, if an employee trained to operate specific tools is not present in a given working area, those tools should remain unused. Therefore, having knowledge of the employees' whereabouts in the working areas enables the allocation of water usage based on the specific equipment they are trained to operate.

To obtain an employee's presence in a specific working area, an employee tracking system can be used. Employee tracking systems are widely implemented in deep-level gold mines to track employees' locations in case of emergencies [47]. Employee tracking systems typically make use of a radio frequency identification (RFID) system, integrated into the employees' headlamps, which transmits unique identification codes intermittently [48–51]. These codes are linked to the employees' clock cards, containing personal information, such as the employee name, employee number, operation name, region, zone, and job description.

RFID tag readers, installed at fixed locations throughout a mine, detect the nearby tags and transmit their codes to a central server, enabling the real-time tracking of employees within each tag reader's coverage zone [52,53]. This system enhances safety and operational efficiency by providing real-time employee location data. The data logged by the RFID tag readers are essential for employee tracking. They will be used to establish personnel movements, which directly correlate to water consumption patterns. Inefficiencies will be pinpointed, as water usage will be associated with specific activities and used as part of a dynamic zero-waste baseline development. The logical map of the process discussed is shown in Figure 2.



Figure 2. Logical map for employee tracking based on job description.

2.1.4. Dynamic Zero-Waste Baseline Development

The zero-waste baselines will be established by integrating the above-mentioned factors. An area's measured water pressure will be inserted into the developed formula to determine the specific equipment's water consumption. The personnel activity will be used to determine the type of water user at any time of the day and assign the corresponding water-consuming tool to them. Doing this will ensure a 24 h benchmark profile that will be measured against the actual measured reading. These baselines will be generated daily for each working area equipped with flow and pressure metering. Through this, the localisation of inefficiencies will be possible, which addresses the literature gaps identified. Each job description will be assigned a water-consuming tool. When the employee tracking system detects a specific job description in a working area, the correlating water-consuming tool will receive water allocation.

The water usage will be determined based on the operational conditions, as represented by the derived formula discussed in Section 2.1.2. By doing so, the baselines will be dynamically adapted based on the operational conditions and employee movements, ensuring the accurate development of zero-waste baselines that can be used for accountability purposes. The accuracy of the baselines is of critical importance to ensure fairness and transparency. The process is schematically shown in Figure 3.

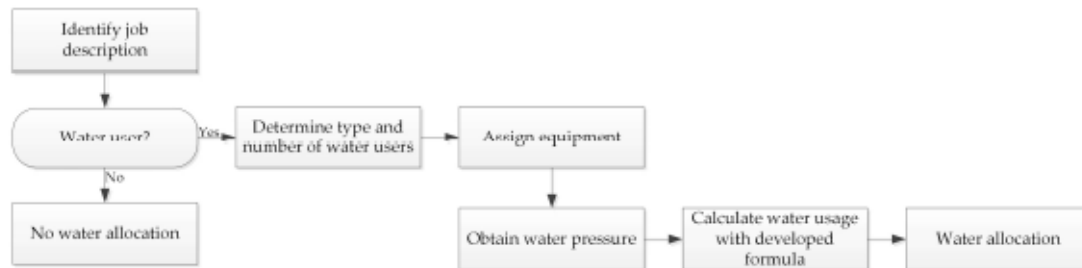


Figure 3. Dynamic zero-waste baseline integration.

2.2. Step 2: Assess

Accurate dynamic zero-waste baselines for each working area are now available. The development of these baselines alone will not mitigate inefficiencies but merely serve as a tool. To address inefficiencies, responsibility allocation should be performed so that all employees are aware of their roles and responsibilities. Given the innovative nature of this approach, it is advisable to implement it in a phased manner to ensure the successful execution of the change management process.

Performance evaluations can be conducted by comparing the developed dynamic zero-waste baselines to the actual water usage for each working area. The employees responsible for the areas of concern will then need to answer for the performance as measured by the comparison to the developed baselines. The working areas' performances should be made available to all stakeholders to ensure transparency and clear expectations.

An example of performance distribution includes platforms and reports to be distributed to all stakeholders to view their performance.

2.3. Step 3: Execute

This step includes repercussions if expectations are met or not. It is important to establish a clear procedure to guide these actions. To align with the literature, recommendations and repercussions should steer clear of social, economic, and political implications, as they often lead to conflict [42]. Instead, it is proposed that hierarchical structures are introduced, where individuals or crews failing to comply are held accountable by higher authorities, as suggested by the literature [43].

Conversely, individuals or crews exceeding expectations deserve recognition, in line with the literature, which suggests the incorporation of social pressure to encourage adherence [35,54]. This involves publicly acknowledging exceptional performance by featuring their names on widely accessible platforms or presenting them with distinctive attire as a symbol of their outstanding achievements. A typical hierarchical structure is shown in Figure 4. The hierarchical structure within a mine is critical to understanding the flow of responsibilities across departments. This structure will be used to identify the key stakeholders responsible for water management. Here, a bottom-up approach can be followed to give personnel at the lower levels of the hierarchy an opportunity to address the identified issues before being publicly identified. Doing this will lead to greater engagement and ownership across all levels.

After all stakeholders are made aware of the repercussions, opportunities to discuss performance should be established before any steps are taken.

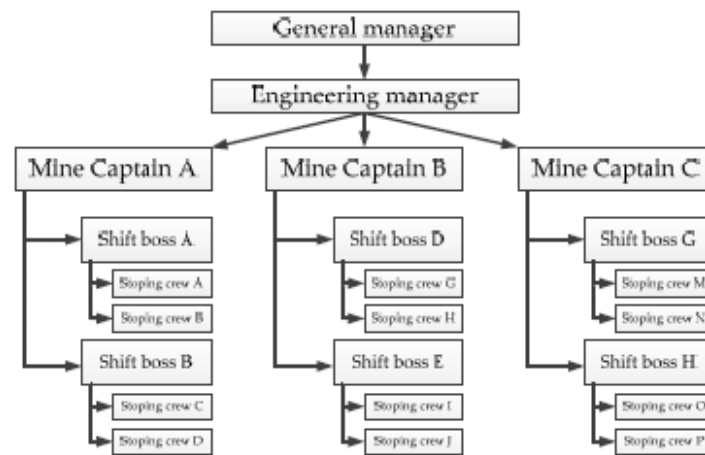


Figure 4. Typical hierarchical structure of a mine.

2.4. Step 4: Communicate

The final step involves the communication of performance and repercussions. Open lines of communication should be established, such as recurring meetings, personal messages, notice boards in working areas, etc., where all problems, solutions, and timelines are discussed. All stakeholders should be present to ensure transparency.

2.5. Verification

The verification of the method should determine if the proposed method successfully addresses the identified problem. Table 1 in Section 1.3 summarises the components of an accountability method; therefore, the proposed method should adhere to all the listed components to comply with the literature. Each component is listed together with the outcomes contributing to the corresponding component. The method is deemed as successful if all the components have been addressed. The logic map for this process is displayed in Figure 5.

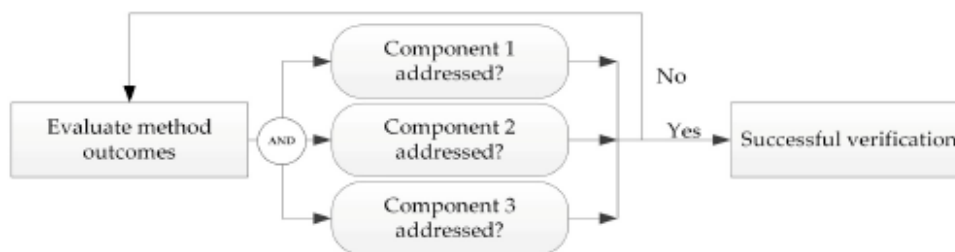


Figure 5. Logic map for method verification.

3. Results

This section entails the implementation of the proposed method, described in Figure 1, to a case study conducted on Mine A. Mine A is a deep-level gold mine situated in South Africa. The mining is based on a scattered mining method, together with an integrated backfill support system. This operation consists of 35 active working areas, producing approximately 6000 kg of gold annually. To produce the gold, Mine A dewateres approximately 36 mL of water per day, which is cooled by large refrigeration systems for reuse underground. The mine's pumping and refrigeration systems account for roughly 16% and 18% of the total power consumption of Mine A, respectively.

3.1. Existing Inefficiency Detection Methods

For this paper, existing inefficiency detection techniques were implemented to serve as a benchmark for comparison with the developed method. The current inefficiency detection methods that allow for the localisation of inefficiencies include drop tests and service audits.

Service water drop tests were conducted on a South African gold mine. These drop tests were conducted during times when no personnel were working underground to identify the wastages present during non-mining periods. A typical portable flowmeter used to measure the water consumption on each half-level is seen in Figure 6. All the crosscuts were closed and then opened one by one to measure the water consumption of each crosscut when no mining was taking place. Since no personnel were working during these times, any water consumption was attributed to wastage.



Figure 6. Portable ultrasonic water flowmeter used for measurements.

Table 2 displays the drop test results for the previous three months for the five crosscuts with the most wastage. It is clear that some areas are present each month without any mitigation, as highlighted in the table. Furthermore, these values are instantaneously measured values and only obtained monthly at times when no personnel are present underground. Therefore, no accountability can be assigned for these instantaneous results and new information is only made available each month after the drop tests are conducted. These results confirm that after three months, no work has been performed to mitigate costly inefficiencies.

Table 2. Drop test results from case study mine.

Month 1			Month 2			Month 3		
Level	XC	Wastage [L/s]	Level	XC	Wastage [L/s]	Level	XC	Wastage [L/s]
A	35	44	A	51	11	B	51	17
A	57	18	B	36	10	A	61	11
A	38	15	A	32	10	A	36	11
B	33	15	A	63	8	B	36	11
A	36	14	A	38	8	A	62	9

In addition, service water audits were conducted for a production level in Mine A. Here, numerous inefficiencies were identified and recommended to be fixed. Three months later, a follow-up audit was conducted to determine if the previously identified inefficiencies had been rectified. The results are depicted below in Figure 7. From the results, it is clear that numerous recurring inefficiencies were detected during the follow-up audit.

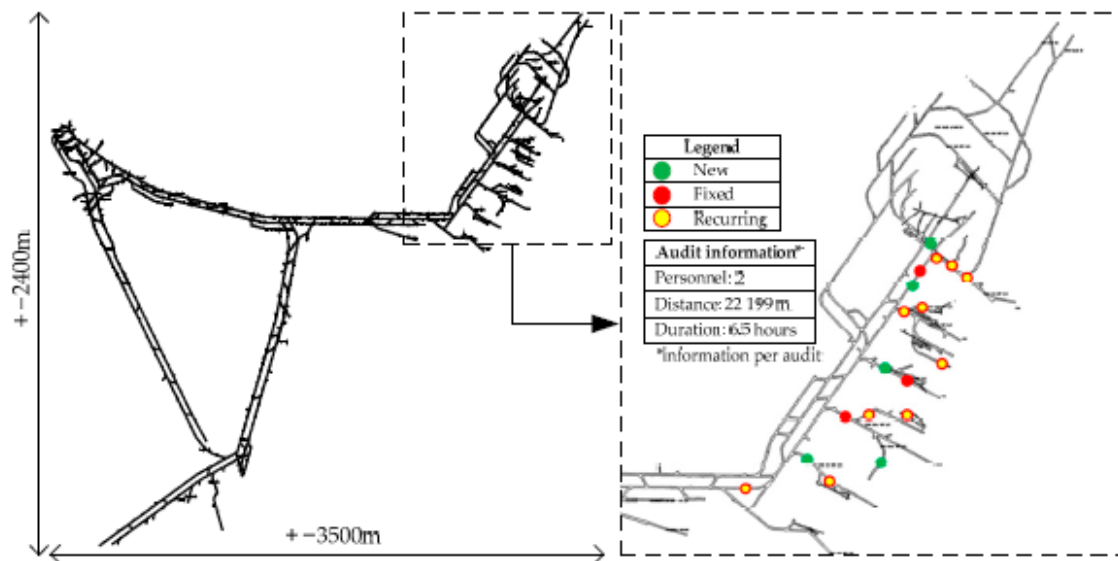


Figure 7. Service audit results (screenshot of only one part of the level is shown).

Furthermore, no indicator exists to determine whether the identified wastages have been mitigated other than by conducting a follow-up underground visit. It is important to note that an audit such as this one is extremely time-intensive. The service water audit of the specific level consisted of two employees having to cover a total of approximately 22.2 km within 6.5 h, with no indication of whether the identified inefficiencies had been mitigated.

3.2. Step 1: Define

The following section will focus on the “define” step of the developed method.

3.2.1. Major Water Consumers

The primary intermittent water users at Mine A have been identified. Actual water tests were conducted to establish the water consumption for all the primary intermittent water equipment at various pressures.

The data were captured using a portable ultrasonic water flow meter and portable pressure gauge. These data were used to develop scatter plots that were utilised to establish trendline equations for all water users, as displayed below in Table 3. This process ensured that the water usage for all the equipment was accurately determined using the actual conditions. The actual water pressures, measured by meters installed in each crosscut, were input into the formula to calculate the water consumption for each piece of equipment based on the observed pressure in the working area. It should be noted that results are only shown for one working area; however, the same principle was applied to the remaining areas.

In the table below, y and x are as follows:

y—Water consumption in l/s;

x—Water pressure in bar.

All the equations in Table 3 have R^2 values close to one (as discussed in Section 2.1.2), indicating that they accurately represent the water consumption of all the water-consuming equipment and will be used accordingly. This addresses the gap identified in the existing research.

Figure 8 displays the pictures taken by one of the authors of the water-consuming equipment at the case study mine.

Table 3. Trendline equations for intermittent water users.

Equipment Name	Trendline Equation	R ² Value
10 mm open hose	$y = -0.0015x^2 + 0.0823x + 0.0127$	0.9986
25 mm open hose	$y = 1.7913\ln x + 0.3892$	0.9992
Venturi	$y = -0.0009x^2 + 0.0542x + 0.0345$	0.9934
Victoria rockdrill	$y = 0.2482\ln x - 0.0284$	0.9907
Conventional rockdrill	$y = -0.0003x^3 + 0.0075x^2 - 0.0144x + 0.2681$	0.9904
Nozzle	$y = -0.0014x^2 + 0.0707x + 0.0937$	0.9981
Omni prop	$y = 0.0181x + 0.076$	0.9979
Blue jackpot	$y = 0.0001x^2 + 0.006x + 0.0062$	0.9821
Waterjet	No correlation function as it uses a high-pressure pump to ensure designed water flow—3.42 L/s.	

**Figure 8.** Water-consuming equipment at case study mine captured by authors.

3.2.2. Employee Tracking Incorporation

For this study, an MPL system was used. This system is widely implemented in South African gold mines. The MPL data are stored in the mine's internal database. It is important to note that the data stored in the database include the tracking information for all employees for all areas in the mine. However, for the purpose of this study, the job descriptions of water-consuming personnel were filtered within the specific areas in question. For this application, Python version 3.12 was used to filter the data; however, any platform can be used to sort the data into the desired format.

The first step was to determine the job descriptions that typically consume water. These are as follows:

- Night shift cleaner;
- Rock drill operator;
- Waterjet operator;
- General miner.

The developed Python script accessed the mine's MPL database, whereafter it automatically sorted the data based on the employee activity for the given job descriptions. The specific working area was inserted into the script along with the desired date. The filtered data were stored and used to develop the zero-waste baselines. The filtered data for working area 1 are shown below in Figure 9. Here, the selected job descriptions' activity can be seen together with the total employee movement in working area 1. By using the data shown below, the time-of-use patterns of the handheld water-consuming equipment could be determined more accurately.

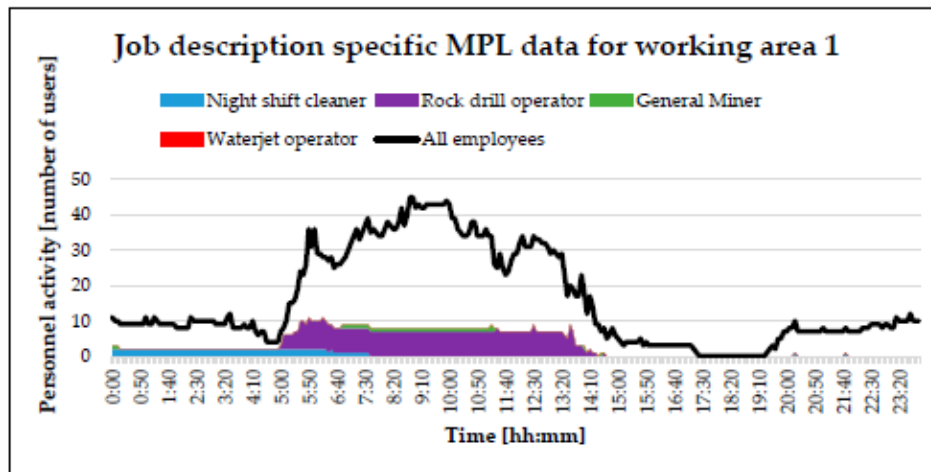


Figure 9. Job description specific MPL data for typical day.

3.2.3. Dynamic Zero-Waste Baseline Development

As mentioned, each job description is allocated a specific piece of water-consuming equipment. The job description and corresponding equipment are shown below in Table 4.

Table 4. Equipment allocation for specific job description.

Job Description	Task	Water-Consuming Equipment
Night-shift cleaner	Cleans the face after blasting.	Rubber hoses and bazookas
Rock drill operator	Drills holes in rockface for explosions.	Victoria and conventional rock drill
Waterjet operator	Cleans the face after blasting.	Waterjet
General miner	Assists with the supporting of rock formations.	Venturi, nozzle, omni prop, and blue jackpot

Together with this, the amount of equipment in the working areas is obtained. Each user entering the area is allocated their specific equipment, but the data provided below are used as a secondary form of assurance for verification. This means that if the MPL data pick up that, for instance, five waterjet users are in the active area, water will not be assigned to all five users, as there are only three waterjets installed in the specific working area. Doing this helps to ensure that the developed baseline is accurate.

Table 5 displays the amount of equipment in working area 1.

Table 5. Amount of equipment in working area 1.

Equipment Name	Quantity
Waterjets	3
Victoria rock drills	13
10 mm rubber hose	8
25 mm rubber hose	2
Bazookas	0
Venturi	1

Incorporating all the above-mentioned factors, the dynamic zero-waste baselines can be developed. Figure 10 shows the zero-waste baseline for working area 1.

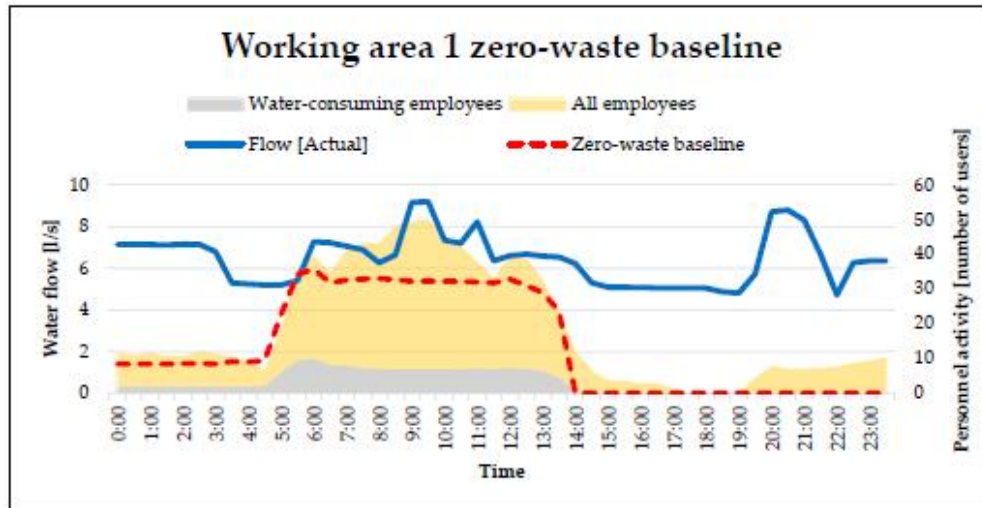


Figure 10. Working area 1 zero-waste baseline comparison for typical day.

Figure 10 displays the water wastage throughout the day, even when no water-consuming personnel were present in the area. To understand why wastage was present, an underground visit to working area 1 was conducted. Figure 11 depicts the inefficiencies observed during the underground visit. These inefficiencies are typically present throughout the day. The proposed accountability method addresses the issues seen in Figure 11 to ensure that the identified water inefficiencies are not only identified and quantified but also mitigated.



Figure 11. Common underground inefficiencies identified at case study mine captured by authors.

3.3. Step 2: Assess

Figure 12 displays a screenshot of the user interface for the performance platform developed to monitor and track system performance. The platform was developed for the purpose of this study; however, any platform could be used that visually represents the desired data. The platform serves as a tool for personnel to view their performance at any given time.

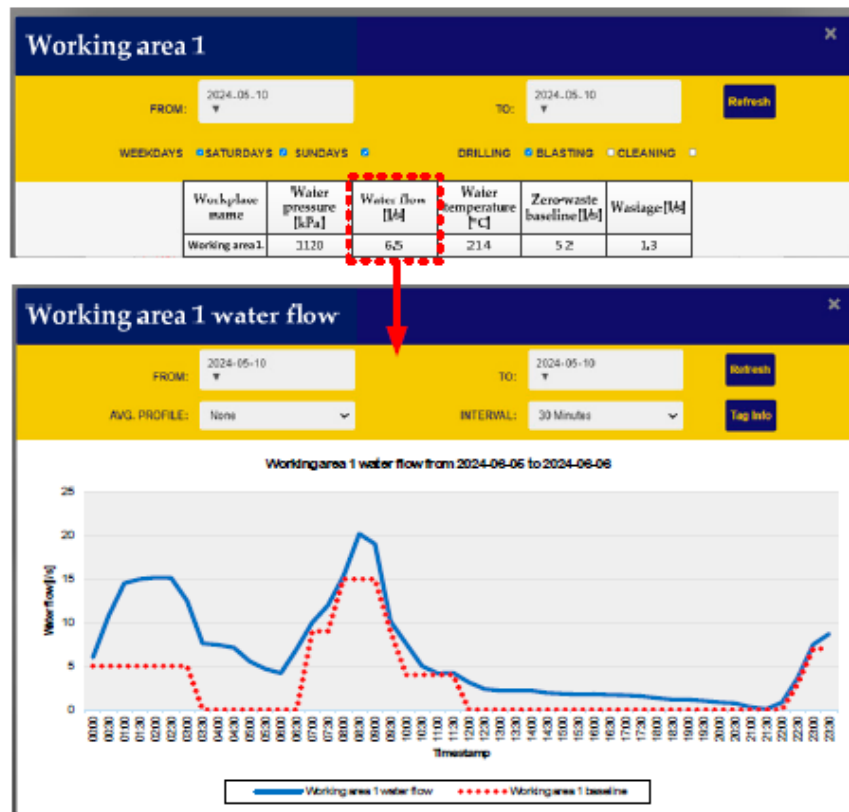


Figure 12. Screenshot of the developed platform showcasing water data for working area 1 in Mine A.

The platform allows the user to select the desired working area. The users have access to information, such as the actual water pressure, flow, and temperature. Together with this, the zero-waste baseline for that specific area is available. Once they have accessed the parameters, the users can select certain dates which display the data captured for that period.

The key stakeholders can stay informed through an automated daily report, specifically developed for the novel accountability approach. This report includes the same information as that seen on the platform. Here, the stakeholders can view their performance, which will be discussed during scheduled meetings. The report includes problematic areas and action lists, which will be discussed during daily meetings.

3.4. Step 3: Execute

As mentioned, personnel will need to answer to supervisors when expectations are not met. Hierarchical structures have been used to steer clear of financial incentives, which

may lead to labour disputes [42]. The following hierarchical structure was put in place, as seen in Figure 13. Here, the engineering and mine managers discuss the results with the mine captains. The mine captains are in discussion with their shift bosses, who in turn appoint certain crew members to mitigate the identified inefficiencies. The engineering and mine managers give feedback to the general manager. For this paper, the focus was placed on the accountability up to the mine captains, as indicated by the red dotted lines in Figure 13.

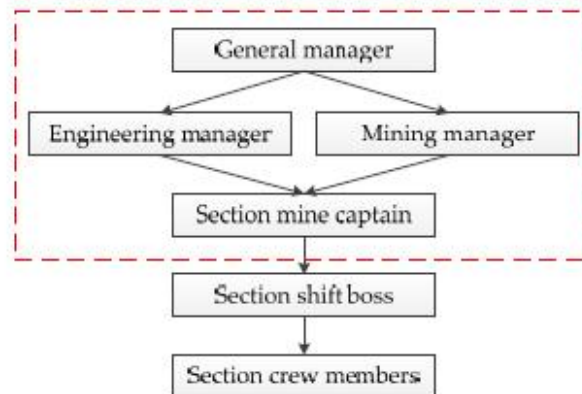


Figure 13. Mine A hierarchical structure.

Following discussions with the mining personnel, it was decided to implement a 3-strike point system. When an inefficiency is identified, it is included in the action list. Each time that the same inefficiency is discussed without any progress or feedback, the mine captain receives a strike. When three strikes have been received, the mine captain is called in by the general manager.

Conversely, the top-performing teams' names are displayed on the notice board, as seen in Figure 14. Through this, a culture is developed where employees strive to earn public recognition for their good work. Furthermore, all the stakeholders work towards the same goal, which is to ensure the life-of-mine and efficient mining practices.



Figure 14. "Good performance" notice board at case study mine captured by authors.

3.5. Step 4: Communication

Existing daily meetings are used to discuss tasks. A slot is allocated during these meetings to discuss the previous day's water performance. The meetings are held between

all mine captains and the relevant managers. Here, the mine captains provide feedback with regards to their performance on the previous day. Once a month, feedback sessions with the general manager are conducted to bring them up to speed and obtain their input if needed. This aligns with the research, which stresses that this mechanism is most effective when employees must face managers in person to account for their performance.

3.6. Method Integration and Results

By following all the above-mentioned steps of the developed accountability method, inefficiencies are identified, mitigated, and continuously monitored to ensure sustainability. The results of implementing the method are shown below. The data shown in the figures below compare the actual water consumption data received from the case study mine to the dynamic zero-waste baselines developed in this study for working area 1.

- High service water consumption is identified by using the developed dynamic zero-waste baselines, as depicted in Figure 15. Here, it is clear that service water is wasted throughout the day, even when no personnel are present in the area.
- To ensure the smooth integration of the accountability method, it was suggested that a phased approach be followed. Phase one consisted of reducing water wastages when no personnel were present underground. This encouraged employees to gradually become more conscious of reducing water wastage.
- Mine captain A was made aware of the water wastage in his area by using the developed reporting and communication structures. He was able to access his area's performance on the dashboard.
- During the allocated slot in a daily meeting, mine captain A was made aware of the phased approach that was going to be implemented. This entailed closing the water isolation valve at the entrance to the working area when the last employee leaves the area. This cuts off the water supply to this working area, resulting in reduced water wastage during times when no personnel are present in the area. Hierarchical structures were used, and mine captain A was made aware that he would be held responsible for ensuring that the valve was closed. He, in turn, allocated a responsible person to mitigate the identified issue.
- Figure 16 displays the results from the first phase, after a week of implementation. Figure 16 confirms that the water valve was indeed closed during times when no personnel were observed underground. Mine captain A successfully guided his team to ensure that wastages were reduced during times when no personnel were observed. It is important to note that in Figure 16, the zero-waste baseline exceeds the actual water consumption profile from approximately 22:00. This happens because the system detects a potential water user and attributes water usage to them. However, in some rare cases, these individuals are present in the area without consuming any water. The main takeaway is that the actual consumption remains below that of the zero-waste baseline. The zero-waste baseline represents the total allowable water consumption during the day based on employee movement.
- Next, the second phase was discussed during a daily meeting. This phase included reducing water wastage throughout the day, including active working hours.
- The developed structures were used to notify mine captain A of issues identified in his area by comparing the actual water consumption to that of the developed zero-waste baseline.
- Mine captain A, after discussions with his team, mentioned that workers opened rubber hoses to release the water pressure in the main pipeline as it posed pressure problems. These rubber hoses were left open, which meant that water was wasted throughout the day. This was due to a faulty pressure relief valve (PRV) that did not reduce the water pressure at the inlet of the area as designed. Furthermore, it was mentioned that a burst manifold was observed, which should be rectified.

- In a daily meeting, it was discussed and concluded that the engineering team was responsible for fixing the faulty PRV. A fitter for the specific section was tasked to replace the broken manifold.
- Figure 17 displays the results of the second phase. Here, it can be seen that the actual water consumption profile follows that of the developed zero-waste baseline. It should be noted that wastages are still observed for certain periods of the day, which also need to be attended to. However, the results presented here confirm that by implementing accountability, water wastage can be reduced throughout the day. Following the developed method, water wastage was reduced from approximately 0.34 mL per day to 0.03 mL per day for working area 1. This equates to a total annual energy cost benefit of approximately USD 1.6 million (ZAR 28.7 million) for Mine A.

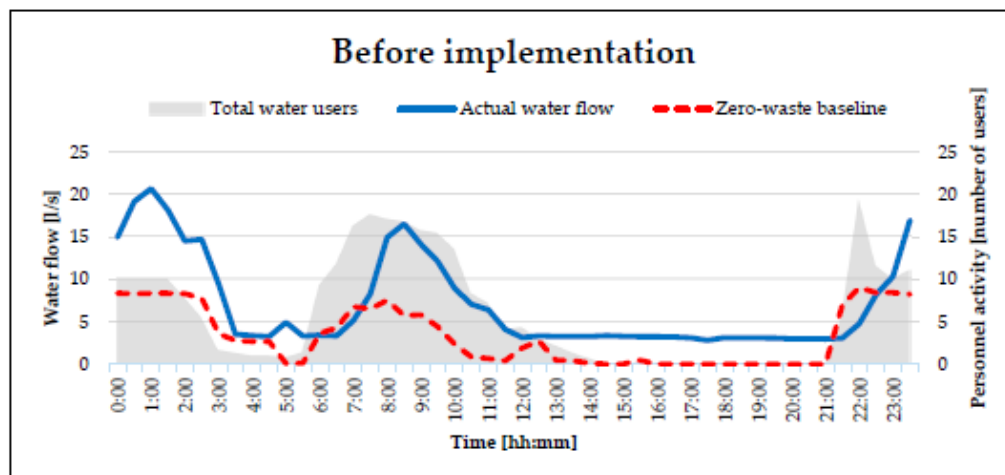


Figure 15. Water wastage identified before method implementation.

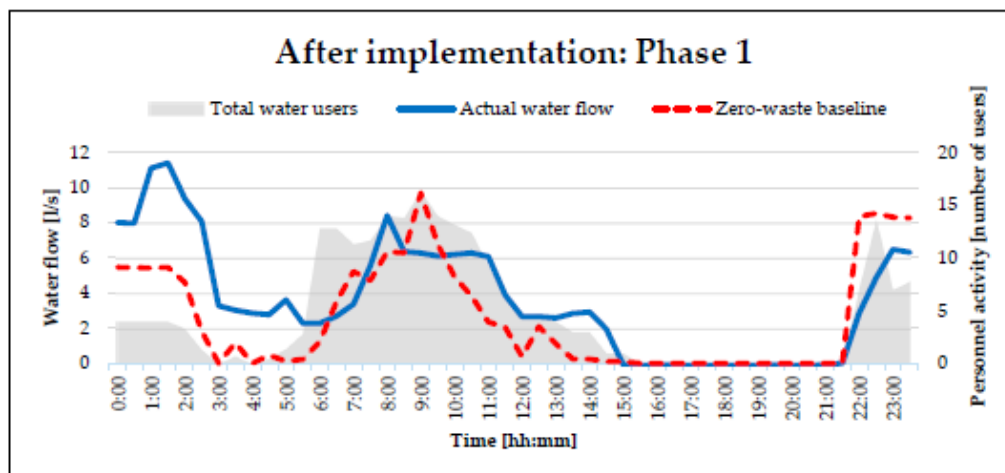


Figure 16. Results after implementing phase 1.

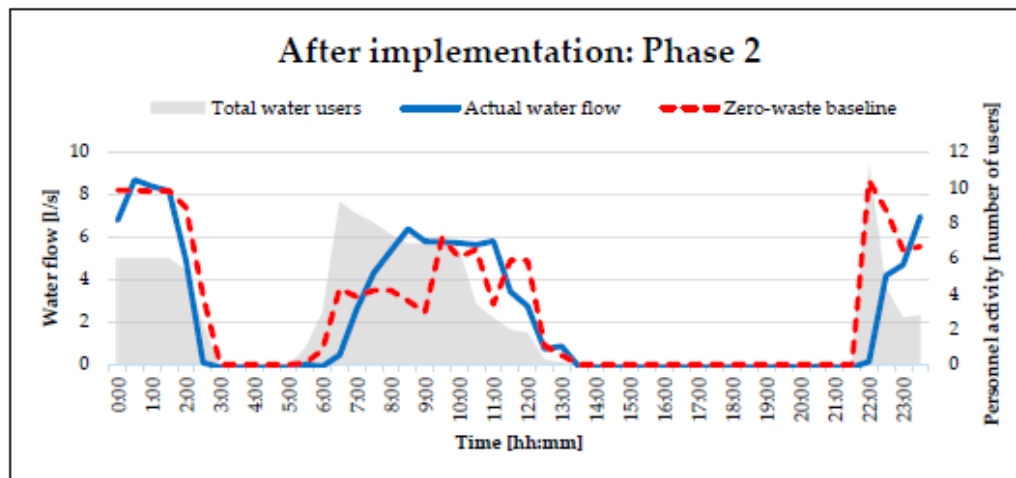


Figure 17. Results after implementing phase 2.

Figure 18 compares the actual water flow profiles before implementation with the results achieved after implementing both phase 1 and phase 2. Phase 1 focused on reducing water wastage during periods when no personnel were underground (between 15:00 and 21:00). After this goal was achieved, the focus was shifted to reducing water wastage throughout the day. The significant achievements are displayed below in Figure 18.

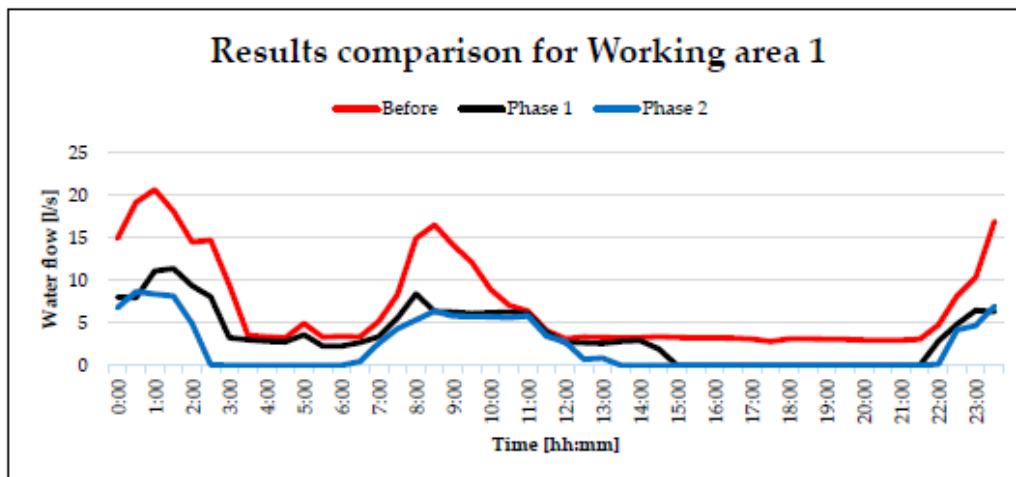


Figure 18. Water flow profiles comparison for working area 1.

Figure 19 displays the total daily water usage over a period of 29 days (excluding weekends). The issues, as mentioned, were discussed on day 1. The team fixed the identified issues by day 7, whereafter a significant water reduction was observed. From there, the daily usage was monitored to ensure compliance. On day 20, high water usage was observed, addressed, and mitigated within one day.

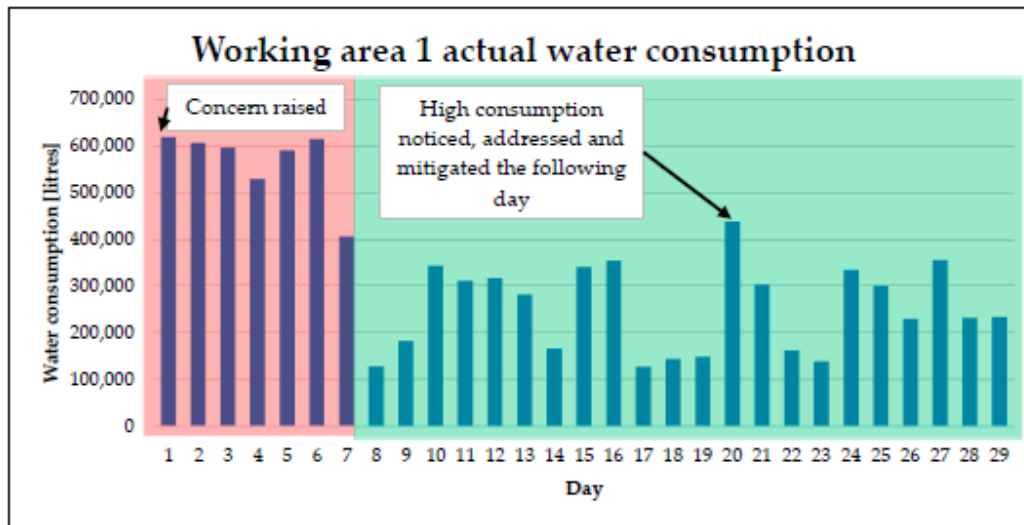


Figure 19. Total daily water consumption for working area 1.

Compared to the existing methods, as discussed in Section 3.1, the developed method enabled inefficiency mitigation within one week of identification. Additionally, the mitigated inefficiencies can now be monitored daily, ensuring compliance and sustainability. If inefficiencies resurface, they will be addressed as demonstrated in this paper. While some inefficiencies may be more complex and require additional time to mitigate, the developed approach ensures they will be rectified in a timely manner.

3.7. Verification

The research has identified several components that should be included in a successful accountability system. These components are listed in Table 1. The developed method was verified by comparing the identified components to the outcomes of this study to ensure that each was addressed. Each component is listed together with the corresponding step of the proposed method where the component is addressed, as seen in Table 6.

Table 6. Accountability components together with the step where the component is addressed.

Component	Addressed in Step Number
Clarified expectations	1 and 3 (define and execute)
Improved performance	2 and 4 (assess and communicate)
Transparency and fairness	2, 3, and 4 (assess, execute, and communicate)
Risk management	3 and 4 (execute and communicate)
Goal alignment	1, 3, and 4 (define, execute, and communicate)
Employee engagement and motivation	3 and 4 (execute and communicate)

The proposed method is deemed as successful, as all the components as set out are addressed by the developed method.

4. Conclusions

Chilled-water wastage is a problem in deep-level gold mining operations. This needs to be addressed to decrease the operational costs of mining operations. Before inefficiencies can be addressed, they need to be identified. However, the existing work conducted on

inefficiency detection relies on broad, infrequent, and labour-intensive work. Furthermore, no comprehensive method could be found to mitigate the identified issues and monitor the mitigated issues to ensure sustainability.

This study addresses water wastage in South African deep-level gold mines by implementing an accountability method that integrates dynamic zero-waste baselines. These baselines are constructed for each working area of a mine and represent an optimal water usage profile based on the working conditions, employee movements, and equipment utilised. The actual water consumption profile is compared to the baseline to successfully identify water wastage in closer proximity to the working areas, where most inefficiencies occur. This approach ensures real-time inefficiency detection and localised monitoring using flow and pressure meters installed in each working area.

The accountability framework developed in this study used four key components: *define*, *assess*, *execute*, and *communicate*. The expectations and goals were first outlined (*define*) to ensure all personnel were aware of the water usage standards. Next, daily water usage data were compared to the zero-waste baseline (*assess*) to identify inefficiencies. Immediate actions were taken to address the identified issues, utilising a hierarchy of accountability to assign responsibilities (*execute*). Daily and monthly meetings (*communicate*) were implemented to discuss water usage performance, reinforcing responsibility among the mine captains and their teams.

This system was implemented in phases, firstly focusing on reducing water wastage during times when no personnel were underground. Next, the focus was placed on water wastage throughout the day. By following a phased approach, this ensured that the personnel were gradually encouraged to adopt water-saving behaviours.

The proposed method reduced the daily water wastage in working area 1 from 0.34 mL to 0.03 mL, which equates to a total annual energy cost benefit of approximately USD 1.6 million (ZAR 28.7 million) for Mine A.

Furthermore, inefficiencies were not only identified faster compared to previous methods, but they were also mitigated and monitored to ensure sustainability.

The results obtained show that by implementing accountability, water wastage can be reduced throughout the day. The method is deemed successful, seeing that all the objectives set out in this paper have been met.

5. Recommendations for Future Research

This study established a single baseline for comparison against the actual water consumption of a mining operation. It is recommended that maximum and minimum ranges be defined as error intervals to create an operational water consumption range for each area, thereby compensating for numerical fluctuations.

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Appendix B: Water users on Mine A

Table 22 and Table 23 displays the water-consuming tools and quantities specifically used during the drilling- and cleaning shifts for working areas. Some other equipment is also used but the remaining equipment was noted in all working areas.

Table 22: Water-consuming tools: drilling shift.

Number	Name	Description	Equipment	Quantity
1	88L 109N XC	Stope Paired Single Sided – 2 Panels	S215 Drills	0
			500 kW CC	2
2	92L 115 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
3	92L 105 XC	Stope Paired Single Sided – 3 Panels	S215 Drills	12
			500 kW CC	1
4	92L 97 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
5	92L 113BN XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
6	92L 114AN XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
			500 kW CC	2
7	92L 106N XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
8	92L 106 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
9	95L 113 XC	Stope Paired Single Sided – 1 Panels	S215 Drills	4
10	95L 113A(1) XC	Stope Paired Single Sided – 1 Panels	S215 Drills	4
			500 kW CC	2
11	95L 104A XC	Stope Paired Single Sided – 1 Panels	S215 Drills	4
12	95L 114 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
13	95L 104B XC	Stope Paired Single Sided – 3 Panels	S215 Drills	12
14	98L 113 XC	Stope Paired Single Sided – 4 Panels	S215 Drills	16
			500 kW CC	2
15	98L 112A1 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	8
16	98L 112(1) XC		S215 Drills	8

Appendix B

		Stope Paired Single Sided – 2 Panels	500 kW CC	2
17	98L 114 XC	Stope Paired Single Sided – 1 Panels	S215 Drills	4
18	98L 112B XC	Stope Paired Single Sided – 5 Panels	S215 Drills	20
19	101L 104 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	4
20	101L 91 XC	Stope Paired Single Sided – 2 Panels	S215 Drills	4
21	88L 107B XC	Development	S25 Drills	2
22	88L 108N XC	Development	S25 Drills	2
23	92L 113A XC	Development	S25 Drills	2
24	95L 104 XC	Development	S25 Drills	2
25	95L 104A XC	Development	S25 Drills	2
26	95L 104B XC	Development	S25 Drills	2
27	98L 113 XC	Development	S25 Drills	2
28	98L 114 XC	Development	S25 Drills	2
29	98L 112B XC	Development	S25 Drills	2
30	98L 114B XC	Development	S25 Drills	2
31	98L 114B1 XC	Development	S25 Drills	2
32	101L 88 XC	Development	S25 Drills	2
33	101L 90 XC	Development	S25 Drills	2
34	101L 89A XC	Development	S25 Drills	2
35	101L 90A XC	Development	S25 Drills	2
36	95L 112(1) XC	Cooling	500 kW CC	1
37	88L 108S XC	Cooling	500 kW CC	1
38	92L 108 XC	Cooling	500 kW CC	1
39	98L 109 XC	BAC	500 kW CC	3
40	98L 111 XC	BAC	500 kW CC	2
41	98L C/Lift XC	Cooling Chairlift	500 kW CC	1
42	101L PZ2 HLGE	BAC	500 kW CC	2
43	101L RAW	Cooling development	500 kW CC	1
44	101L 87 XC	Cooling	500 kW CC	1
45	101L RAW S	Cooling development	500 kW CC	3

Table 23: Water-consuming tools: cleaning shift.

Number	Name	Description	Equipment	Quantity
1	88L 109N XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
			500 kW CC	0

Appendix B

2	92L 115 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
3	92L 106N XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
4	92L 105 XC	Stope Paired Single Sided – 3 Panels	Waterjet	1
			500 kW CC	0
5	92L 97 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
6	92L 113BN XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
7	92L 114AN XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
			500 kW CC	0
8	92L 106 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
9	95L 113 XC	Stope Paired Single Sided – 1 Panels	Waterjet	1
10	95L 113A(1) XC	Stope Paired Single Sided – 1 Panels	Waterjet	1
			500 kW CC	0
11	95L 104A XC	Stope Paired Single Sided – 1 Panels	Waterjet	1
12	95L 114 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
13	95L 104B XC	Stope Paired Single Sided – 3 Panels	Waterjet	1
14	98L 113 XC	Stope Paired Single Sided – 4 Panels	Waterjet	1
			500 kW CC	0
15	98L 112A1 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
16	98L 112(1) XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
			500 kW CC	0
17	98L 114 XC	Stope Paired Single Sided – 1 Panels	Waterjet	1
18	98L 112B XC	Stope Paired Single Sided – 5 Panels	Waterjet	1
19	101L 104 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1
20	101L 91 XC	Stope Paired Single Sided – 2 Panels	Waterjet	1

Appendix C: Intermittent scatter plots and MAPE verification

The scatter plots of water-consuming equipment are shown in Figure 54 to Figure 60. Here, the equations and R^2 values are also displayed. Moreover, MAPE verification of these equations compared to actual tested values are shown in Table 24 to Table 30.

It is important to note that four entries have a MAPE greater than 10%. This discrepancy may be due to several factors; however, for these specific entries, the flow measurements taken at the corresponding pressures had not yet stabilised. As a result, the recorded flow values may differ slightly, and a longer stabilisation period should have been allowed before taking measurements.

Despite this, the equations still provide accurate results, with the MAPE of the affected entries remaining below 16%.

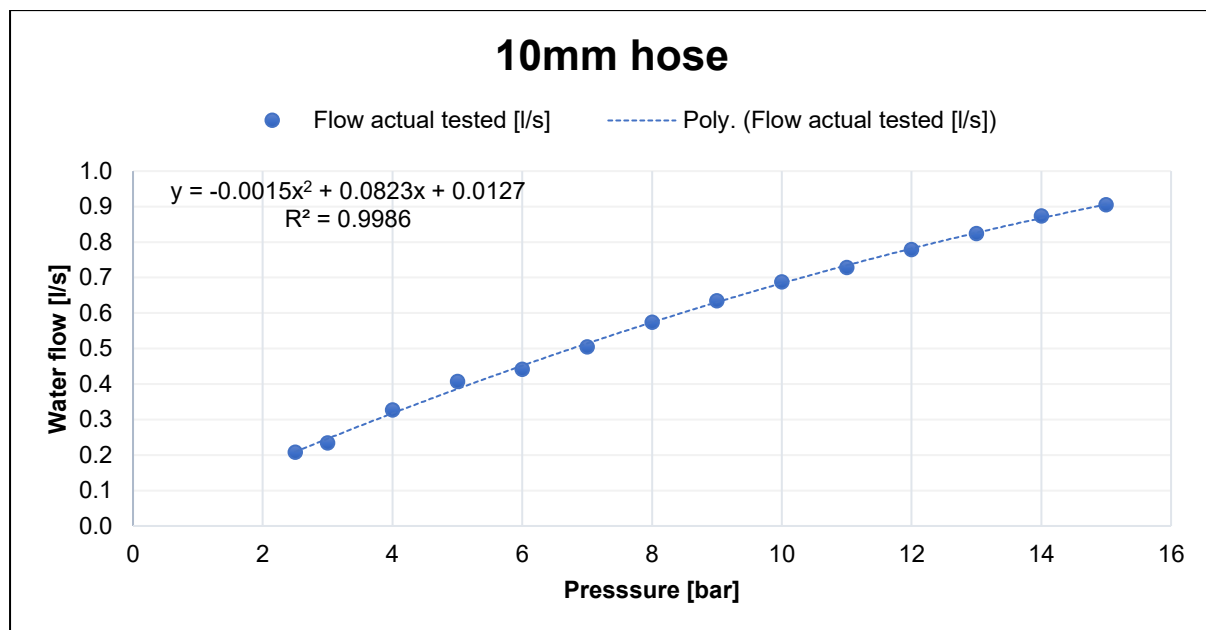


Figure 54: 10mm hose scatter plot.

Table 24: 10mm MAPE verification.

10mm hose			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
3	0.207	0.209	0.8%
3	0.234	0.246	5.3%

Appendix C

4	0.327	0.318	2.9%
5	0.407	0.387	5.0%
6	0.442	0.453	2.4%
7	0.505	0.515	2.0%
8	0.574	0.575	0.1%
9	0.634	0.632	0.4%
10	0.688	0.686	0.3%
11	0.728	0.737	1.1%
12	0.779	0.784	0.7%
13	0.824	0.829	0.6%
14	0.873	0.871	0.3%
15	0.906	0.910	0.5%

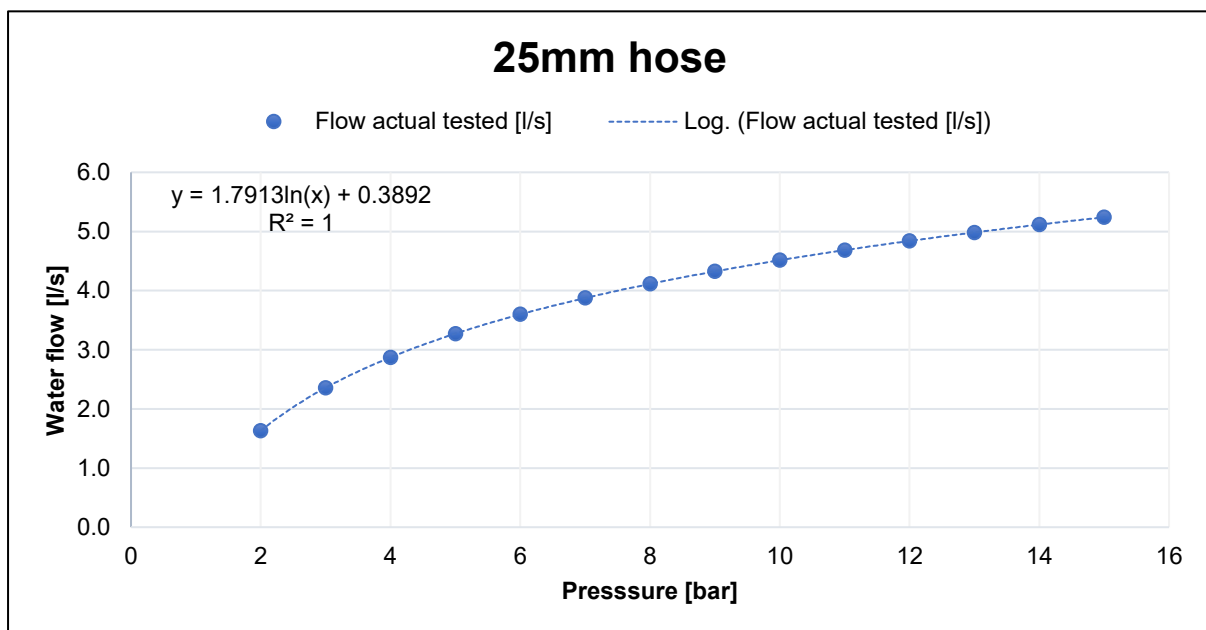


Figure 55: 25mm hose scatter plot.

Table 25: 25mm MAPE verification.

25mm hose			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
2	1.631	1.631	0.0%
3	2.357	2.357	0.0%
4	2.872	2.872	0.0%
5	3.272	3.272	0.0%
6	3.599	3.599	0.0%
7	3.875	3.875	0.0%
8	4.114	4.114	0.0%
9	4.325	4.325	0.0%
10	4.514	4.514	0.0%

Appendix C

11	4.685	4.685	0.0%
12	4.840	4.840	0.0%
13	4.984	4.984	0.0%
14	5.117	5.117	0.0%
15	5.240	5.240	0.0%

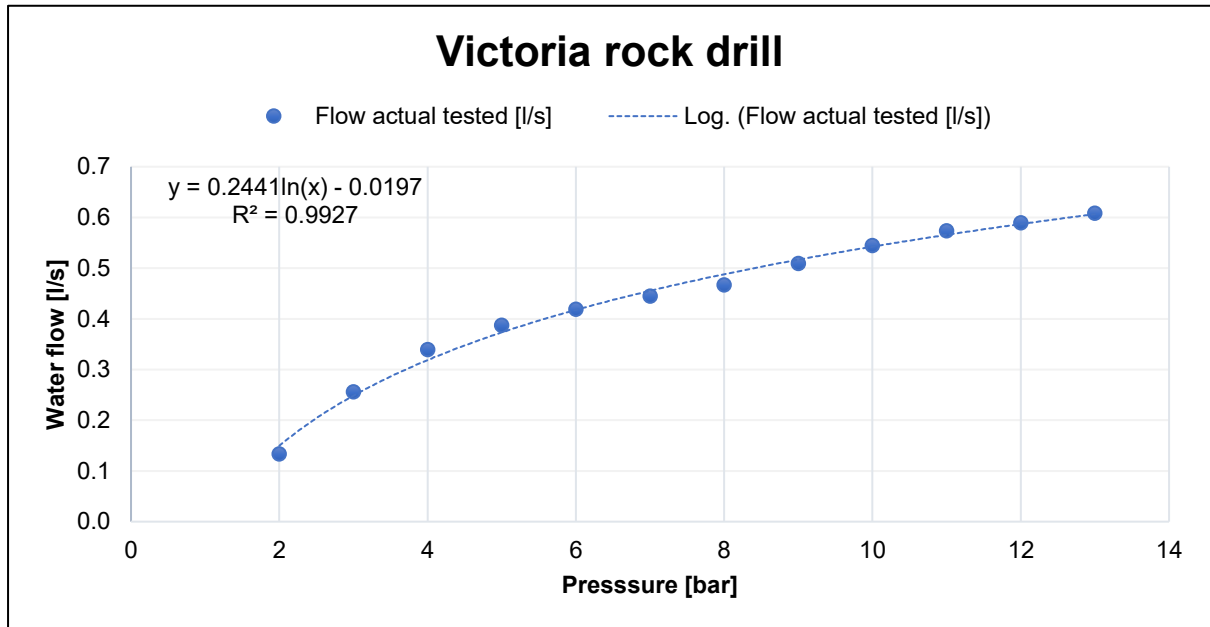


Figure 56: Victoria rock drill scatter plot.

Table 26: Victoria rock drill MAPE verification.

Victoria rock drill			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
2	0.133	0.149	12.4%
3	0.256	0.244	4.5%
4	0.339	0.316	6.9%
5	0.387	0.371	4.2%
6	0.419	0.416	0.6%
7	0.445	0.455	2.3%
8	0.466	0.488	4.6%
9	0.509	0.517	1.6%
10	0.545	0.543	0.3%
11	0.573	0.567	1.2%
12	0.589	0.588	0.2%
13	0.608	0.608	0.0%

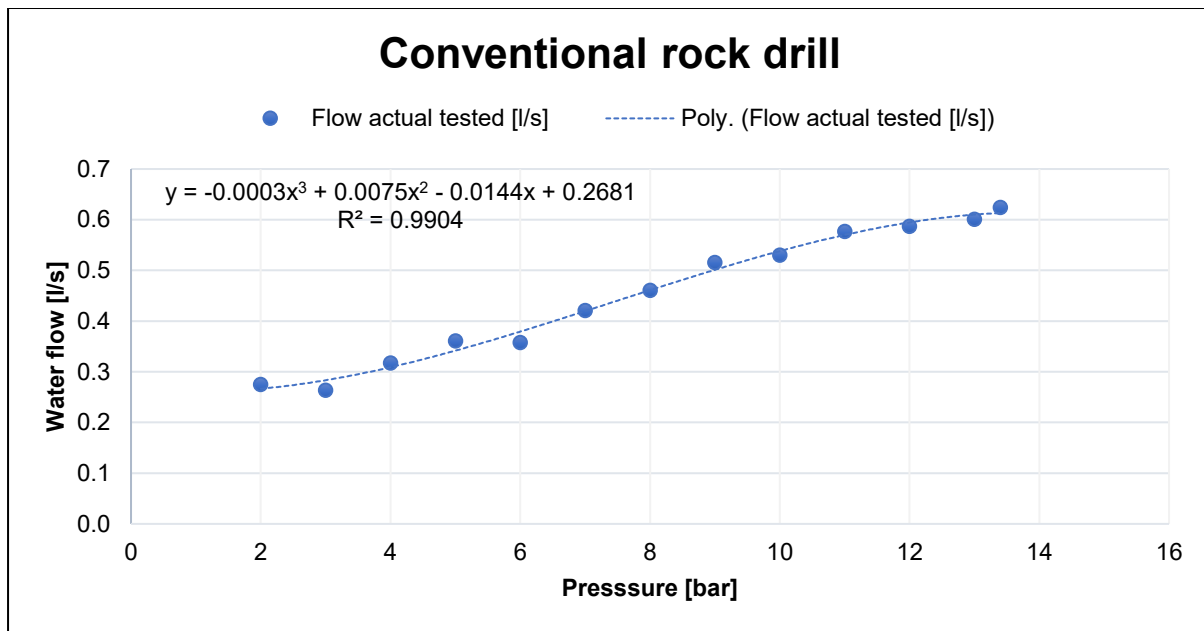


Figure 57: Conventional rock drill scatter plot.

Table 27: Conventional rock drill MAPE verification.

Conventional rockdrill			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
2	0.275	0.267	2.8%
3	0.264	0.284	7.8%
4	0.317	0.311	1.8%
5	0.361	0.346	4.1%
6	0.358	0.387	8.1%
7	0.420	0.432	2.7%
8	0.460	0.479	4.1%
9	0.515	0.527	2.4%
10	0.530	0.574	8.3%
11	0.576	0.618	7.2%
12	0.587	0.657	11.9%
13	0.601	0.689	14.8%
13	0.624	0.700	12.2%

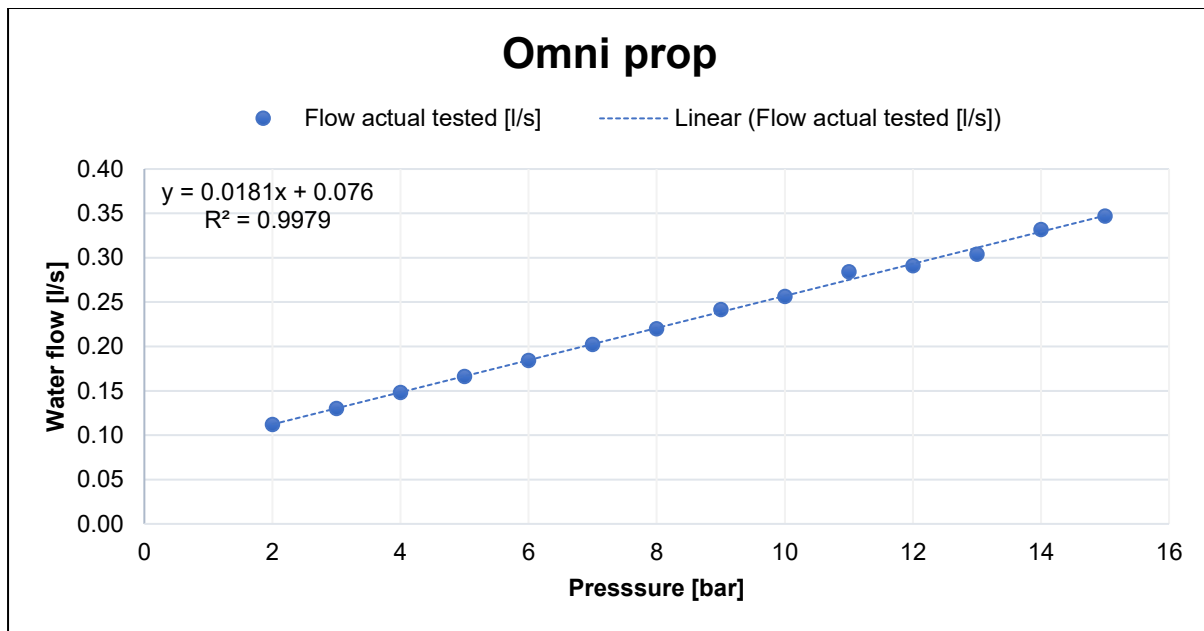


Figure 58: Omni prop scatter plot.

Table 28: Omni prop MAPE verification.

Omni prop			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
2	0.112	0.112	0.4%
3	0.130	0.130	0.3%
4	0.148	0.148	0.3%
5	0.166	0.167	0.2%
6	0.184	0.185	0.2%
7	0.202	0.203	0.2%
8	0.220	0.221	0.4%
9	0.241	0.239	1.0%
10	0.256	0.257	0.3%
11	0.284	0.275	3.2%
12	0.291	0.293	0.8%
13	0.304	0.311	2.4%
14	0.332	0.329	0.7%
15	0.347	0.348	0.2%

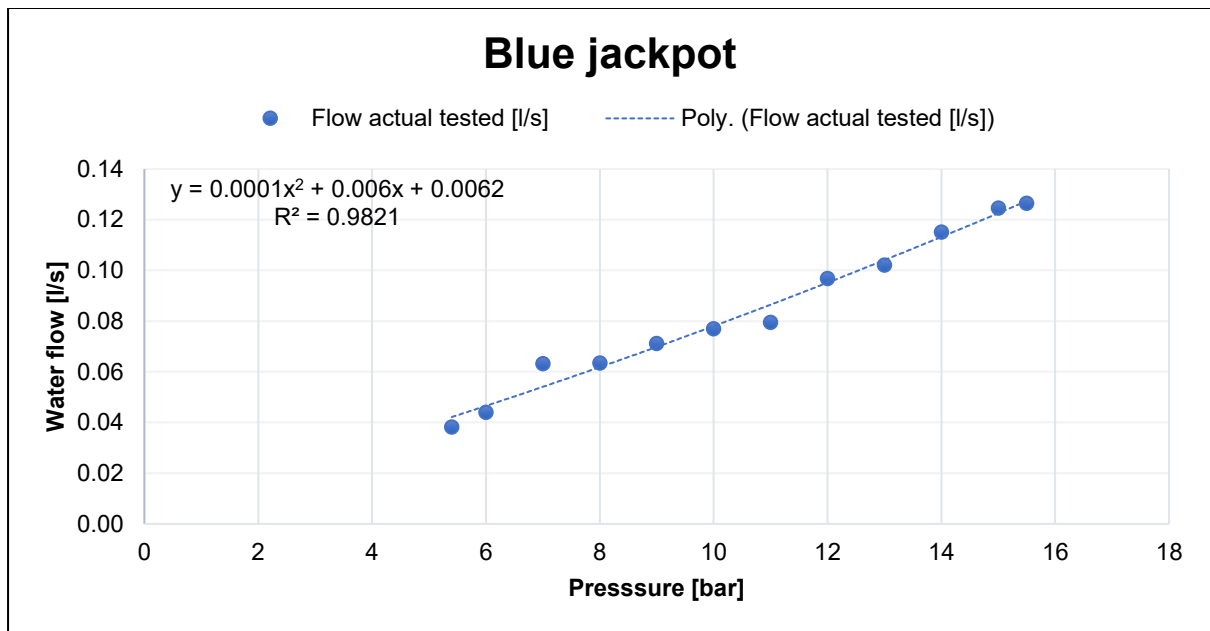


Figure 59: Blue jackpot scatter plot.

Table 29: Blue jackpot MAPE verification.

Blue jackpot			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
5	0.038	0.042	8.7%
6	0.044	0.046	4.2%
7	0.063	0.053	15.9%
8	0.063	0.061	4.4%
9	0.071	0.068	3.9%
10	0.077	0.076	1.0%
11	0.080	0.084	6.0%
12	0.097	0.093	4.3%
13	0.102	0.101	1.0%
14	0.115	0.110	4.5%
15	0.125	0.119	4.7%
16	0.126	0.123	2.5%

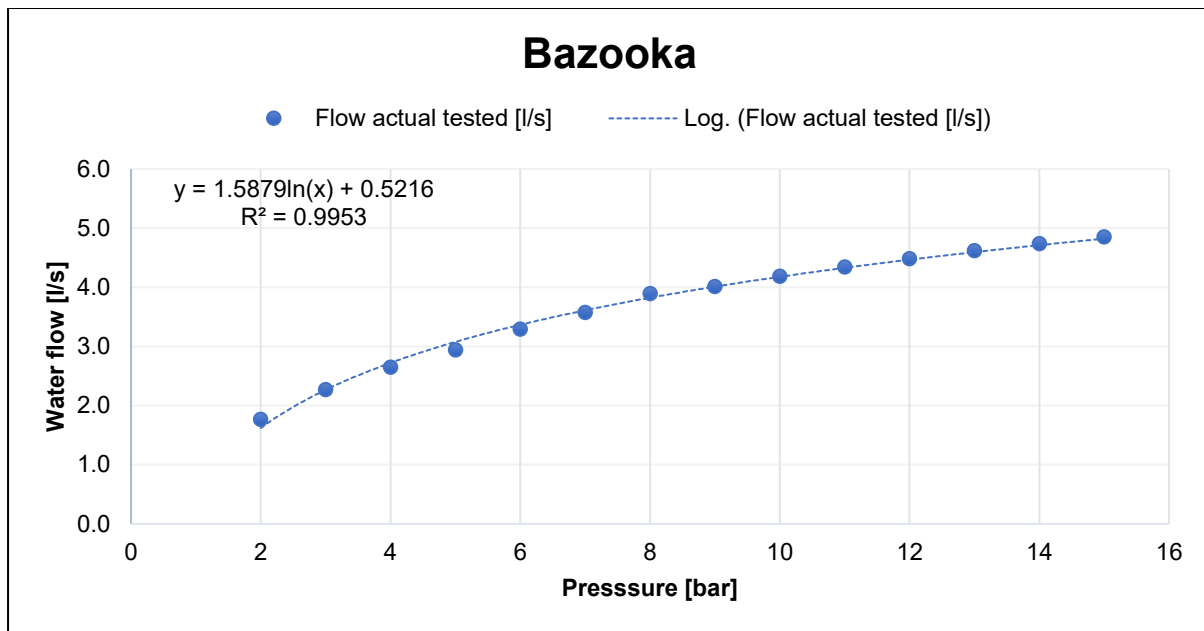


Figure 60: Bazooka scatter plot.

Table 30: Bazooka MAPE verification.

Bazooka			
Pressure [bar]	Flow: actual tested [l/s]	Flow: using equation [l/s]	MAPE [%]
2	1.763	1.622	8.0%
3	2.269	2.266	0.1%
4	2.646	2.723	2.9%
5	2.943	3.077	4.6%
6	3.290	3.367	2.3%
7	3.576	3.612	1.0%
8	3.891	3.824	1.7%
9	4.012	4.011	0.0%
10	4.185	4.178	0.2%
11	4.341	4.329	0.3%
12	4.484	4.467	0.4%
13	4.615	4.594	0.5%
14	4.737	4.712	0.5%
15	4.850	4.822	0.6%

Appendix D: Portable ultrasonic water flow meter calibration certificate

INSPECTION RECORD OF ULTRASONIC FLOWMETER

Model	<u>UFP-20</u>
Serial No.	<u>2887</u>
Work Order No.	<u>53-2486</u>
Test Date	<u>14. Apr. 2021</u>
Customer's Test Date	<u></u>
Customer's Inspector	<u></u>

Inspector M. Oshima

Approval T. Hosokawa

TOKYO
KEIKI
TOKYO KEIKI INC.

Appendix D

Portable Ultrasonic Flowmeter		
Model : UFP-20	Serial No. : 2 8 8 7	
Work Order No. : 5 3 – 2 4 8 6	Voltage : 1 1 ~ 3 0 V D C	
Inspection items	Inspection procedure and standards	Result
1. Component inspection	Check items according to approved Drawings and Specifications	<u>Good</u>
2. Appearance, structure and dimensional inspection	Check items according to approved Drawings and Specifications	<u>Good</u>
3. Self-Check	Check Start-up self-check is done without any errors.	<u>Good</u>
4. Display functional check	Check cotrast and backlight function shall be available. Check each key operation links menu operations.	<u>Good</u>
5. LED lamp check	Check DC-IN LED on when AC adaptor plugged in. Check Charging LED on when it charges internal battery.	<u>Good</u>
6. Analog Output Check	Check analog output with allowable resistance 550 ohm as Max.	<u>Good</u>
7. Thickness measurement check	Check thickness measurement performance after calibration.	<u>Good</u>
8. Flow measurement functional check	Check measuring performance with specified standard transducer.	<u>Good</u>
Large Transducer Type: UP04AST Serial No <u> </u> Medium Transducer Type: UP10AST Serial No <u>D17690001C, D17690002C</u> Small Transducer Type: UP50AST Serial No <u> </u> Thickness/Sound Speed probe Type: TH5010L Serial No <u> </u>		
Through all above inspections, TOKYO KEIKI INC. certifies that total system performance is in accordance with the specifications.		
Inspection Date; 1 4 . A p r . 2 0 2 1 Conditions; Temperature 2 2 °C / Humidity 3 9 %		

YMR-3003

TOKYO KEIKI INC.

Test Date 20 / april / 2021

TOKYO KEIKI
ACTUAL FLOW TEST REPORT

Inspected by: 		Approved by: 				
M.oshima		T.hosokawa				
1. TEST Ultrasonic Flowmeter Actual Flow Test						
2. DUT Main Unit: UFP-20 Model: UFP10AST S/N: 2887 S/N: D17690001C, D17690002C (Transducer Installation: V-method)						
3. TEST METHOD Transducer Model: UFP10AST S/N: D17690001C, D17690002C (Transducer Installation: V-method) Cross-Section Area: 0.009m ² Material: SUS304 According to our quality manuals and operation procedures (sub equal to JIS B7552) PIPE Size: DN100mm Dia.: 0.114m						
4. ACCURACY ±1.5% of reading, however ±0.015m/s for velocities less than 1m/s						
5. RESULT						
Test Conditions						
Test No.	Set Flow Value	Number of Test	Time	Actual	Desired	Error
	m ³ /h		sec	m ³ /h	m ³ /h	m ³ /h
				Flow Rate	Flow Rate	Flow Rate
				Velocities	Velocities	Velocities
				m/s	m/s	m/s
				Error	Error	Error
2104200101	300	2	125	302.7	300.6	+0.7%
2104200101	150	2	126	150.3	149.1	+0.8%
2104200201	30	2	125	30.3	30.0	+1.2%
2104200201	15	2	126	15.1	14.8	+1.6%
Fluid temp.: 15.3°C ~ 15.4°C						
6. STATUS						
Good						

TOKYO KEIKI INC.
Measurement Systems
Company

Appendix E: 98L XC 113 cost saving calculation

A daily water reduction of 0.31 MI was achieved through the implementation of this method on a single working area, 98L XC 113. To evaluate the energy and cost benefit of the water reduction, a site-specific energy intensity factor was used (same principle as Equation 1). The energy intensity factor was determined from historical mine data and reflects the average energy required to handle 1 MI of water in Mine A's integrated water system, including pumping and refrigeration systems.

Using historical data, an energy intensity value of 6 509 kWh/MI was obtained over a representative operational period. The pumping and refrigeration systems' electricity consumption was normalised against the total water flow volumes measured over the same timeframe, producing a weighted average energy intensity factor. Therefore, the daily energy saving is calculated as:

$$\text{Daily energy saving} = 0.31 \frac{\text{MI}}{\text{day}} \times 6\,509 \frac{\text{kWh}}{\text{MI}} = 2\,018 \text{ kWh/day}$$

To convert the energy savings into a cost benefit, Mine A's Eskom Megaflex tariff (Non-Local Authority, Transmission zone $\leq 300\text{km}$, voltage range $\geq 500\text{V}$ & $< 66\text{kV}$), inclusive of admin and network charges, was used. The tariffs were as follow:

- Summer tariff: R1.72/kWh; and
- Winter tariff: R2.48/kWh

This equates to a combined average monthly cost benefit of R235 000 (R1 300 000 annual benefit) for 98L XC 113. The following assumptions were made to obtain this value:

- A water saving of 0.31 MI is assumed to be constant throughout the year;
- The energy intensity factor of 6 509 kWh/MI accurately represents the average energy intensity of both water pumping and refrigeration of Mine A, based on actual operational data;
- Summer periods are defined as September to May (to align with Mine A's tariff structure);
- Winter periods are defined as June to August (to align with Mine A's tariff structure);
- Eskom's Megaflex tariff values include all relevant administrative, transmission, and service charges specific to Mine A's supply agreement; and

- The analysis excludes indirect or secondary cost benefits (reduced equipment strain or deferred maintenance costs).

Appendix F: Walk-through audit results from Mine B

Figure 61, Figure 62 and Figure 63 displays the results obtained from the walk-through audits conducted on Mine B. This confirms that water wastage remains an ongoing problem for deep-level gold mining operations in South Africa.

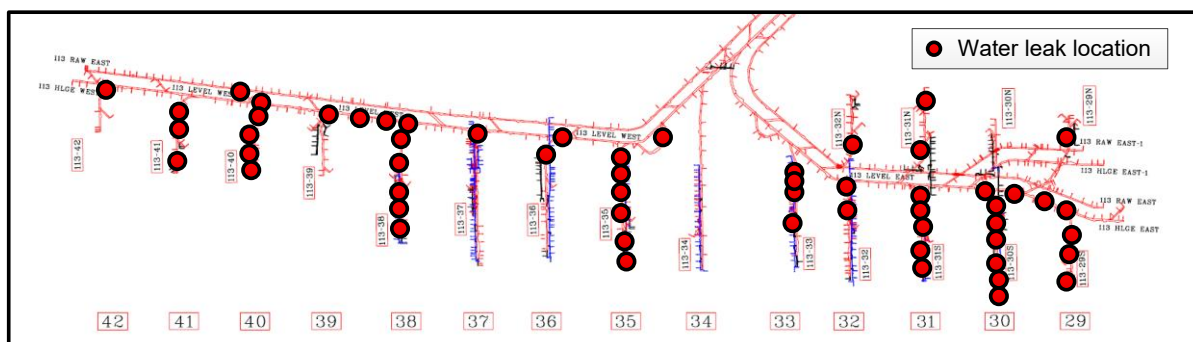


Figure 61: Mine B Level 1.

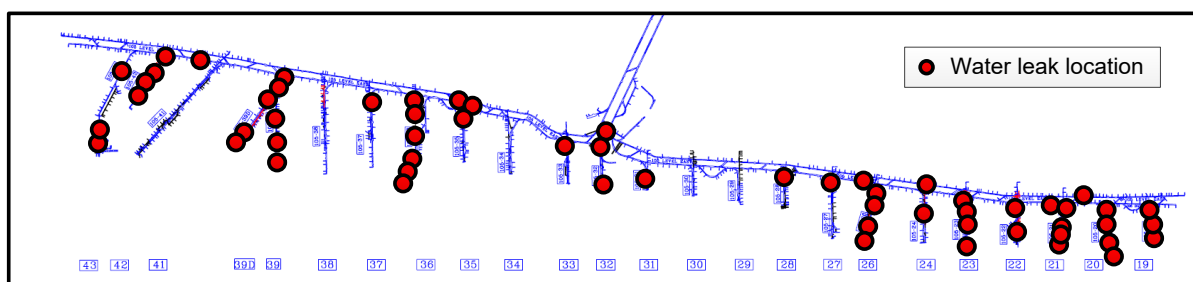


Figure 62: Mine B Level 2.

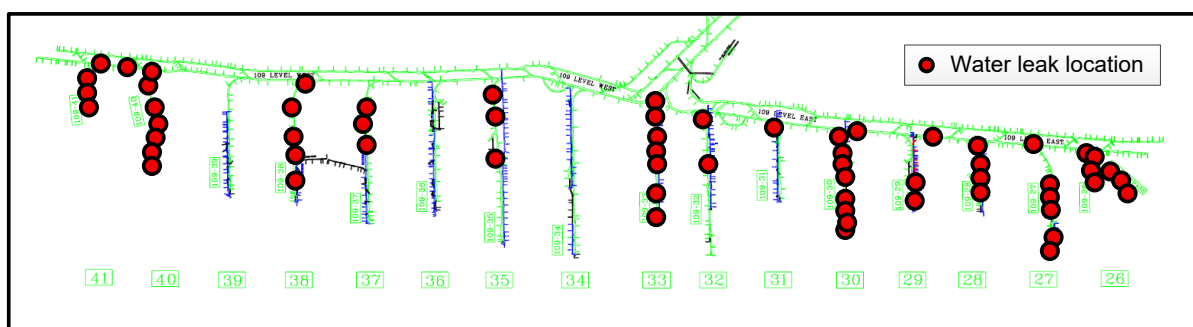


Figure 63: Mine B Level 3.