



Improving legal compliance of water quality management data in mines

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ABSTRACT

Water is a limited resource in South Africa, and water quality is declining due to growing pollution and poor land use management. Mines use large volumes of water and gold mines are particularly susceptible to water pollution.

Water quality monitoring reports in South African mining operations often fail to meet regulatory compliance. Many mines continue to operate without valid water use licences, exposing them to serious penalties, including substantial fines, legal action, or even operational closure, as stipulated by the National Water Act and related sectoral regulations.

This study addresses the need for an accurate, reliable, and regulation-compliant water quality monitoring system tailored to the mining sector. A comprehensive review of legislation, current monitoring practices, and available technologies revealed critical gaps, including the absence of standardised protocols for gold mines and limited adoption of digital tools for data management.

To close these gaps, a monitoring framework was developed and implemented to improve the collection, traceability, and reporting of water quality data. The framework integrates mobile data capture, automatic metadata recording, photo verification, and centralised cloud storage to ensure data integrity and streamline compliance reporting.

The results show that 34–39% of mean monitoring points fall more than 5 km from their Water Use Licence Application approved locations, while 61–66% remain within the prescribed 5 km range. Despite these deviations, the study demonstrates measurable improvements in data quality, consistency, and traceability following the implementation of the digital monitoring framework. Surface water reports increased by approximately 24% following the introduction of mobile monitoring, while all captured samples were time-stamped, geo-referenced, and user-verified. Although full adoption was achieved progressively, the digital framework produced reliable datasets that met regulatory submission requirements and strengthened long-term data management.

Overall, the framework strengthens environmental governance by providing a transparent and auditable record of sampling activities, promoting regulatory compliance, and supporting sustainable water resource management in South Africa's mining sector.

Key terms: water quality monitoring, gold mining, compliance monitoring, digital monitoring systems

LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
CCME	Canadian Council of Ministers of the Environment
CME	Compliance, Monitoring and Enforcement
DEIMS-SDR	Dynamic Ecological Information Management System – Site and Dataset Registry
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
GRI	Global Reporting Initiative
GW	Groundwater
HIS	Hydrological Information System
IoT	Internet of Things
IWQS	Institute for Water Quality Studies
MAIS	Monitoring and Assessment Information System
NWA	National Water Act
NWRS	National Water Resource Strategy
OWQM	Online Water Quality Monitoring
PTE	Potentially toxic elements
RDM	Resource Directed Measures
RQO	Resource Quality Objective
RWD	Return water dam
SA	South Africa
SW	Surface Water
TSF	Tailings Storage Facility
WAD	Weak acid dissociation
WMS	Water Management System
WQ	Water Quality
WQI	Water Quality Index

WQIMS	Water Quality Information Management System
WQM	Water quality management
WRC	Water Research Commission
WRD	Waste rock dump
WUL	Water Use License
WULA	Water Use License Application

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CHAPTER 1 BACKGROUND AND LITERATURE REVIEW

1.1 The water landscape in South Africa

South Africa (SA) is a water-stressed country with limited water resources. However, it continues to support a dynamic, growing economy driven by mining, agriculture, and industrial manufacturing [1-3].

South Africa has an average annual rainfall of 464 mm [4]. In addition to experiencing low annual rainfall, South Africa displays an uneven rainfall distribution spanning from 100 mm in its western areas to 1 500 mm in the eastern regions [5]. Due to climate change, SA has low and high rainfall variability and is ranked the 30th driest country in the world [6].

The country's natural water supply is unevenly distributed and exhibits significant seasonal variability [1]. River and wetland ecosystems are under considerable pressure, with approximately 60% of river ecosystems classified as threatened and 25% regarded as critically endangered. Only 15% of river ecosystems fall within protected areas, while nearly half (48%) of wetland ecosystems are at risk [7].

To make matters worse, South Africa is currently facing a water crisis caused by a combination of insufficient infrastructure maintenance and investment, droughts, unequal access to water and sanitation, declining water quality, and a shortage of qualified water engineers [4].

South Africa's water resources are primarily allocated to agriculture, which consumes 61%, as seen in Figure 1.1, reflecting the sector's significant demand. Municipal use follows with 27%, largely driven by urban areas. Industrial activities, afforestation, and power generation each use 3%, while mining, livestock watering, and conservation claim 2% each. This distribution highlights the critical role of agriculture and urban needs in water management, with smaller yet vital allocations to other sectors [4].

South Africa's water sources exhibit a reliable yield of approximately 15 billion kL/year, comprising 77% surface water, 14% desalination, and 9% groundwater (Figure 1.2) [5, 6]. This reliable supply is supported by a high assurance rate of 98%, with a mere 2% annual probability of supply failure [6].

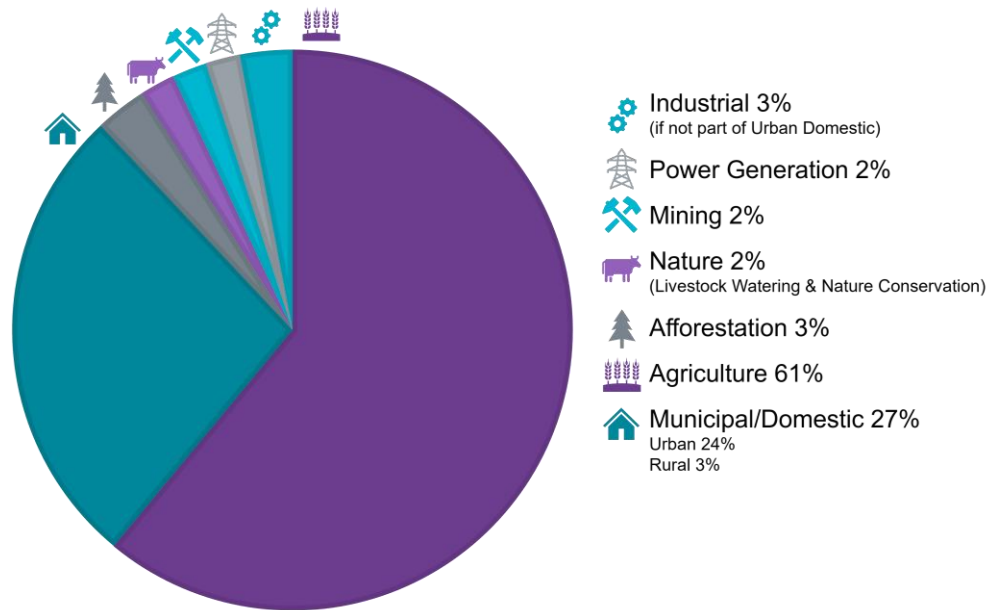


Figure 1.1: Water sources users in South Africa. [4]

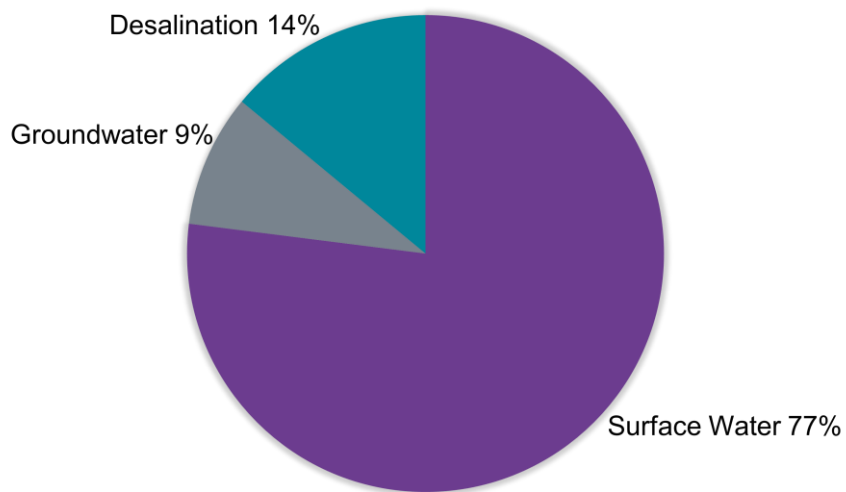


Figure 1.2: Water sources in South Africa. [4]

The average person in Southern Africa consumes 237 L/d (Litres per day) of water which is far above the world average of 173 L/c/d [4, 6].

Human well-being depends on water and the environment it supports. Effective water management considers both the quality and quantity of water, considering its movement through the hydrologic cycle. A vital aspect of water management involves understanding and assessing the flow, storage, and quality of water within a specific basin or region [8].

1.2 Water quality and the effect of mining

Water quality is measured based on chemical, physical and biological characteristics of water, and is evaluated against specific standards or requirements. It is too complex to classify water quality as “good” or “bad” due to the diverse requirements for different purposes of water use. Therefore, the quality of water should be compliant to a set of standards or suitability criteria [4].

Surface water pollution occurs when an undesirable or harmful substance is discharged into a resource beyond its natural acceptance capacity, rendering the water unfit for future use, while groundwater pollution happens when harmful substances infiltrate into the ground and come into direct contact with underground water, exceeding the natural acceptance capacity of the soils overlying the aquifer system [9].

Declining water quality has the potential to restrict economic growth and development in affected regions. The quantity of water decreases when water quality deteriorates because more water must be used to dilute contaminants, reducing its overall availability for other uses. This can lead to increased costs associated with water treatment and supply [4].

Understanding the impact of mining on these characteristics is essential. The consequences of mining activities on water quality are diverse and can manifest in various ways. These effects can take several forms and are also dependent on the mineralogy and geochemistry of the ore body being mined, influencing the nature and extent of contaminant release [10, 11].

According to Orimoloye and Ololade [12], the environmental consequences of gold-mining activities encompass significant harm to natural landscapes, water pollution, ecosystem destruction, and the discharge of hazardous substances like mercury and cyanide into the environment [12].

In the first edition of the National Water Resource Strategy (NWRS) [9], it is mentioned that only 2% of the Waterval catchment area’s water reaches the Vaal Dam. This area is populated with mining, industries and power generation. That 2% is responsible for 12% of the pollution in the Vaal Dam which provides domestic water to 10 million people [9].

In developed countries, heavy metal pollution primarily stems from diverse industrial activities. In less developed countries, the predominant contributors to heavy metal pollution often lie in extensive mining operations, particularly in the case of gold mining and open-cast coal mining. In South Africa, these two activities significantly contribute to soil and water pollution, particularly in terms of potentially toxic elements (PTE) pollution and pose a grave concern as they are concentrated in the primary staple food production regions of the country [13].

Water quality can be impacted at different stages of the mine's life, beginning with the extraction of valuable minerals from the earth. The extraction of gold or other commodities involves not only the removal of the ore body itself but also the handling of other geological materials, which are disposed of on land in the form of waste rock dumps [11, 13].

As the ore is extracted, subsequent stages involve crushing and grinding, followed by chemical extraction to separate valuable minerals from the rest of the ore. The mineral processing phase, aimed at maximising mineral extraction and minimising waste, introduces chemicals that can alter water quality. Further refinement of the separated minerals may generate large amounts of fine material with potentially hazardous chemical properties [13].

These water quality impacts highlight the need for effective regulation and management of mining activities to minimise their impact on water resources in South Africa.

1.3 South African legislation on water quality management

The mining industry is a major water user in South Africa, and it can have a significant impact on water quality. The National Water Act (NWA) [14], the Water Services Act, and the Water Quality Management Policy all have provisions that specifically address the water use and water quality impacts of mining.

Water is utilised in mining operations in a variety of ways, such as taking water from water resources, storing it, obstructing, or diverting the flow of water in a watercourse, reducing stream flow, and discharging waste or waste-containing water into water resources via pipes, canals, sewers, or other conduits [15].

South Africa has developed progressive and advanced water management policies and legislation to address the challenges of water scarcity [16].

The Department of Water and Sanitation (DWS) is the main governing body responsible for water management in South Africa [14]. The DWS ensures sustainable use and management of water resources across the country, by implementing the National Water Act (NWA) of 1998, and other legislation related to water management [14, 17]. The DWS, through its Compliance Monitoring and Enforcement (CME) function, ensures that the regulatory framework is upheld in accordance with the NWA and related regulations. Its CME function aims to promote and monitor adherence to water use authorisation conditions across all sectors and to take appropriate administrative, civil, or criminal action against non-compliance [18].

The National Water Act (36 of 1998) provides for resource-directed measures (RDM) to classify and set reserve limits for water resources, considering basic human needs and ecological water requirements. Quantifiable targets, or Resource Quality Objectives (RQOs) are set for each watercourse component, but many resources have not yet been classified, indicating the ongoing process to achieve these objectives [5, 14].

In South Africa, obtaining permission to use water resources is done through the process of water use licensing [14]. This process aims to guarantee the responsible use of water resources, preventing overuse and maintaining water quality integrity. It is implemented to safeguard South Africa's water resources, ensuring they are protected, managed, and controlled in accordance with the NWA [5].

A water use, defined in Section 21 of the act, must be licensed in accordance to the NWA in order to ensure that neither its quantity or quality will be compromised [5, 14]. Section 21 of the NWA states that all water users, including those that are exempt from obtaining a water use license (WUL), are required to register and keep records of their water use with the appropriate water management institution [14]. Section 21 defines a water use that requires a license as any of the following:

- a) *Taking water from a water resource.*
- b) *Storing water.*
- c) *Impeding or diverting the flow of water in a watercourse.*
- d) *Engaging in a stream flow reduction activity contemplated in section 36.*
- e) *Engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1).*
- f) *Discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit.*
- g) *Disposing of waste in a manner which may detrimentally impact a water resource.*
- h) *Disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process.*
- i) *Altering the bed, banks, course, or characteristics of a watercourse.*
- j) *Removing, discharging, or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people.*
- k) *Using water for recreational purposes.*

Low impact activities, such as domestic use, gardening and certain livestock watering, are exempt from obtaining a WUL [14].

The license application process involves a thorough assessment of the impact of the proposed water use on the catchment and the country's ability to reach the objectives set out in the Water Resource Strategies [5].

In adherence to the regulatory provisions outlined in Section 21 of the NWA and the licensing requirements to safeguard water quantity and quality, it is crucial to delve into the specific implications for the mining industry. Mining operations often involve several water-intensive activities that fall within the scope of Section 21, requiring careful management and compliance [10, 19]. The DWS has developed several guidelines and best practices for water management in the mining industry.

Building on the Section 21 framework outlined earlier, it is important to highlight its practical implications for the mining sector. Gold-mining operations typically engage in multiple licensed water uses, including abstraction, storage, and the management of contaminated discharges. These activities create complex interlinkages between water quantity and quality, necessitating integrated monitoring and compliance systems. In particular, Section 21(f) and (j) uses represent critical areas where inadequate management can directly affect both regulatory compliance and environmental integrity [8].

South Africa's water quality management (WQM) has evolved from basic pollution management to an integrated approach that includes source management, remediation, and resource management. This approach is implemented through the NWA using a combination of resource-directed and source-directed measures [16].

Water resource management should consider the integrated nature of surface and ground water, the management class, international obligations, the availability of water quantity and quality, authorised uses, and potential impacts on downstream users. Inadequacy of information can lead to ineffective decisions affecting the optimal use of water resources [16].

Resource-directed measures focus on protecting the water resource itself, considering the health of aquatic habitats and wildlife. Source-directed controls set limits on water use to achieve the desired level of protection. These limits are based on RQOs that balance environmental protection with development needs [16].

The setting of RQOs is fundamental to the classification of water resources and provides for numerical and descriptive statements related to the biological, chemical, and physical attributes of the water resource [16].

Water use and its impact on quality are controlled through permits. Pricing for waste discharge is also used to encourage reduced water usage and minimise environmental impact [19].

National-level actions for water quality management include setting pollution management objectives, benchmarking water quality, identifying and prioritising emerging threats, and focusing on remediation and regulation of degraded resources using source-directed controls [9].

National water management policies, such as the Mine Water Management Policy, play a vital role in guiding the operational practices of mining companies. These policies mandate integrated water resource management and strict compliance with regulatory standards. Understanding water usage in gold mining is therefore essential for evaluating how regulatory measures are translated into operational practices for effective water management [20, 21].

1.4 Water usage in gold mining

Water usage in mining is a critical aspect of operations, as it is essential for various processes such as ore processing, dust suppression, sweeping, and the operation of water-powered equipment such as drills.

Mining techniques vary depending on the location, type, and size of mineral resources. The two primary types of mining are surface mining and underground mining. Surface mining is most cost-effective when mineral deposits are close to the surface or part of surface deposits, such as coal, salts, gold, diamonds, and heavy mineral sands [22].

Several underground mines in South Africa reach 1.2 km to 3.7 km below the earth's surface, with temperatures as high as 60 °C, putting miners' lives in danger. Therefore, it is critical to provide adequate cooling systems to prevent heat-related illnesses and ensure the miners' safety. Furthermore, access to potable water is critical for preventing dehydration and maintaining the miners' overall health [22].

Refrigeration plants are used to send cold water to heat sources underground and send it back up to be cooled again. The circulation of cold water helps to regulate the temperature and prevent overheating in the mine [17, 22].

Deep-level gold mining typically follows the procedure and water reticulation illustrated in Figure 1.3.

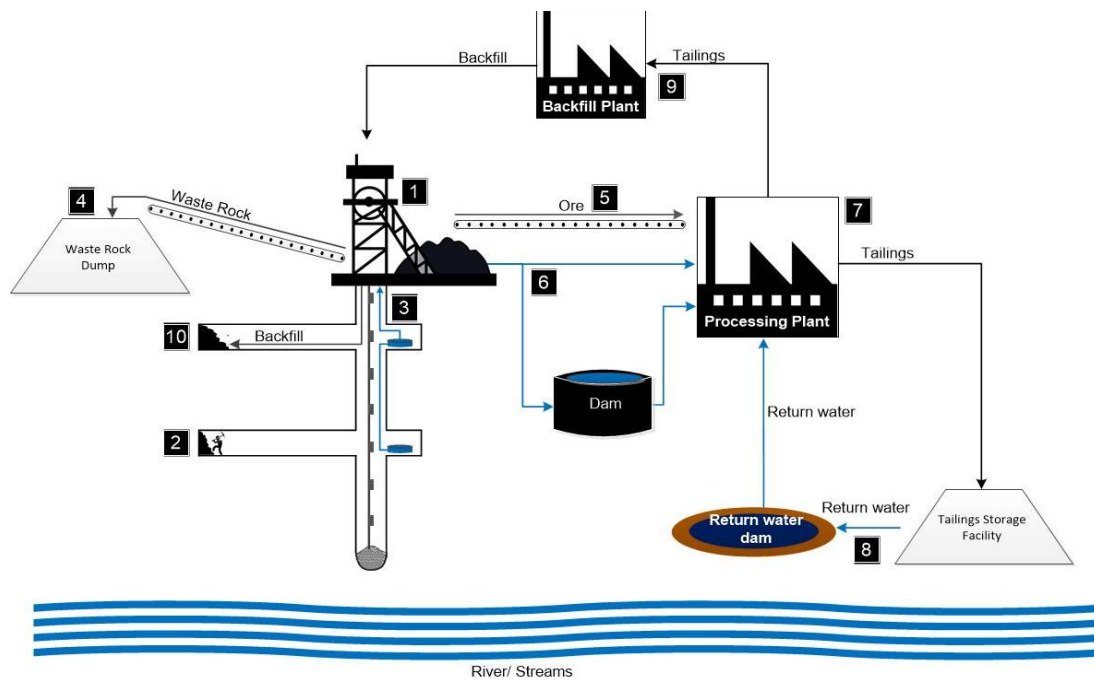


Figure 1.3: Basic flow diagram of a typical deep-level gold mine in South Africa. [17]

Mining activities initiate at the shaft, identified as number 1 on Figure 1.3, where rock is mined and hoisted to the surface. Ore extraction occurs in the stopes (number 2), with subsequent hoisting of ore to the surface. Rock containing minimal gold-bearing ore is disposed of onto a waste rock dump (WRD) (number 4 in Figure 1.3). Gold-bearing ore is then conveyed to the processing plant (number 5).

Due to mining activities and underground fissure water, water accumulates below ground and is channelled to settlers before being pumped into dams. Eventually, it is pumped out of the shaft (number 3). This water is then directed either to a holding dam or to the processing plant (number 6).

The ore undergoes processing through crushing, grinding, and chemical extraction of gold. This process generates a significant amount of very fine material, known as slurry, which is discharged from the processing plant as tailings (number 7). These fine materials are disposed of in the form of extensive mounds known as tailings storage facilities (TSFs) or slime dams.

Most of the water present in the tailings can be effectively recovered from the TSF. This involves a comprehensive system wherein drains and a penstock are strategically deployed within the TSF to facilitate the collection of water from the tailings. The water collected from the drains, aided by the penstock, is then directed to a return water dam (RWD) (number 8). In the RWD, the recovered water is stored for subsequent use. This stored water is then systematically pumped back to the processing plant (number 6).

During the backfilling process, a portion of the tailings (number 9) is directed to the backfill plant, from where it is sent to the shaft and then pumped back underground into cavities (number 10) [17, 22].

Although SA has established regulatory frameworks to manage water use in mining, compliance across the sector remains inconsistent. The CME Annual Report 2023/2024 indicates that overall compliance for mining is approximately 60%, reflecting ongoing challenges in meeting water use and environmental management requirements [18, 23]. Additionally, many mining operations in SA continue to operate without valid WULs, posing significant risks of unregulated abstraction and potential contamination of water resources [17]¹. These activities generally do not occur under official temporary approvals, as most water uses require prior authorisation. Instead, ongoing unlicensed operations are typically considered illegal, reflecting significant enforcement and monitoring challenges [23]¹.

1.5 Data management in mining

To ensure the accuracy of water quality sampling, it is vital to maintain high data quality. Poor sampling methods can compromise the reliability of the dataset, thereby undermining the credibility of the water quality analysis itself [24].

High-frequency monitoring approaches generate large datasets that require efficient data management, validation, and visualisation systems to be effective. Without adequate infrastructure, these datasets risk being overlooked despite their scientific value [25].

Reliable water quality management depends on effective data systems that minimise loss, ensure accuracy, and allow timely reporting. However, Kirschke *et al.* (2020) show that many countries struggle with capacity challenges across the data cycle, particularly in measurement, transfer, and handling [26]. This highlights the need for mining operations to strengthen their own data management frameworks to overcome similar risks to data credibility and compliance.

Organisations rely heavily on various data resources for effective and efficient management of their operational processes. In the context of gold mining operations, the Water Use License

¹ AfriForum. "Illegal mining operations: 76 mines mining without water licenses." Internet: <https://www.artikels.afriforum.co.za/en/illegal-mining-operations-76-mines-mining-without-water-licenses/>

Application (WULA) serves as a crucial document that outlines regulatory requirements and specific water quality objectives that must be met.

The NWA has reformed water management laws to ensure fair, sustainable, and economically efficient use of water resources. The Act shifted water management responsibilities to local levels. To monitor water quality and usage effectively, the government now tracks compliance with water resource standards and permits at national, regional, and local scales. This involves a comprehensive approach considering surface water, groundwater, air, land, and human activities. Successful monitoring depends on collaboration among various government agencies, organisations and sectors [27].

The Act requires that the Minister of Water and Sanitation establish national water resource monitoring systems. Data on water quantity, quality, rehabilitation, adherence to quality goals, aquatic ecosystem health, atmospheric conditions, and other relevant factors must be gathered by these systems [9].

The quality and reliability of information are being compromised due to ineffective dissemination. This can lead to misinformed decision-making and hinder effective water resource management. Additionally, accessing data from other organisations, including government departments, water boards, private sector organisations, and water users, is sometimes problematic [9].

One of the earliest water quality practices in South Africa was the Water Quality Sampling Manual for the Aquatic Environment developed by the Department of Water Affairs and Forestry's Institute for Water Quality Studies (IWQS). The manual outlines protocols for sampling water, sediment, and biota (the living organisms within an aquatic ecosystem, such as plants, invertebrates, and fish), focusing on preservation, safety, and health. It highlights the significance of reliable sampling, accurate labelling, and data registration via systems like the Water Quality Information Management System (WQIMS) and the Hydrological Information System (HIS) [28].

Emerging technologies like Online Water Quality Monitoring (OWQM) systems offer potential solutions by enabling real-time monitoring of physiochemical parameters. These systems leverage intelligent monitoring and data processing to detect and alert stakeholders of any emerging water quality issues. However, no universal framework exists for such technologies, and the need for affordable, reliable, and integrated systems remains [29]. Simulation models based on water quality, such as those incorporated in the HIS, also play a crucial role in managing water resources. These tools, combined with long-term monitoring data, provide invaluable insights for both decision-making and regulatory compliance [8].

Rapid growth of information, data formatting and fragmentation can lead to major challenges related to data quality and any flaw in this data management can make them vulnerable to low quality data [30, 31].

In regions where mining activities and natural ecosystems intersect, such as in sub-Arctic environments, continuous monitoring has proven essential. For example, electrical conductivity monitoring in these sensitive areas offers an early-warning method to detect sudden changes in water quality, allowing for timely intervention [10].

Systems like the Monitoring and Assessment Information System (MAIS), established in 2001, and the later Water Management System (WMS) of 2007, were developed to streamline data management and improve coordination between various government agencies. The Department of Water Affairs and Forestry developed the Monitoring and Assessment Information System (MAIS) in 2001 to improve decision-making processes and better manage water resources within South Africa [32].

Current water monitoring systems face challenges in alignment and data integration across different platforms, which can sometimes lead to coordination inefficiencies and duplicated efforts. Furthermore, there is a need for a comprehensive framework to unify information requirements across all water management institutions. The MAIS was designed to address these issues and enhance the effectiveness of water management [32].

In 2007 the Water Management System (WMS) was established, which entails the same concept as the previous 2001 MAIS system. These systems focus on a monitoring framework combined with the governments and organisations' involvement. This system lacks the accountability of visibility in the field.

Water quality indices (WQIs) are internationally used to summarise complex datasets into a single index of information about water resources. This system acts as a valuable tool for decision-making by providing a clear and easily understandable snapshot of water quality conditions. The most widely used WQI is that of the Canadian Council of Ministers of Environment Water Quality Index (CCME WQI). It can hold a large database of water quality information and provide information on spatial and temporal variations of water quality. Disadvantages include giving equal weight to all variables, ignoring biological and hydro morphological components, and uncertainties in aquatic environments [33, 34].

The CCME WQI is calculated using three main components: the Scope (F1), Frequency (F2) and Amplitude (F3) shown in Equations (1) – (4) [34].

Scope (F1) is the percentage of water quality parameters that do not meet their objectives.

Frequency (F2) is the percentage of individual tests that do not meet their objectives.

Amplitude (F3) is the amount by which failed test values do not meet their objectives.

$$F1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100 \quad (1)$$

$$F2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \quad (2)$$

$$F3 = \left(\frac{\sum \left(\frac{\text{Failed test value}}{\text{Objective value}} \right) - 1}{\text{Number of failed tests}} \right) \quad (3)$$

$$CCME\ WQI = 100 - \sqrt{\left(\frac{F1^2 + F2^2 + F3^2}{3} \right)} \quad (4)$$

Here, Scope (F1) is the percentage of water quality parameters that do not meet their objectives, Frequency (F2) is the percentage of individual tests that do not meet their objectives, and Amplitude (F3) is the amount by which failed test values do not meet their objectives.

The categories for the CCME WQI are then as follows:

1. 95-100: Excellent
2. 80-94: Good
3. 65-79: Fair
4. 45-64: Marginal
5. 0-44: Poor

Inefficiencies caused by manual data handling and fragmented monitoring systems undermine the accuracy, consistency, and timeliness of water quality data in mining operations [26, 32]. These challenges contribute to delayed reporting and inconsistent monitoring practices, which limit the ability of operators to manage and respond to water quality deviations proactively [6, 35]. Consequently, mining operations often struggle to demonstrate sustained compliance with the provisions of the NWA, increasing the risk of legal penalties and adverse environmental impacts [14, 16, 18]. Collectively, these shortcomings pose risks to both long-term water resource management and the overall credibility of regulatory oversight.

While existing data management frameworks such as MAIS and WMS provide important foundations for monitoring and compliance, challenges in data accuracy, timely reporting, and integration persist, particularly due to manual processes and fragmented systems [26, 27, 35]. Automation, through advanced digital technologies, offers a pathway to streamline workflows, improve data integrity, and enable real-time access to actionable information, addressing these longstanding limitations [29, 36]. Such developments are critical for sustainable and compliant water resource management in mining operations [15, 32].

1.6 Automation of data management

Automation of data management involves using technology and digital systems to perform data collection, entry, processing, verification, and storage tasks with minimal human involvement, thereby improving efficiency, accuracy, and speed while reducing errors. Automation incorporates tools like mobile applications, barcode scanners, handheld devices, and centralised databases to streamline workflows in a variety of instances, including environmental reporting in the gold mining industry, fisheries management, and water quality studies. They include error-checking features, standardised processes and features that enforce data quality, such as mandatory input fields and verification through photographs.

By consolidating diverse data sources and enabling real-time or near-real-time processing, automation enhances data integrity, consistency, and accessibility; supports compliance with international standards like GRI and ISO 14001; and ultimately improves decision-making across sectors [35, 37-39].

1.7 Current water management in mining

The mining organisation operates under five WULAs, each covering several mining areas. Although the characteristics of these WULA areas differ, all of them use the same water sampling method. Table 1.1 provides an overview of the sampling method currently applied across the WULA areas.

Table 1.1: Water sampling method across the current WULA areas

Mining Operations	Water sampling method	
	Digital	Paper-based
WULA 1		✓
WULA 2		✓
WULA 3		✓
WULA 4		✓
WULA 5		✓

The current water management system used across the WULA areas relies entirely on a paper-based framework, which is illustrated in Figure 1.4. During sampling of groundwater and surface water sources, the sampler (designated person employed to take samples) is responsible for recording all relevant information directly on paper forms. Surface water samples are collected monthly, while groundwater samples are collected quarterly. The specific data fields recorded on these forms are based on the monitoring framework developed for the study site, aligned with the site's WUL requirements. Although the sampling frequencies and field sheets differ slightly between surface- and groundwater points, both form part of a single, integrated monitoring programme used to assess overall site compliance.

Environmental Department
Operations: Water samples

14.02.2023
Date submitted to laboratory:
Received by at laboratory:
Tel:
Email:

2 FEBRUARY
Month: 2
Cost code: 3
Operation/Mining Right:

1 Sample date: 08-02-2023
Sampler:

4 Analysis (Groundwater/Determinants) BH BH BH BH BH BH

Field						
Level before (Ground to water)				2.33	7.55	8.22
Volume purged				SLT	SLT	SLT
Level after (Ground to water)				2.27	7.48	
pH - Initial sample	3.47	3.16		5.56	5.42	5.40
Conductivity - Initial sample						
Redox - Initial sample			DRY			
pH - Treated sample						
Conductivity - Treated sample						
Redox - Treated sample						
Temperature	23.0	23.1		23.8	22.4	22.6
Dissolved oxygen						
Free Cyanide						
WAD Cyanide						
Visual Environmental Inspection						
Cattle	8	15	2	4	0	5
Human Influence e.g. Herdsman	0	0	0	0	0	0
Other animals, birds, reptiles etc	4	0	7	3	3	0
Weather conditions	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny

Figure 1.4: Example of the current paper-based water sampling schedule for mines.

There are nine distinct data entries required from the sampler for each sampling event:

1. Sample date: The specific date when the sample is collected.
2. Sample month: The calendar month during which sampling occurs.
3. Operation location: The name of the operation where the sample is taken.
4. Sample name (monitoring point): Identification of the monitoring point.
5. Ground water level (if applicable): The water level is measured and recorded before sampling for groundwater samples.
6. On-site pH reading and sampling validity: The pH level of the sample is measured on-site. At this stage, the sampler also notes if the sample could not be collected.
7. Sampling purge: although the form references additional parameters such as dissolved oxygen, free cyanide, and weak acid dissociable (WAD) cyanide, only pH is measured in the field. This section primarily captures information regarding the purging method used during groundwater sampling.
8. Environmental observations: Any presence of livestock, birds, or other environmental aspects observed in the sampling area.
9. Weather conditions: A record of the weather at the time of sampling.

The current data management process consists of the paper-based system described above. At the end of each month, the accumulated paper records are compiled into an Excel spreadsheet by a designated person (usually a different person than the sampler). Once the data is transferred, the original papers are returned to the site for filing. The data capturing does not occur on site; instead, the papers are collected and then returned later. Sometimes, papers may get lost during this process. If the data logger misses any entries during the transfer, someone must manually search through the physical documents to locate the missing information. However, there are instances when no missing documents can be found because the samples were never captured in the first place, which adds further complexity to the process.

Previous studies and industry reports highlight the limitations of paper-based water management systems in mining, noting frequent documentation errors, missing records, and poor traceability that compromise both data reliability and regulatory compliance [1, 28, 35]. These weaknesses not only compromised data integrity but also posed the risk of regulatory non-compliance and unreliable water quality assessments [23].

1.8 Problem statement

Gold mining operations in South Africa face significant challenges in meeting water quality compliance due to inconsistent monitoring practices, manual data handling, and delayed

reporting. These inefficiencies compromise data accuracy, delay timely decision-making, and limit the ability to demonstrate compliance with the National Water Act which can result in failure to take appropriate administrative, civil, or criminal action.

1.9 Literature on mine water compliance management

1.9.1 Preamble

To address the problem, this section sets out to identify current solutions or practices that will assist deep-mine operations in improving compliance.

The literature review is structured in four main sections to evaluate the existing water management practises critically. Within the framework of South African gold mining, the current water management (1.9.1) analyses current practices, highlighting their advantages, disadvantages, and areas of non-compliance. The screening procedure (1.9.2) outlines a targeted literature search conducted with six key terms identified that symbolise the fundamental components of an effective and compliant environmental monitoring system.

A thorough analysis (1.9.3) is then provided of the most relevant studies with an emphasis on their methods, findings, and applicability to gold mine water quality monitoring. The applicability of each evaluation screening to each study is shown in a matrix presentation of the state-of-the-art summary (1.9.4). The review's conclusions will directly guide the development of a new, enhanced gold mine water quality monitoring programme (Chapter 2).

1.9.2 Literature search criteria

The literature search was implemented by systematically inputting targeted keywords into relevant academic databases. The purpose was not only to collect literature on water quality outcomes, but to evaluate how monitoring systems were designed, how data was gathered and managed, and whether new frameworks or approaches were successfully implemented. This approach ensured that the review addressed both the technical and methodological dimensions of environmental monitoring.

Databases such as ScienceDirect, Google Scholar and Scopus were used to identify relevant peer-reviewed studies. To account for the South African context, national policy and regulatory

documents were sourced directly from the Department of Water and Sanitation (DWS) online document library².

A set of keywords combinations was applied to cover topics of relevance, including “water quality monitoring”, “environmental impact of mining”, “legal compliance frameworks”, “data management innovations”, and “reporting practices”.

Examples of core search terms included:

- Water quality monitoring
- Field sampling monitoring
- Water quality framework
- Data collection methods

To strengthen the search, *AI Undermind*³ was also employed to refine queries on digital transformation in field sampling. This allowed for the identification of additional studies that evaluate mobile applications versus paper-based methods with respect to data accuracy, geolocation, error reduction, and documentation quality.

The search yielded two main groups of material:

- **Academic literature (52):** This group comprises 36 peer-reviewed journal articles, eight postgraduate theses and dissertations, three books or handbooks, and three conference papers. Collectively, these sources emphasised monitoring system design, data collection processes, optimisation of programmes, technological innovations (mobile devices, sensors, drones), and frameworks for environmental monitoring.
- **Policy and legal frameworks (14+8):** Fourteen national government and policy documents were identified, including the *National Water Act* (No. 36 of 1998), the *National Water and Sanitation Master Plan*, the *National Water Resource Strategy* (NWRS I & II), Department of Water and Sanitation (DWS) notices, and technical field guides. In addition, eight of the identified reports or working papers were issued by the DWS and therefore also contribute to the national policy and implementation context.

² Department of Water and Sanitation. “National policy and regulatory documents.” Internet: <https://www.dws.gov.za>

³ Undermind AI. “Research platform.” Internet: <https://www.undermind.ai>

In total, 74 documents were analysed, encompassing both academic and policy-based sources. Figure 1.5 summarises the relative contribution of each document type in a pie chart, whereas Figure 1.6 depicts the distribution of studies over time, highlighting the increase in publications after 2020.

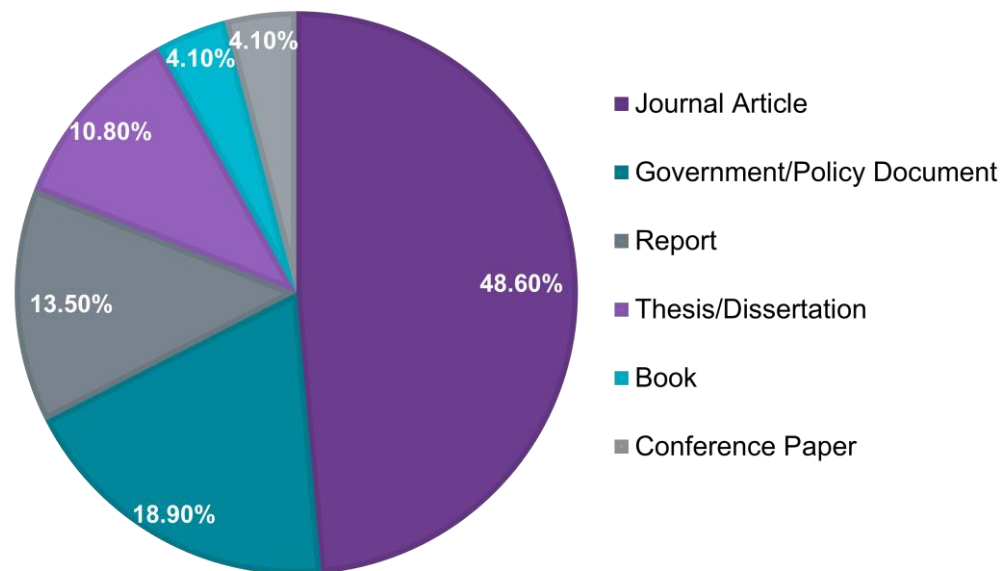


Figure 1.5: Distribution of reviewed sources by document type.

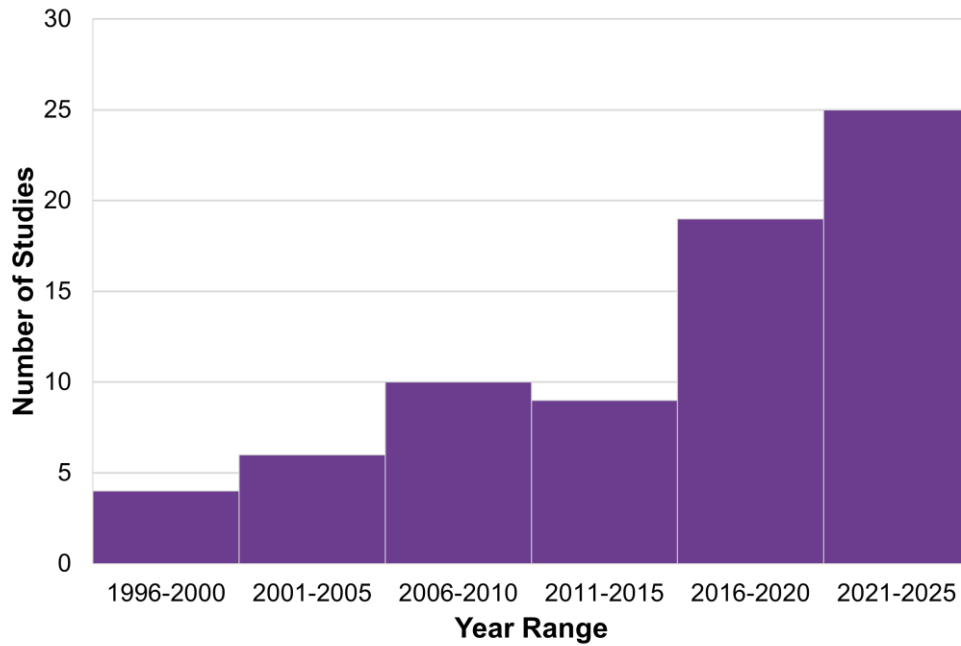


Figure 1.6: Chronological distribution of reviewed literature by publication period.

1.9.3 State-of-the-art review

Following the application of the state-of-the-art search criteria, ten studies were identified as the most relevant to this research. These studies were selected not only for their subject matter but also for their substantial methodological contributions that align with the objectives of this thesis. Collectively, they provide a comprehensive overview of water quality monitoring system design and data management, offering valuable insights into the development of monitoring frameworks, the organisation of data collection strategies, and the implementation of innovative systems. While some focus on specific sectors such as gold mining, others address broader applications, together informing effective practices relevant to this research.

Study 1: Water Quality Monitoring System Design [8]

Overview

Year 2015

Authors C. Borden and D. Roy

The study aimed to provide a structured framework for developing water quality monitoring programmes that effectively address specific resource issues while balancing scientific, economic, and management considerations, enabling stakeholders to understand spatial and seasonal water quality variations to support sustainable planning and operational decisions.

Key outcomes

The study highlighted that effective water quality monitoring requires careful consideration of system design, including site selection, monitoring frequency, and reporting methods. The study made use of HISs as best practice tools for managing monitoring data. The importance of collaboration among government agencies and stakeholders is highlighted in integrating hydro-meteorological, surface water, and groundwater monitoring networks. For example, the study recommends best practices such as involving local communities in site selection, establishing daily monitoring for surface water, and implementing cloud-based data management systems. Ultimately, the study demonstrated that integrating both water quantity and quality data by monitoring and reporting that is effective provides a strong foundation for evaluating stream conditions and understanding the broader impacts of development activities on ecosystems.

Study 2: Water Improving data management for environmental reporting in the gold mining industry [35]

Overview

Year 2019

Authors H. Janse van Rensburg, A. G. S. Gous, J. C. Vosloo and M. Van Heerden

The study aimed to develop and implement an integrated data management framework to improve environmental reporting in the gold mining industry, aiming to centralise data, standardise procedures, and reduce errors to meet stakeholder needs and improve accuracy.

Key outcomes

The study found that fragmented and inconsistent data collection methods can compromise data accuracy and legal compliance. Reporting procedures were more efficient, dependable, and accountable with the adoption of a structured data management framework supported by digital platforms. The updated system made data integration simpler, decreased human error, and improved environmental information traceability. Digitising environmental data management not only improves compliance with regulatory requirements but also supports proactive water and environmental management within the gold mining sector.

Study 3: Impacts of gold mine effluent on water quality in a pristine sub-Arctic river [10]

Overview

Year 2020

Authors N. Yaraghi, A.K. Ronkanen, A. T. Haghighi, M. Aminikhah, K. Kujala, and B. Kløve

The study aimed to evaluate the environmental impact of gold mine effluent on the water quality of the Seurujoki river. Water quality data were collected upstream and downstream of the mining activities and analysed. Assessing the level of contamination and locating trustworthy markers for ongoing water quality monitoring were the objectives.

Key outcomes

The study found that the Seurujoki river's water quality was greatly affected by gold mining operations. Higher electrical conductivity (EC), sulphates and other chemicals were present in the downstream analysis. Due to a correlation analysis, EC is a reliable metric for ongoing water quality monitoring and is especially helpful in identifying mining-related events such as tailing dam breaches. The results highlight the necessity of efficient monitoring techniques to lessen the negative environmental effects of mining on aquatic environments.

Study 4: Key issues for water quality monitoring in the Zambezi River Basin in Mozambique in the context of mining development [40]

Overview

Year 2015

Authors C. M. C. Nhantumbo, R. Larsson, D. Juárez, and M. Larson

The study aims to establish a sustainable water quality monitoring framework that can predict and manage the potential long-term effects of acid mine drainage (AMD) impacts on the Zambezi River while ensuring adherence to legal compliance requirements.

Key outcomes

The study highlighted that the current monitoring programme is inconsistent with the governmental body and the stakeholders working in isolation. The authors proposed two alternative monitoring procedures to be later combined into one system. The first option is the improvement of the current situation, which is characterised by multiple actors performing monitoring in isolation, by standardising analytical methods and improving data sharing via a web-

based reporting system. The second option is to develop a centralised system to do the monitoring of the whole river basin in Mozambique.

The advantage of centralising the monitoring programme is improving the consistency and comparability of the data. It is concluded that the best way forward is to implement the first procedure and move to the second approach over a period.

Study 5: A Framework for ‘Constructing’ Water Quality Monitoring Programs [41]

Overview

Year 2003

Authors A. P. Charles and C. W. Robert

The study aimed to provide a structured framework for developing water quality monitoring programmes that are both scientifically robust and practically implementable. It focused on guiding water managers and practitioners in selecting appropriate monitoring sites, parameters, and frequencies to ensure that water quality data effectively supports management decisions and regulatory compliance.

Key outcomes

The study focused on developing monitoring programmes in a systematic step-by-step manner, which includes clear goals by understanding the water reticulation and aligning monitoring procedures with management. It highlights the importance of tailored programmes for specific water sources rather than depending on general templates. It has been determined that well-designed monitoring systems improve data dependability, support well-informed decision-making, guarantee regulatory compliance, and allow for the early identification of problems with water quality.

Study 6: Water quality monitoring with purpose: Using a novel framework and leveraging long-term data [42]

Overview

Year 2022

Authors N. da Luz, J. E. Tobiasson and E. Kumpel

The study aimed to develop a purpose-driven framework for water quality monitoring. To guarantee that the data gathered is relevant, actionable, and customised to site-specific

circumstances, it concentrated on coordinating monitoring objectives with management, regulatory, or research aims.

Key outcomes

The study indicated that tailored monitoring programmes designed for a specific goal work better than generic programmes. The framework improves the capacity to recognise trends, interpret variability, and identify new problems with water quality by integrating historical data. Integrating monitoring goals with real-world objectives improves resource utilisation, prevents unnecessary sampling, and enhances data quality. It emphasises the need for custom sampling techniques and adaptive management for efficient water quality monitoring.

Study 7: When are mobile phones useful for water quality data collection? An analysis of data flows and ICT applications among regulated monitoring institutions in Sub-Saharan Africa [43]

Overview

Year 2015

Authors E. Kumpel, R. Peletz, M. Bonham, A. Fay, A. Cock-Esteb and R. Khush

The study aimed to incorporate mobile phones and other communication technologies in water quality data sampling among governmental monitoring institutions within sub-Saharan Africa. It examined data flows and identified potential enhancements through mobile-based systems, assessing their overall effectiveness. The research tested frameworks in 26 organisations across six countries to understand how programme structure and information flow influence the success of communication technologies in water quality monitoring.

Key outcomes

The study found that mobile phones improved water quality monitoring in sub-Saharan Africa by increasing efficiency, reducing data entry errors and enabling real-time reporting, especially in decentralised systems and remote locations with stable network coverage. The success is, however, dependent on tailored communication technology integration, user training and support. Challenges included unreliable connectivity, high costs and resistance to adopting new technologies. Mobile phones were most useful for regular monitoring tasks, but they were not as effective for complex analyses requiring laboratory equipment.

Study 8: Evaluation of electronic and paper-pen data capturing tools for data quality in a public health survey in a health and demographic surveillance site, Ethiopia: randomized controlled crossover health care information technology evaluation [44]

Overview

Year 2019

Authors A. A. Zeleke, A. G. Worku, A. Demissie, F. Otto-Sobotka, M. Wilken, M. Lipprandt, et al.

The study aimed to evaluate and compare the data quality, efficiency and user acceptability of electronic data capturing tools versus traditional paper-based methods in a public health survey conducted at a health and demographic surveillance site in Ethiopia.

Key outcomes

The study indicates that electronic data capture enhances data quality by reducing errors via automated validation and improves efficiency by streamlining workflows, shortening collection and processing times, and minimising data cleaning. Fieldworkers found electronic tools user-friendly, despite initial training requirements and technical issues like battery life. Although electronic tools have higher initial costs, they are more cost-effective long-term. Their offline capabilities make them suitable for low-resource settings and scalable for large surveys, presenting electronic tools as a sustainable method for more accurate, timely, and reliable data collection.

Study 9: Designing and implementing a data model for describing environmental monitoring and research sites [45]

Overview

Year 2022

Authors C. Wohner, J. Peterseil and H. Klug

The study aimed to develop and implement a standardised data model, Dynamic Ecological Information Management System – Site and Dataset Registry (DEIMS-SDR). This model will systematically document global environmental monitoring research sites across the world, enhancing compatibility, data sharing and collaboration across monitoring programmes by providing a comprehensive framework that captures metadata on site locations, ecosystems and other environmental aspects.

Key outcomes

This model facilitates the integration of diverse datasets by standardising metadata on site characteristics, sampling designs, and research activities, thereby enhancing their research and regulatory importance. The approach utilises a modular, hybrid relational–document data model which enables machine- and human-readable metadata. While demonstrating improved data discoverability, usability, transparency, and collaboration, the implementation requires stakeholder training and initial setup.

Study 10: Systematic and Automatized Hydrogeological Data Capturing for Provision of Safe Drinking Water in Daudkandi, Bangladesh [46]

Overview

Year 2021

Authors M. Boberg and M. Selander

The study aimed to design a smart water quality monitoring system in Daudkandi, Bangladesh, consisting of core subsystems for data collection, transmission, and management of hydrological information. The main goal was to evaluate the feasibility and effectiveness of this digital platform in supporting safe drinking water provision.

Key outcomes

The study demonstrated that integrating mobile data collection tools with a centralised database enhanced the quality, reliability, and consistency of hydrogeological data. Automated workflows reduced manual errors, streamlined data management, and enabled real-time visualisation of sediment stratigraphy, groundwater pressure, and arsenic concentrations. The system showed that online water quality monitoring can provide real-time detection, early identification of risks, and improved decision-making for water resource management. Strategic site selection and optimised sampling strategies were found to reduce costs while improving data quality. However, challenges remain in the absence of a universal monitoring framework, the high costs of implementation, and reliability issues with emerging technologies, highlighting the need for continuous technological improvements and robust management strategies to ensure sustainable and effective implementation.

1.9.4 State-of-the-art summary

Table 1.2 summarises the reviewed studies, highlighting their methodological contributions across six key themes: data management, data quality, gold mining, legal compliance, traceability, and reporting. The matrix illustrates the extent to which each study engages with

these themes and includes brief comments outlining their main findings or methodological innovations.

Table 1.2: State-of-the-art summary table.

	Data Management	Data Quality	Gold Mine	Legal Compliance	Traceability	Reporting	Comments
[8]							Monitoring and reporting that is effective and provides clear and relevant data.
[35]							Developed a centralised data management framework that standardised environmental reporting in the gold mining industry, reducing data errors and enhancing transparency.
[10]							Long-term water quality data from monitoring stations upstream and downstream of a gold mine was compared to that for pre-mining periods, to assess the impact of mining on the region's rivers.
[40]							Establishing a monitoring framework / water quality monitoring system that considers the problem of lack of resources.
[41]							Use a monitoring framework to minimise the potential that information will deviate from the original information.
[42]							Evaluate the effects of sampling frequency on long-term trend detection.
[43]							A smart option of monitoring sites and sampling intervals can lower monitoring costs while also increasing the accuracy and completeness of data on water quality.
[44]							The data collection system was designed to maximise data collection quality and efficiency.
[45]							Collecting site information and making that standardised information publicly available.
[46]							Applying a digital solution for collecting and managing hydrogeological data in a quality assured platform.

	Included in the scope of reference
	Not within scope of reference

The state-of-the-art summary (Table 1.2) provides a structured framework for developing a new water quality monitoring method:

1. Data management forms the foundation of this research, as the study seeks to explore ways to improve the collection, storage, and processing of water quality data.
2. Data quality ensures that water data is accurate, consistent, and fit for both decision-making and regulatory compliance.

3. Gold mining was included as a filter to ensure relevance to the specific operational, environmental, and regulatory challenges within South Africa's gold mining sector.
4. Legal compliance was screened to evaluate how current systems align with water-related legislation and to consider whether an improve data management can improve adherence to legal requirements.
5. Traceability highlights the importance of transparent and accurate data flows, which are essential for accountability in both internal management processes and external audits.
6. Reporting focuses on the transformation of raw data into meaningful, actionable outputs for both regulators and internal decision-makers.

Together, these six criteria evaluate the capabilities and limitations of existing systems. They also serve to identify opportunities where a new monitoring system could deliver improvements in creating an integrated and efficient water quality management approach for legal compliance.

1.9.5 Need for the study

Although several gold-mining companies in South Africa demonstrate strong practices in water sustainability, monitoring, and accountability, significant gaps persist in water and operational management [47]. Despite the Water Use Licence (WUL) framework designed to regulate water use, ineffective monitoring systems, outdated technologies, and fragmented data integration continue to undermine compliance and adaptive management [4, 32]. These challenges underscore the need for a more efficient and transparent monitoring framework that enhances data quality, traceability, and reporting.

This study addresses these systemic limitations by developing an improved data management and monitoring approach that strengthens legal compliance, improves the reliability of water-quality information, and aligns with the Department of Water and Sanitation's regulatory objectives. By integrating digital tools and structured data processes, the research aims to demonstrate how gold-mining operations can transition from fragmented, paper-based systems to real-time, verifiable, and regulation-compliant monitoring practices.

1.9.6 Aim and objectives

The aim of this study is to evaluate and enhance WQ data management compliance in the gold mining context through the integration of automation technologies to improve efficiency, traceability, and regulatory compliance.

To achieve this, the following objectives are set out:

1. Evaluate existing methodologies for developing and integrating a new water quality monitoring data management system.
2. Identify and interpret the requirements set out in the WULA framework in gold mining.
3. Develop a structured reporting system that ensures traceability of sampling activities that can be seamlessly transferred to a centralised database.
4. Incorporate the new data management system into the current monitoring process to validate its applicability and effectiveness.

1.10 Research methodology

This study implements a case study design, as it provides an in-depth understanding of water quality data management in a gold mining environment. The monitoring programme developed in this study will result in quantitative data and can be applied to similar monitoring systems.

The case study method offers an organised way to assess practical problems, create customised solutions and validate the practicality thereof. Furthermore, the use of multiple sources of evidence and validation against WULA requirements helps to minimise researcher bias in the evaluation process [48].

The researched methodology employed in this study is illustrated in Figure 1.7.

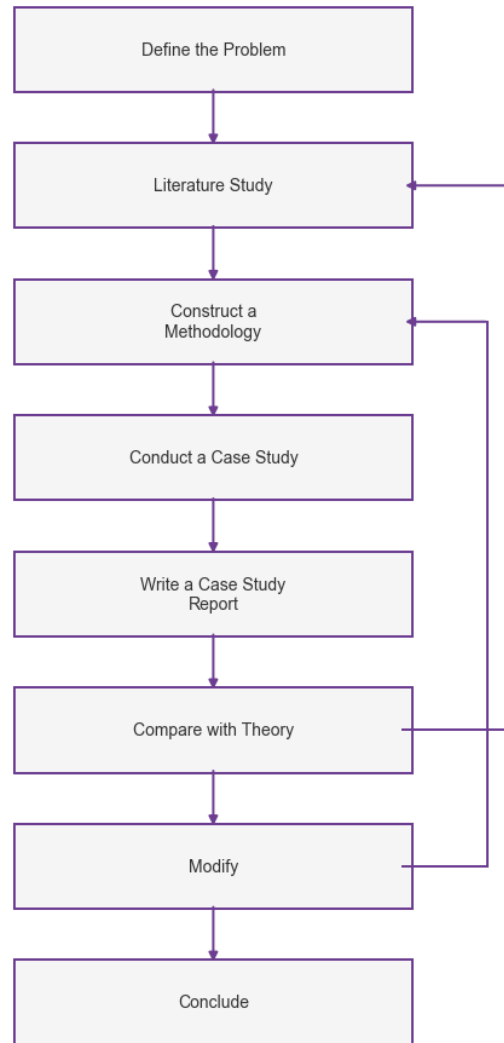


Figure 1.7: The case study research methodology. [48]

1.11 Thesis layout

The structure of the study will follow the steps illustrated in Figure 1.8.

Chapter 1: Background and literature review

This chapter introduces the South African water landscape, highlighting concerns around water quality and the specific impacts of gold mining operations. It reviews the regulatory framework governing water use, with particular focus on requirements for mining, and examines data management practices within this context. Key literature is evaluated to identify gaps in compliance, traceability, and reporting. The chapter concludes by outlining the need for the study, the research objectives, and an overview of the proposed methodology.

Chapter 2: Methodology

This chapter develops a modular framework designed to improve water quality monitoring in gold mining contexts. The framework is structured in six steps, namely data management, data quality, mining context, legal compliance, traceability, and reporting. The chapter ends with a verification of the proposed approach.

Chapter 3: Results and discussion

The methodology is applied to a large-scale gold mining case study, monitoring locations across surface and groundwater systems. The chapter presents the results of data collection, transfer, and storage using digital tools, compares them with WULA requirements, and assesses data quality improvements through automation and verification. Mining-related constraints, legal compliance challenges, and reporting practices are critically evaluated, with key findings discussed in relation to the modular framework.

Chapter 4: Conclusion

This chapter synthesises the key findings of the research, reflecting on their significance for water quality monitoring in the South African gold mining sector. It evaluates how the modular framework improves legal compliance, data reliability, and reporting efficiency, while acknowledging persisting limitations and uncertainties.

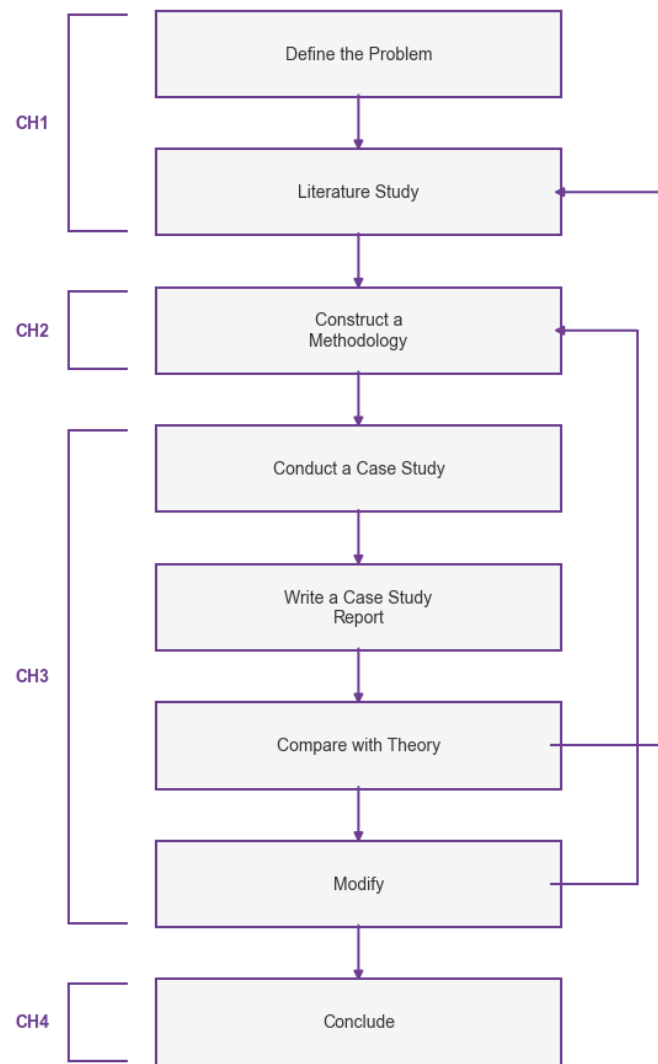


Figure 1.8: Thesis layout and alignment with case study research methodology.

CHAPTER 2 DEVELOPMENT OF SOLUTION

2.1 Preamble

This chapter details the systematic procedures and techniques utilised to develop a modular framework for monitoring and surveying environmental water quality impacts in gold mining operations. Building on Chapter 1, which emphasised the necessity of a monitoring system within the mining industry, this chapter aims to create a flexible system that can be used for a variety of water quality monitoring systems in the gold mining industry. The developed framework aims to quantify and address environmental impacts accurately, ensuring adherence to legal regulations.

In line with the case study methodology, Chapter 2 sets the groundwork for the construction of a framework, seen in Figure 2.1. The design of this framework is discussed in subsequent sections (Section 2.2 to Section 2.7).

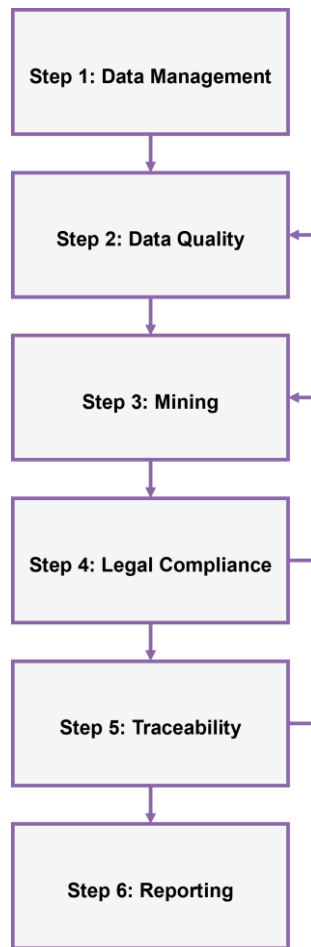


Figure 2.1: Proposed framework for monitoring and surveying environmental water quality impacts in gold mining.

2.2 Step 1: Data management

2.2.1 Preamble

Monitoring of environmental conditions is fundamental to effective water quality management, as it establishes reliable baselines, supports adaptive management, and enables regulatory accountability [49].

2.2.2 Data collection

The data gathered during this phase refers specifically to the methods of sampling and record logging, rather than the quality of the water itself.

As highlighted in the state-of-the-art summary (Table 1.2), all ten studies made use of some form of automated data collection, which reflects the global trend of monitoring systems becoming more digital. In the mining context, online sensors have increasingly been implemented to enable

real-time monitoring of physiochemical parameters, allowing for immediate detection of changes in water quality conditions [29].

In the broader literature reviewed, various methods for collecting water quality data were identified, ranging from traditional manual sampling to automated and IoT (Internet of things)-enabled systems. These systems are more efficient, cost-effective, and capable of real-time monitoring compared to conventional approaches. However, challenges remain in terms of deployment, sensor reliability, communication stability, and system resilience [36].

The ten studies selected for detailed analysis mainly applied automated or hybrid approaches, reflecting the ongoing shift toward real-time, digital monitoring. Table 2.1 summarises the data collection methods used in these key studies while recognising the broader methodological variety across the wider body of literature.

Table 2.1: Data collection method and number of studies.

References	Data Collection Method	Number of Studies	Year Published
[8, 45]	Fully automated sensors	2	2015, 2022
[10, 41, 42]	Combination of manual and automated	3	2020, 2003, 2022
[40, 43, 44, 46]	Mobile devices and paper-based forms	4	2015, 2015, 2019, 2019
[35]	Digital template entry	1	2019

This illustrates a gradual shift from traditional manual-only techniques in the early 2000s to contemporary systems that integrate mobility, digitisation, and automation, improving traceability and operational efficiency over time. Notably, even early studies, such as Charles & Robert (2003), demonstrate the adoption of automated sensor technologies.

While mobile devices and digital platforms have enhanced data quality and supported more immediate management actions, the overall effectiveness of these monitoring systems remains closely tied to strong collaborative design and clear alignment of objectives among all stakeholders [50].

In this study, data collection focused on capturing water sampling data from SW and GW monitoring points. The proposed method aims to replace and improve the existing paper-based water sampling schedule used by mines as seen in Table 2.1. Each sampling event requires the recording of the date, time, GPS coordinates, and field notes, supported by photographic evidence to verify sampling activities and site conditions.

To meet these requirements, an integrated automated system was selected to assist with scheduling and data capture. The configuration of an existing mobile application was identified as the most suitable approach, as it can be customised to include all mandatory fields and metadata necessary for compliance and traceability.

2.2.3 Data transfer

As discussed in Chapter 1 (Section 1.5), poorly aligned systems can lead to a lack of coordination, often resulting in duplication of efforts and inefficient use of resources [32]. Within the ten studies reviewed (Table 1.2), it was evident that every monitoring programme included some form of data transfer to another platform, regardless of the method of collection.

The most common method of transferring manual data is through the transcription of paper-based field records into spreadsheets. While straightforward, this practice is prone to transcription errors, delays in data availability, and challenges in data standardisation and validation, which undermine the reliability of water quality assessments [26].

Studies that used automated systems, on the other hand, usually depended on integrating with digital platforms that enable data sharing in almost real-time data integration software, including cloud-based databases or custom monitoring software.

Effective data transfer systems are essential for minimising data loss, preserving accuracy, and ensuring the timely availability of information, all of which are fundamental to informed water quality management and regulatory compliance [36].

The data transfer component of this study was designed to establish a reliable, automated link between field data collection and central data storage. In the existing system, no digital process existed for transferring or verifying sampling records. Field schedules were collected monthly and digitised to enable structured storage and review. The proposed method introduces a standardised process that allows field data captured through the mobile application offline or online with the necessary metadata.

2.2.4 Data storage

After collection and transfer, properly storing water quality data is essential to ensure traceability, accessibility, and long-term usability of information. Secure and organised data storage enables effective data management by improving the ease of access [26].

Three different approaches were noticed in the state-of-the-art matrix and are highlighted in Table 2.2.

Table 2.2: Data storage method.

References	Data Storage Method	Number of Studies	Comment
[10, 40, 41]	Local	3	Excel spreadsheets and manual
[8, 35, 43]	Semi-centralised	3	Web portals, SMS/ voice data stored in existing institutional systems, structured frameworks.
[42, 44-46]	Centralised	4	Integrated frameworks with databases, online, offline systems, ASMITAS applications and GeoGIS 2020 systems.

The emphasis on data transfer highlights the critical role of centralised systems, which act as storage facilities for coordinating data from different sources. However, storage should not only be seen as a technical endpoint but as a structured process aimed at ensuring long-term accessibility, security, and usefulness of information. Kaplan *et al.* (2021) reinforce this perspective by showing that storage must form part of a broader framework of embedded data management, where databases are designed to support both immediate research needs and future reuse.

Their study of the Shortgrass Steppe Long-Term Ecological Research site illustrates a multi-layered storage strategy: local repositories to facilitate day-to-day collaboration, community repositories for standardised network-level sharing, and institutional repositories for long-term preservation. This layered approach demonstrates that robust storage systems should integrate metadata, compatibility, and redundancy, thereby aligning with the FAIR principles (Findable, Accessible, Interoperable, and Reusable) [51].

In the proposed method, all information captured through the mobile application is synchronised automatically to the central database. This step ensures that data collected in the field are securely stored, centrally accessible, and available for subsequent validation, analysis, and reporting.

The central dashboard is structured in two configurations, one for SW and one for GW monitoring points. Each dashboard displays all relevant data attributes, including sampling date, location, monitoring points, and associated metadata. Users will be accessing site photographs directly through the interface, with options to download or view images captured during field sampling.

Figure 2.2 provides an overview of the data flow within the proposed monitoring framework. Field measurements and photographs are recorded through the mobile application, synchronised to the central online database, and subsequently used to generate the final field report.

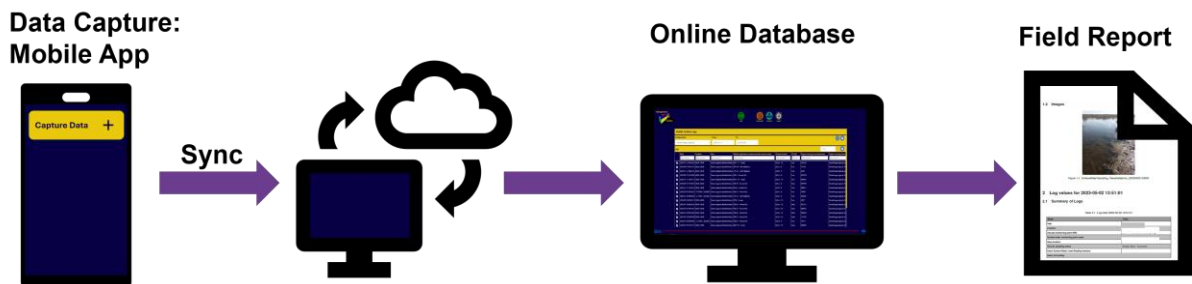


Figure 2.2: Diagrammatic representation of the proposed digital monitoring framework.

2.3 Step 2: Data quality

2.3.1 Preamble

Systematic processes of cleaning, verification, and comparison with expected ranges or additional documentation are necessary to ensure accuracy as well as reliability of water quality data. Proactive data quality management is critical for ensuring that datasets remain credible and suitable for reuse [52].

2.3.2 Filtering and cleaning

The studies which used automated sensors incorporated range checks, automatic flagging of errors, and even infilling of missing data, all of which significantly reduced manual effort [8, 35, 45]. Similarly, mobile applications and other automated tools improved data reliability by embedding validation rules directly into the data entry process, thereby minimising the need for post-collection cleaning [40, 41, 43, 44, 46]. In contrast, studies relying on manual collection and spreadsheet entry reported higher risks of transcription errors, missing values, and inconsistencies, which required substantial post-processing to ensure data quality [10, 42].

Data cleaning will be addressed through built-in controls within the mobile application. Mandatory fields and predefined dropdown lists will ensure that each sampling point contains standardised information, including monitoring point identification, date, GPS coordinates, and photographic evidence of the surrounding environment. These features will minimise input errors and improve consistency across datasets. Occasional duplicate entries will be detected within the system and manually removed through the dashboard interface to maintain data integrity. These automated

features will reduce the need for extensive post-processing, shifting most cleaning and validation actions to the point of data entry in the field.

In this study, data filtering will focus on ensuring completeness between field sampling and laboratory reporting. After each sampling round, the recorded field data will be compared with the sampling schedule and the analytical results received from the laboratory. This comparison will identify any scheduled samples that were not taken or do not appear in the laboratory results. Sites without corresponding data will be flagged for follow-up and re-sampling during the next monitoring cycle to maintain full dataset coverage.

This process will serve as a practical filtering step to confirm that the dataset reflects only verified sampling events. Rather than removing faulty data, the approach will focus on detecting missing samples and ensuring that all monitoring points required by the WUL are consistently represented in the collected dataset.

2.3.3 Data verification

Verification processes varied across the studies. In more common approaches, verification relied on manual cross-checking of field sheets versus duplicate samples. In more advanced systems, digital verification methods were implemented. Zeleke *et al.* (2019) used a randomised controlled trial to demonstrate that electronic tools significantly reduced transcription errors [44]. Digital templates used in Janse van Rensburg *et al.* (2019) reduced error rates from 20% to 4% [35]. Boberg and Selander (2011) incorporated verification through automated comparison of arsenic levels with sediment colour using mobile applications and cross-validating field results against reference values in online databases [46].

Verification will form a key component of the data quality management process and will be used to confirm the completeness and accuracy of captured records. A monthly review process will be implemented to cross-reference uploaded data against the sampling schedule, ensuring that all required SW and GW sites are represented. The main cross-referencing step will involve comparing field monitoring records with the analytical results received from the laboratory to verify that all submitted samples are processed and reported.

Because the field sampling process will initially operate in both digital and manual formats, paper field sheets will also be reviewed alongside the digital entries. This additional step will ensure that all sampling events are recorded and that no data are omitted during the transition to the automated system.

2.4 Step 3: Mining

Previous studies indicate that mining operations can have significant and specific impacts on water resources and therefore require monitoring programmes tailored to the sector for specified RQOs that balance environmental protection [16]. Mining-related discharges and processes commonly elevate sulphates, cyanides, and heavy metals and can produce (AMD) that can alter both surface and groundwater chemistry. It is necessary to monitor current changes and long-term trends driven by mining activities such as dewatering, tailing seepage and historical contamination [8, 10]. Table 2.3 presents the mining commodities extracted from the state-of-the-art summary shown in Table 1.2.

Table 2.3: Mining type relevance.

Reference	Mining type	Relevance to mining
[8]	Gold	Includes mining examples in monitoring design, site specific selection, frequency
[35]	Gold	Focus on mining-sector data management and reporting workflows
[10]	Gold	Demonstrates ecological and chemical impacts of gold-mine effluent; parameter sets and sampling strategies to detect mine-related impacts
[40]	Coal	Discusses basin-scale monitoring challenges under mining development, highlights coordination and cumulative impact assessment
[42]	Not specified	Provides framework for purpose-driven monitoring; applicable to mining for establishing baselines and detecting operational trends

Mining monitoring data is used to comply with regulatory compliance (i.e. WUL), enforcement actions, and stakeholder engagement.

The mining sector has increasingly recognised the importance of efficient data management. Gold Fields⁴ highlights in its Water Stewardship Report 2023 that automated data synchronisation and digital capturing have been employed to enhance timeliness and accuracy in water-related information management.

⁴ G. Fields. "Water stewardship report." Internet: <https://www.goldfields.com>

2.5 Step 4: Legal compliance

Legal compliance plays a critical role in water quality management. As outlined in Section 1.3, the National Water Act requires that all significant water users in South Africa obtain a WUL. Therefore, monitoring programmes need to show that they comply with regulatory standards in addition to collecting and storing data.

From the state-of-the-art, six studies made no mention of legal compliance, while four incorporated elements of regulation or compliance.

7. Yaraghi *et al.* (2020) considered compliance with regulatory guidelines in relation to gold mine effluent in a sub-Arctic river.
8. Nhantumbo *et al.* (2015) highlighted legal frameworks in the Zambezi Basin, emphasising the role of regional water authorities and the alignment of monitoring with transboundary policies.
9. Da Luz *et al.* (2022) explicitly linked long-term monitoring with regulatory needs, suggesting that monitoring programmes should be designed with reporting obligations in mind.
10. Wohner *et al.* (2022) discussed compliance indirectly through environmental data models that were designed to integrate with national and international reporting obligations.

Designing a monitoring programme in South Africa must therefore comply with the WUL obligations.

Step 4 of the framework ensures that all monitoring activities comply with the mine's internal sampling procedure and the conditions of its water-use authorisation. The procedure requires that every sampling point be clearly indicated on a map and accompanied by photographs and GPS coordinates. When new sampling points are established, their locations must also be documented with photographic and coordinate evidence.

These requirements were incorporated into the framework by embedding GPS and photo-capture functions within the mobile application. Each sampling event therefore generates a verifiable, spatially referenced record that links field activities directly to digital data management. This configuration ensures that sampling documentation meets the procedural standards required for compliance audits and legal reporting.

2.6 Step 5: Traceability

Traceability refers to the ability to retrieve and verify previously collected water quality data over time. As highlighted in Section 2.1, studies that employed semi-centralised or centralised data management systems demonstrated stronger traceability than those relying on local, uncoordinated methods.

Table 2.2 is repeated here as Table 2.4 with added traceability elements. Seven studies used a semi-centralised or centralised collection method, ranging from structured Excel workbooks to dedicated local or premium databases, which supported long-term data searchability. Three studies used local, uncoordinated data collection and reported only moderate traceability, with records scattered across different sources.

Table 2.4: Frequency of data traceability from state of the art.

References	Data Collection Method	Number of Studies	Traceability
[10, 40, 41]	Local	3	Moderate retrieval data, scattered data
[8, 35, 42-46]	Semi-centralised & Centralised	7	Long-term data searchability

2.7 Step 6: Reporting

Reporting is to ensure that the collected water quality data are transformed into meaningful information for decision making, legal compliance and stakeholder engagement. The format, frequency, and target audience of reporting practices varied considerably among the reviewed studies.

Table 2.5: Frequency of data reporting from the state of the art.

References	Reporting Method	Number of Studies	Comment
[8, 41, 43, 46]	Manual Reporting	4	Manual compilation or emailed spreadsheets; higher risk of transcription errors and inconsistent formats.
[10, 35, 44]	Semi-Automated	3	Structured templates or semi-centralised systems improved consistency and timeliness but still required manual checks.
[40, 42, 45]	Automated	3	Centralised databases or dashboards with built-in analytics, automated validation, and regulatory integration.

As shown in Table 2.5 some studies utilised automated or semi-automated report generation through dashboards, online portals or integrated templates. These systems help produce consistent outputs and reduce manual data entry. Additionally, they simplify compliance with

environmental regulations and water use licenses by enabling users efficiently to create summaries tailored for internal management or regulatory agencies.

Manual reporting relied heavily on manual data compilation, which increases the risk for transcription errors and inconsistencies. Several studies highlighted delays in reporting due to fragmented records or the need for additional cleaning and verification before producing final outputs.

The WUL for this study specifies that monitoring should be continuously assessed against the applicable compliance limits and subjected to trend analysis throughout the operational phase of the mine. To support this requirement, the reporting component of the framework was designed to visualise and summarise in-field sampling data. The dashboard compiles readings directly from the mobile application and displays key indicators for each SW and GW site.

2.8 Summary of the Proposed Water Quality Monitoring Framework

The constructed framework is summarised in Figure 2.3 and illustrates the six steps of the monitoring framework together with their main considerations.

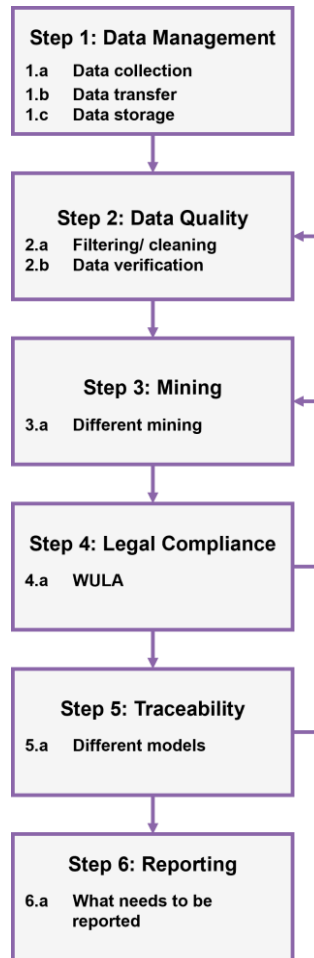


Figure 2.3: New proposed framework for mine water quality management.

2.9 Verification of method

The proposed method was verified against the state-of-the-art matrix in Table 2.6. Data management is integrated from the beginning and is strengthened in Step 2 during data validation and in Step 5 during processing. Data quality is improved through early checks in Step 2, strengthened in Step 5, and finalised in Step 6. Gold mining considerations are integrated in Step 3, with legal compliance assessed in Steps 3 and 4 to ensure regulatory compliance. Traceability is incorporated in Step 5, linking results back to their sources, and reporting is finalised in Step 6 for clear and compliant reports. This representation confirms that the method is comprehensive, systematic, and adaptable to both operational and regulatory needs.

Table 2.6: Verification of Method/Framework development.

Criteria from Table 1.1	Step number in the proposed framework					
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Data Management	✓	✓			✓	
Data Quality		✓			✓	✓
Gold Mining			✓			
Legal			✓	✓		
Traceability					✓	
Reporting						✓

2.10 Conclusion

Chapter 2 reviewed the existing methods related to water quality monitoring, highlighting both the strengths and shortcomings. The literature showed that, while data management, quality assurance and traceability are considered as essential, their implementation is inconsistent and fragmented amongst studies. Legal compliance and reporting place further demands on monitoring systems, as many South African gold mines face difficulties meeting the requirements of the National Water Act and water use licences.

To fill in the gaps, the method's verification verified that the suggested framework methodically incorporates these six essential themes: data management, data quality, gold mining context, legal compliance, traceability, and reporting. This provides a comprehensive and practical framework for creating a monitoring system that is both operationally effective and regulator compliant. Building on this, Chapter 3 provides a detailed approach for developing and testing the suggested framework.

CHAPTER 3 RESULTS AND DISCUSSION

3.1 Preamble

As outlined in the case study methodology (Figure 1.8), this chapter presents the practical implementation of the monitoring framework developed in Chapter 2. The framework is applied to a selected mining operation to evaluate its effectiveness in addressing the monitoring challenges identified in earlier chapters. The findings are discussed in relation to data management, data quality, gold mining practices, legal compliance, traceability, and reporting, maintaining consistency between the methodological design and the assessment of outcomes.

Each section highlights both the strengths and limitations identified during implementation, supported by figures and outputs generated from the monitoring programme. Particular attention is given to the accuracy of sampling locations, compliance with WULA requirements, and improvements in reporting and data accessibility. The results are interpreted with reference to the practical challenges of monitoring in the South African gold mining context, as well as the opportunities for enhancing efficiency and reliability through digital data collection systems.

This chapter presents results from a one-year test run of the mobile application, during which a subset of surface water and groundwater samples was captured digitally. The analysis focuses only on samples with complete location metadata to ensure reliability of the geographical comparisons.

For confidentiality, the true geographic coordinates of monitoring points are not presented in this chapter. Instead, all locations were centralised around a neutral point in the South Pacific. In addition, monitoring point names were anonymised and replaced with generic numbering. These adjustments preserve the geographical relationships and analytical validity of the results while ensuring that no sensitive operational information is disclosed.

3.2 Case study background

The selected case study focuses on a gold mining company in South Africa that has five WULAs and multiple mining operations, selected due to the scale and complexity of its water monitoring requirements.

The operation has a total of 255 sampling locations, which include 143 surface water sites and 112 groundwater sites. Monitoring frequencies differ between the two: surface water samples are collected monthly, while groundwater samples are collected quarterly.

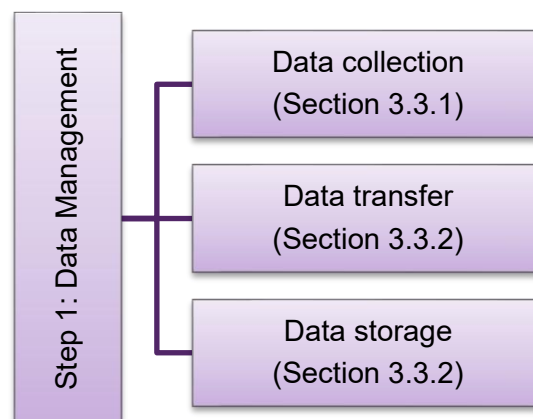
In line with the conditions of its WULA, the mine is required to submit biannual water quality reports to the DWS.

For the purpose of this study, the monitoring programme across all five mining sites was treated as a single integrated case study. This unified approach provides a holistic view of the mine's water system while recognising that SW and GW components operate under different conditions and monitoring frequencies. To reflect these operational differences, the results are presented separately for SW and GW monitoring points. This structure allows for detailed evaluation of data management, sampling procedures, and compliance performance within each component, while still assessing the overall effectiveness of the integrated monitoring framework across the mining complex.

3.3 Step 1: Data management

3.3.1 Preamble

In Section 1.7, the current method of managing the monitoring programme was outlined. To recap, the sampler is responsible for travelling to all designated monitoring points and capturing the required data on field reports. The programme is guided by surface water and groundwater schedules, which indicate when each sample must be collected.



3.3.2 Data collection

The original sampling process relied on paper-based schedules and field reports, which were completed manually by the sampler during site visits. These records, later stored in bins at the mine, required physical collection and exchange on a monthly basis. This system was highly

dependent on manual handling, created opportunities for errors, and required significant administrative effort.

From the literature review, two studies used fully automated systems for monitoring. While effective in reducing the manual workload, such systems were not a practical solution for this operation. Many monitoring points are located in easily accessible areas, raising the risk of theft or vandalism of costly equipment. In addition, with 255 sampling locations, the financial outlay for a fully automated system was rejected by the mining operation.

Four of the reviewed studies utilised mobile devices in combination with paper-based forms. This hybrid approach offers a more practical and cost-effective alternative. Implementing such a method in this operation required only the use of a mobile device, significantly reducing costs compared to automated systems.

To improve efficiency, the operation adopted an in-house mobile application for use during fieldwork. Alternatively, various commercial and cloud-based mobile platforms are commonly employed in monitoring programmes, offering features such as offline data entry, GPS-enabled sampling, and integration with existing databases. These options may be suitable depending on resource availability and operational scale. The in-house application was configured with separate components for surface- and groundwater monitoring, each tailored to the parameters and processes relevant to that medium. For both components, the date, user, and location are automatically recorded, and dropdown menus enable the sampler to select the mine and the designated monitoring point. This standardisation reduces the risk of transcription errors while also ensuring consistency across the five mines that form part of the monitoring programme.

The surface water module captures key information such as water level (full, low, dry), in-field measurements (pH, EC, TDS, temperature), sampling status, photographs, and a visual environmental inspection. The groundwater module includes additional fields for the method of sampling, specifying whether water was extracted by pumping, using mechanical pumps to draw water continuously, or by bailing, using a manual bailer to lift water from the well. It also records water levels before and after purging, the volume purged, in-field parameters, and environmental photographs. This design ensures that all information necessary for WULA compliance is collected at the point of sampling.

During the initial testing phase, dropdown menus for the five mines were incorporated to simplify navigation. In addition, the application allowed the sampler to save the sampling location rather than relying solely on automatic GPS coordinates. This was particularly important because

laboratory analysis occurs off-site, and saved locations ensure that each sample remains linked to the prescribed WULA coordinate.

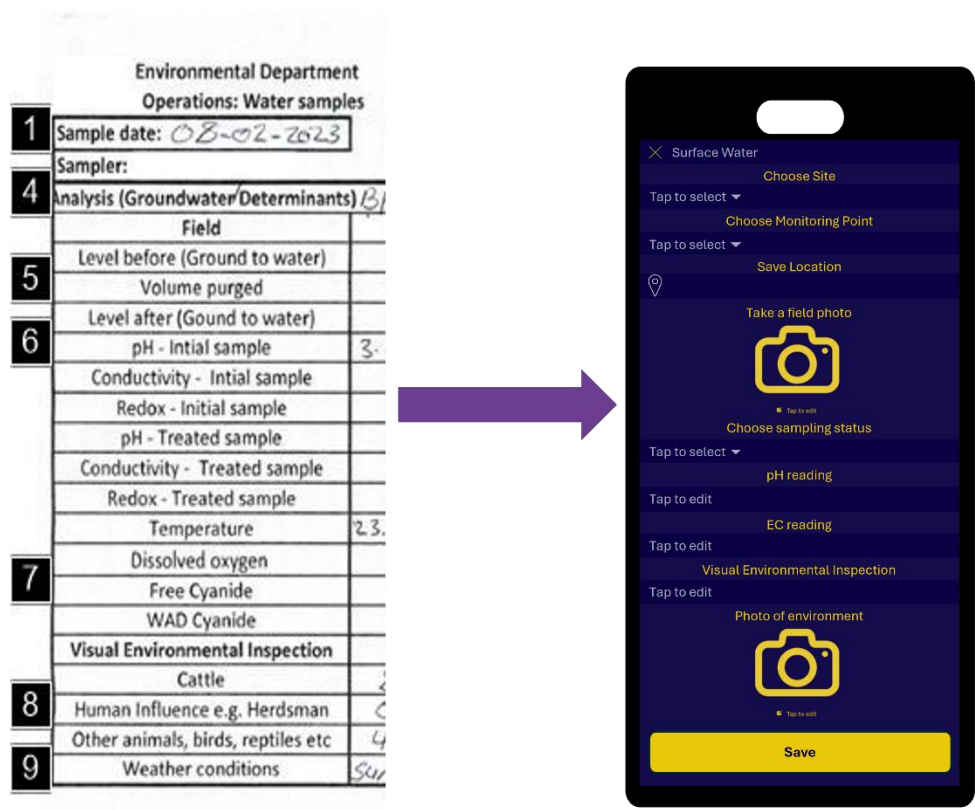


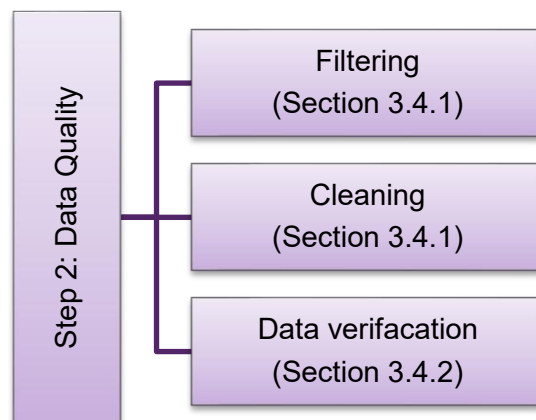
Figure 3.1: Comparison of paper-based sampling with mobile application fields (surface water example).

3.3.3 Data transfer and storage

The paper-based sampling required monthly collection of field reports, transcription into Excel and manual filing. This created unnecessary delays, was prone to transcription errors, and made central access to information difficult.

With the introduction of the in-house mobile application, field data is now captured digitally and transferred directly to a web-based server. This server acts as a monitoring dashboard, allowing authorised personnel to view field activities across all five mines in near real time. The change has reduced the administrative burden, improved transparency, and ensured that sampling information is consistently accessible.

3.4 Step 2: Data quality



3.4.1 Filtering and cleaning

The paper-based water management system proved to be unreliable and inefficient for meeting regulatory monitoring requirements. One of the main issues was the frequent occurrence of incorrect sample months on the forms, when unforeseen circumstances like flooded roads, locked gates, or illegal mining activities prevented access to sampling sites, so samplers would sometimes record the planned sampling month instead of the actual month when samples were taken, often months later. This practice resulted in discrepancies between reported and actual sampling times.

Additionally, the paper system lacked effective accountability and traceability, making it difficult to verify whether samples were collected from the correct locations as specified in the WUL. Without a systematic method to confirm site compliance, there was no way to ensure that all mandated sampling points were being monitored regularly.

The design of the mobile application made extensive post-collection data cleaning largely unnecessary in practice. Mandatory fields and predefined dropdown lists prevented missing entries and site identification errors during sampling, resulting in a highly consistent dataset with minimal incomplete records. The capacity to capture field images and conduct visual inspections further improved data trustworthiness by linking each record to verifiable, site-specific evidence.

Actual data cleaning during the study was limited to resolving occasional duplicate entries, which occurred when a sample was mistakenly saved more than once. These duplicates were easily identified and manually removed through the dashboard interface, eliminating the need for labour-

intensive corrections such as renaming sites or filling in missing information. As a result, the “cleaning” process effectively shifted from the backend to the point of entry in the field, where built-in validation controls ensured accuracy at the source.

A limitation of this approach is the potential for incorrect dropdown selections. The sampler could accidentally select the wrong mine or monitoring point, creating inconsistencies between recorded metadata and the actual sampling location. Such errors can usually be detected and corrected during verification, but they emphasise the importance of maintaining additional cross-checks, such as comparing entries with GPS coordinates, to safeguard data integrity.

The paper system lacked effective accountability and traceability, making it difficult to verify whether samples were collected from the correct locations as specified in the WUL. Without a systematic method to confirm site compliance, there was no way to ensure that all mandated sampling points were being monitored regularly.

To assess field accuracy, in-field GPS coordinates were exported from the mobile application and compared with the prescribed WULA coordinates using a custom Python script developed for this study. The script plotted both coordinate sets on a scatter plot using matplotlib and calculated spatial differences to identify positional deviations between WULA points and in-field readings. The results for both surface water and groundwater monitoring points are presented in Figure 3.2 and Figure 3.3. To evaluate coordinate accuracy in greater detail, each WULA point was compared with the average of multiple in-field measurements. While some points showed close alignment, others deviated by several kilometres. Additional representative examples are provided in Appendix A (Figures A.1–A.4).

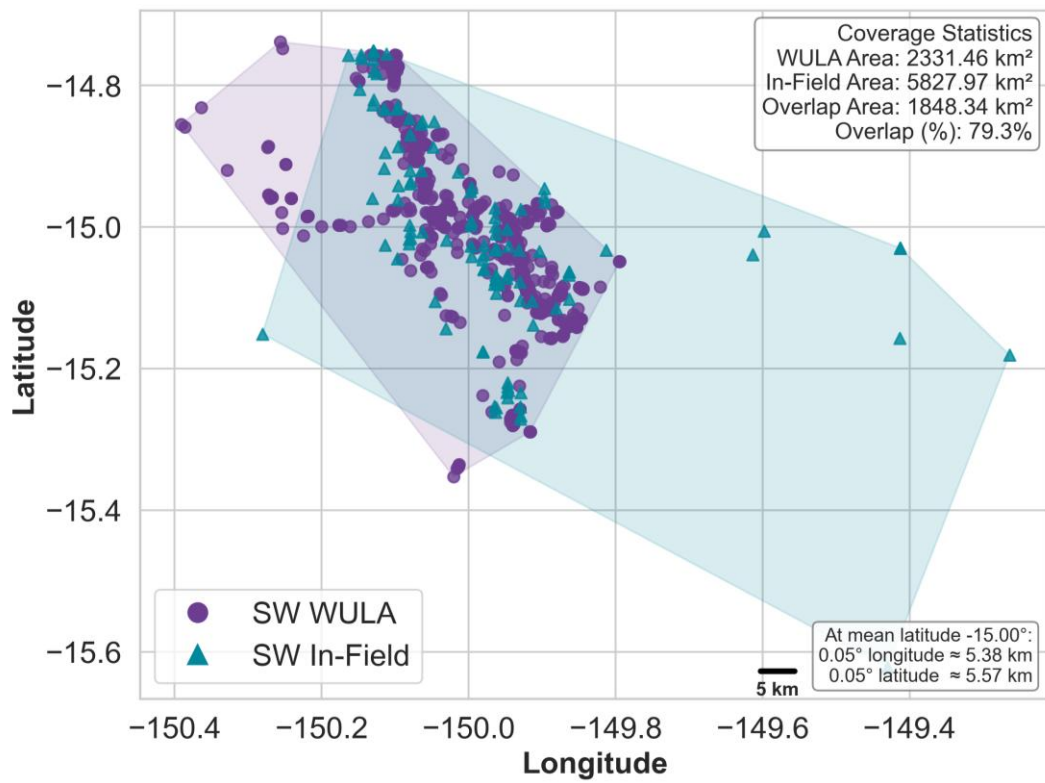


Figure 3.2: Scatterplot of surface water monitoring points (in-field vs WULA).

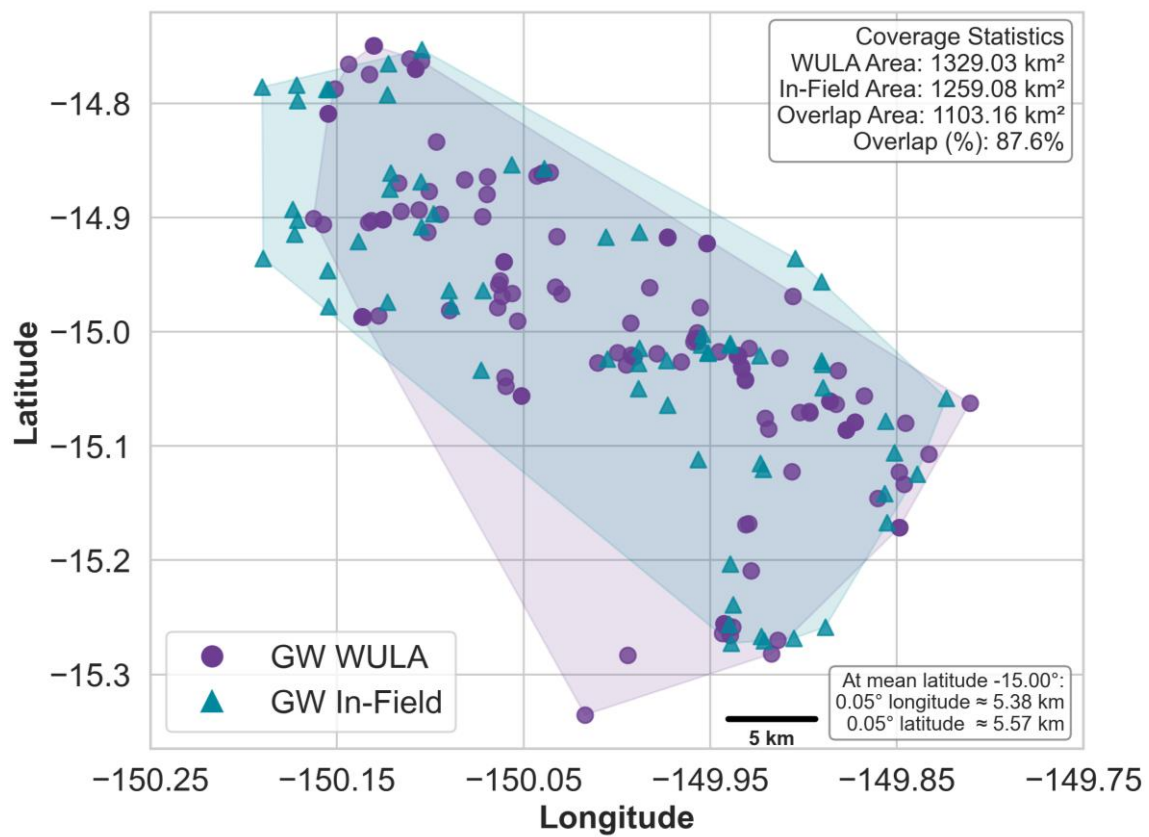


Figure 3.3: Scatterplot of groundwater monitoring points (in-field vs WULA).

These plots demonstrate that the majority of in-field coordinates fall within the spatial extent defined by the WULA monitoring programme, indicating good overall alignment with the prescribed sampling locations. Surface water showed a 79.3% spatial overlap between in-field and WULA points, while groundwater exhibited an even stronger overlap of 87.6%. Groundwater locations also display a tighter clustering and smaller overall footprint, consistent with their fixed and well-defined borehole infrastructure. In contrast, surface water points show broader dispersion, driven by accessibility constraints, seasonal flow variability, and flexible sampling paths.

The convex-hull comparisons also highlight differences in spatial coverage, with some in-field points extending beyond the WULA footprint. These deviations reflect differences between the WULA and the dedicated in-field sampling programme and may result from extra monitoring points in the sampling programme that are not part of the WULA.

3.4.2 Data verification

A further limitation observed in the old paper-based system was the way sampling dates were recorded. For example, if a July sample could not be collected due to obstructions such as illegal mining activity or restricted access, the sampler would sometimes still record the sample as “July” when it was eventually taken months later. This introduced discrepancies between the scheduled and actual sampling dates, reducing reliability. The mobile application addresses this by automatically recording the true date and time of each entry.

Before the implementation of the mobile application, verification of sampling completeness relied entirely on manual consolidation of field reports and laboratory results. Figure 3.4 illustrates this process, showing the monthly comparison between laboratory data received and the records retrieved from paper-based reports. Each monitoring point was checked individually, and the missing data were identified by physically reviewing archived field sheets.

Check marks represent complete records where both the field report and the laboratory results were available. Yellow exclamation marks indicate laboratory results received without a corresponding field report, while red crosses show cases where a field report was found but the laboratory data were missing. Blue-shaded cells denote months with no field or laboratory data available. This manual cross-referencing was time-consuming and prone to error, highlighting the need for a digital system to link sampling records with laboratory outputs automatically.

Surface Water									
Monitoring Point	Sept-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22	Mar-22	Apr-22	May-22
MP SW 9		✓	✓	✗	✓		✓		✓
MP SW 11	!	✓	✓	✓	✓	!	✓	!	✓
MP SW 58		✓	✗		✓	!		✓	✓
MP SW 59	✓	✓	✓	✓	✓	✓	✓	✓	✓
MP SW 4		✓	✓	✓	✓	✓	✓	✓	✓
MP SW 5	✓	✓	✓	✓	✓	!	!	✓	✓
MP SW 6		✓	✓	✓	✓	✓	✓	✓	✓
MP SW 10			✓	!	!	!	✓	!	✓
MP SW 7		✓	✓	✓	✓	✓	✓	✓	✓
MP SW 8	✓	✓	Crossed Out	✓	✓	✓	✓	✓	✓
MP SW 1	✓	✓	✓	✓	✓	✓	✓	✓	✓
MP SW 2	✓	✓	✓	✓	✓	✓	✓	✓	✓
MP SW 3	✓	✓	✓	✓	✓	✗	✓	✓	✓
MP SW 137	✓	✓	✓	✓	✓	✓	✓	✓	✓
MP SW 138	✓	✓	✓	✓	✓	✓	✓	✓	✓
MP SW 139	✓	✓	✓	✓	✓	✓	✓	✓	✓
MP SW 141							!	✓	✓

✓	Field Report and Data
!	Lab Data - No Field Report
✗	Field Report - No Lab Data
	No Field Report/ No Lab Data SW

Figure 3.4: Manual verification matrix showing the comparison between field and laboratory reports for SW.

During the testing phase of the mobile application, verification became far more efficient and structured. Laboratory results were received in digital format, and corresponding field records could be downloaded directly from the dashboard. This made it possible to compare field and laboratory datasets side by side without relying on physical field sheets.

When discrepancies were detected between the two datasets, for example, where a laboratory result existed without a corresponding field record, manual verification was still carried out by reviewing the original field reports to confirm whether the sample had not been captured using the mobile device.

Figure 3.5 presents the verification summary generated during the digital testing phase for surface-water monitoring points. The table illustrates monthly completeness, indicating where both field and laboratory data were successfully captured. Entries marked “Yes” confirm that samples were collected and processed, while “Dry” or “No access” denote legitimate reasons for missing data. This system reduced administrative effort, improved traceability, and ensured that all sampling activities were accurately represented within the central database.

Surface Water						
Monitoring Point	Field Report	Lab Report	Field Report	Lab Report	Field Report	Lab Report
	May-23		Jun-23		Jul-23	
MP SW 9	Yes	Yes	Yes	Yes	Dry	
MP SW 11	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 47	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 59	Yes	Yes	Yes	Yes	Yes	
MP SW 4	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 5	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 6	Yes	Yes	Yes	Yes	Yes	
MP SW 10	Yes	Yes	Yes	Yes	Yes	
MP SW 7	Yes	Yes	Yes	Yes	Yes	
MP SW 8	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 1	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 2	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 3	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 137	Yes	Yes	Yes	Yes	Dry	
MP SW 138	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 139	Yes	Yes	Yes	Yes	Yes	Yes
MP SW 141	Yes	Yes	Yes	Yes	Yes	

Figure 3.5: Digital verification summary showing monthly completeness between field and laboratory data for SW.

It is important to note that the verification results presented here are based on a one-year test run of the mobile application. During this period, 771 surface water (SW) and 133 groundwater (GW) samples were captured digitally. In total, 880 SW samples and 202 GW samples were collected across the operation, but 109 SW and 69 GW entries were excluded because location data was not saved by the device. Including these incomplete records would have distorted the calculation of mean deviations, as missing coordinates artificially inflate geographical averages and reduce the reliability of the analysis. The results therefore reflect only the samples with complete location metadata.

To quantify geographical accuracy, the distances between in-field coordinates and WULA-prescribed locations were calculated. Figure 3.6 and Figure 3.7 presents the frequency distribution of these deviations.

A uniform 2.5 km bin size was applied to both SW and GW histograms to support direct comparison of spatial accuracy. While SW samples should ideally be collected at fixed locations, field conditions often result in slight shifts along a river, dam, or channel, and these sites are generally easier to relocate. In contrast, GW sampling requires finding specific boreholes, making positional accuracy far more critical.

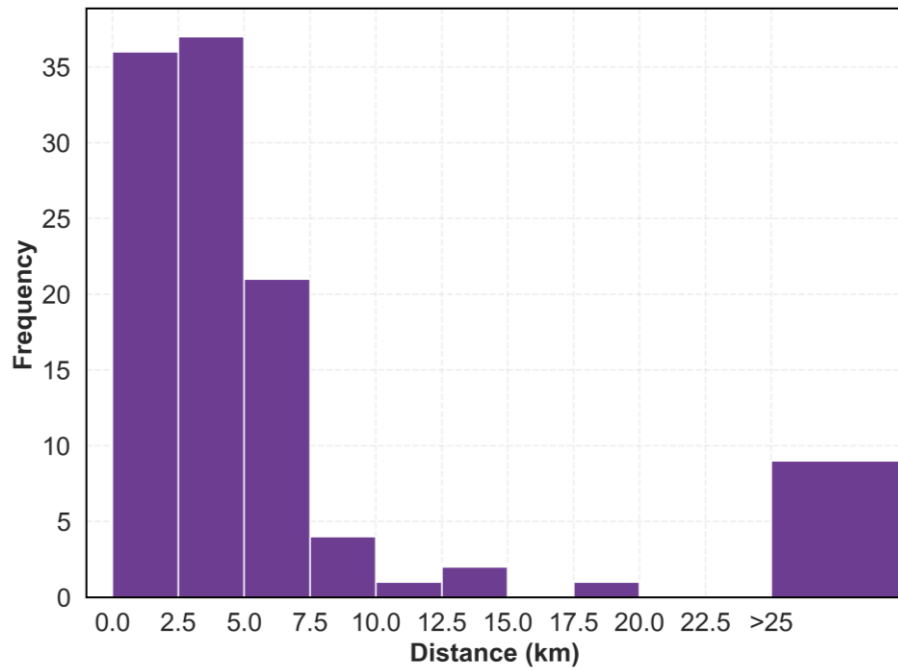


Figure 3.6: Histogram of the frequency distribution against distance from WULA point (SW).

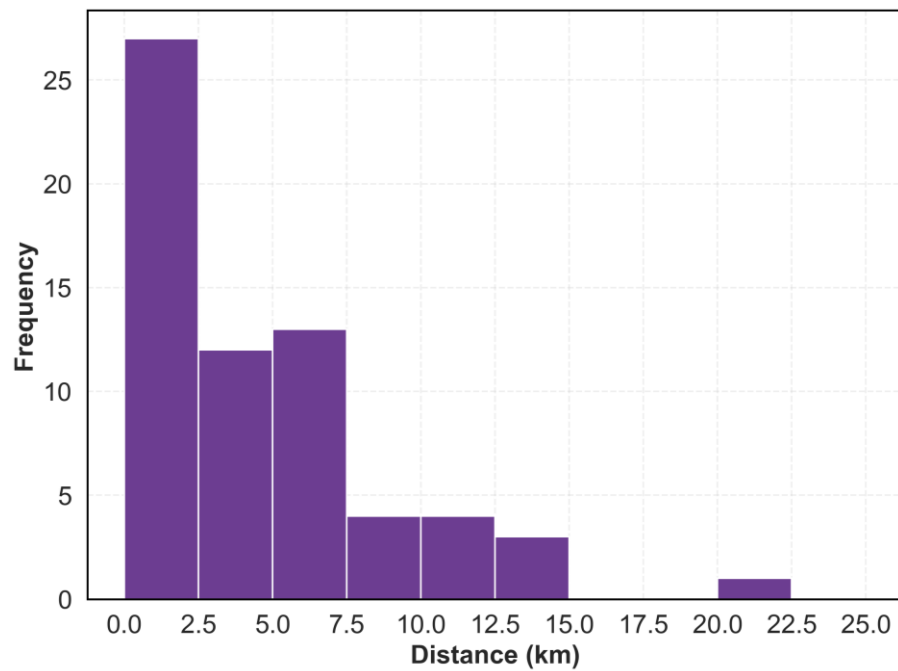


Figure 3.7: Histogram of the frequency distribution against distance from WULA point (GW).

Most samples fall within a short distance of their prescribed locations, but some outliers exhibit much larger deviations. Table 3.1 shows the proportion of samples that fall within 5 km of their WULA locations, as well as those that exceed this threshold. The 5 km threshold was selected

because most sampling events occur within this range, and distances greater than 5 km represent rare outliers that indicate substantial misalignment between the in-field and WULA locations.

Table 3.1: Frequency of sampling distances from WULA.

Distance Category	SW (n, %)	GW (n, %)
Within 5 km	73 (66%)	39 (61%)
>5 km (Error)	38 (34%)	25 (39%)

The majority of SW samples (66%) and GW samples (61%) were taken within 5 km of their prescribed WULA locations, indicating generally good alignment between in-field sampling and licensed monitoring points. However, 34% of SW samples and 39% of GW samples exceeded the 5 km threshold, reflecting substantial spatial deviations in a portion of the dataset.

These deviations may result from three main sources:

- **Inaccurate WULA coordinates:** Some authorised locations were defined with low GPS precision when licences were issued.
- **Sample error:** The field sampler may select the wrong monitoring point or take a sample at an incorrect site.
- **Device/GPS error:** Mobile devices inherently include a margin of error in recorded coordinates.
- **Negligence:** Sampler lies.

Recognising that discrepancies can arise from multiple sources is important when interpreting results. While the mobile application reduces the likelihood of manual errors, the persistence of outliers indicates that compliance verification requires both accurate licence information and reliable field practices.

3.5 Step 3: Mining

Step 3: Mining

The monitoring programme covers five mines, incorporating both surface water and groundwater resources. Surface water sites are monitored monthly due to their higher variability, while groundwater sites are monitored quarterly given their slower response to change.

To evaluate consistency across the operation, the mean deviation between in-field and WULA coordinates was calculated for each monitoring point. Results are shown in Figure 3.8 and Figure 3.9.

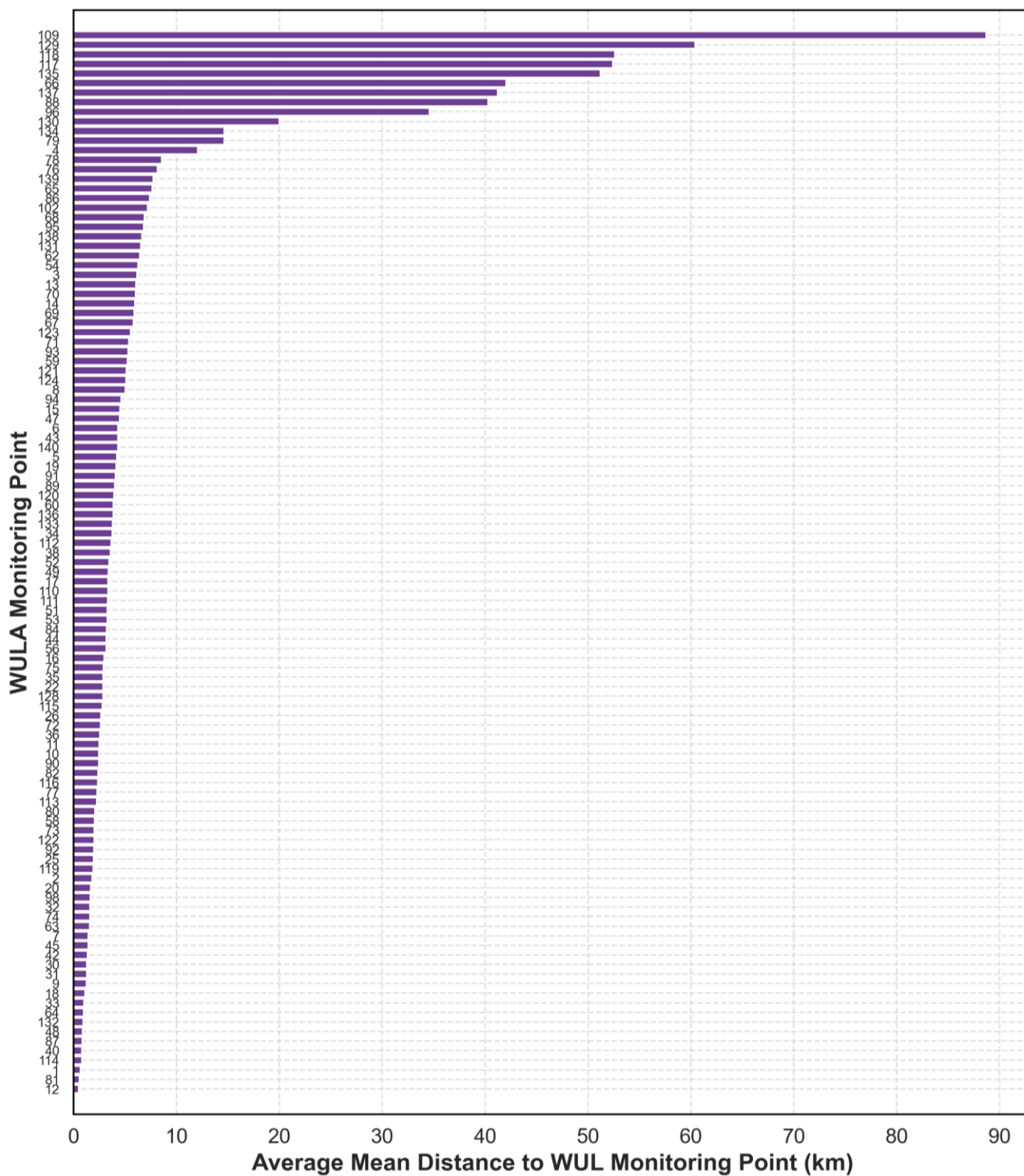


Figure 3.8: Average SW mean distance to each individual WULA monitoring point.

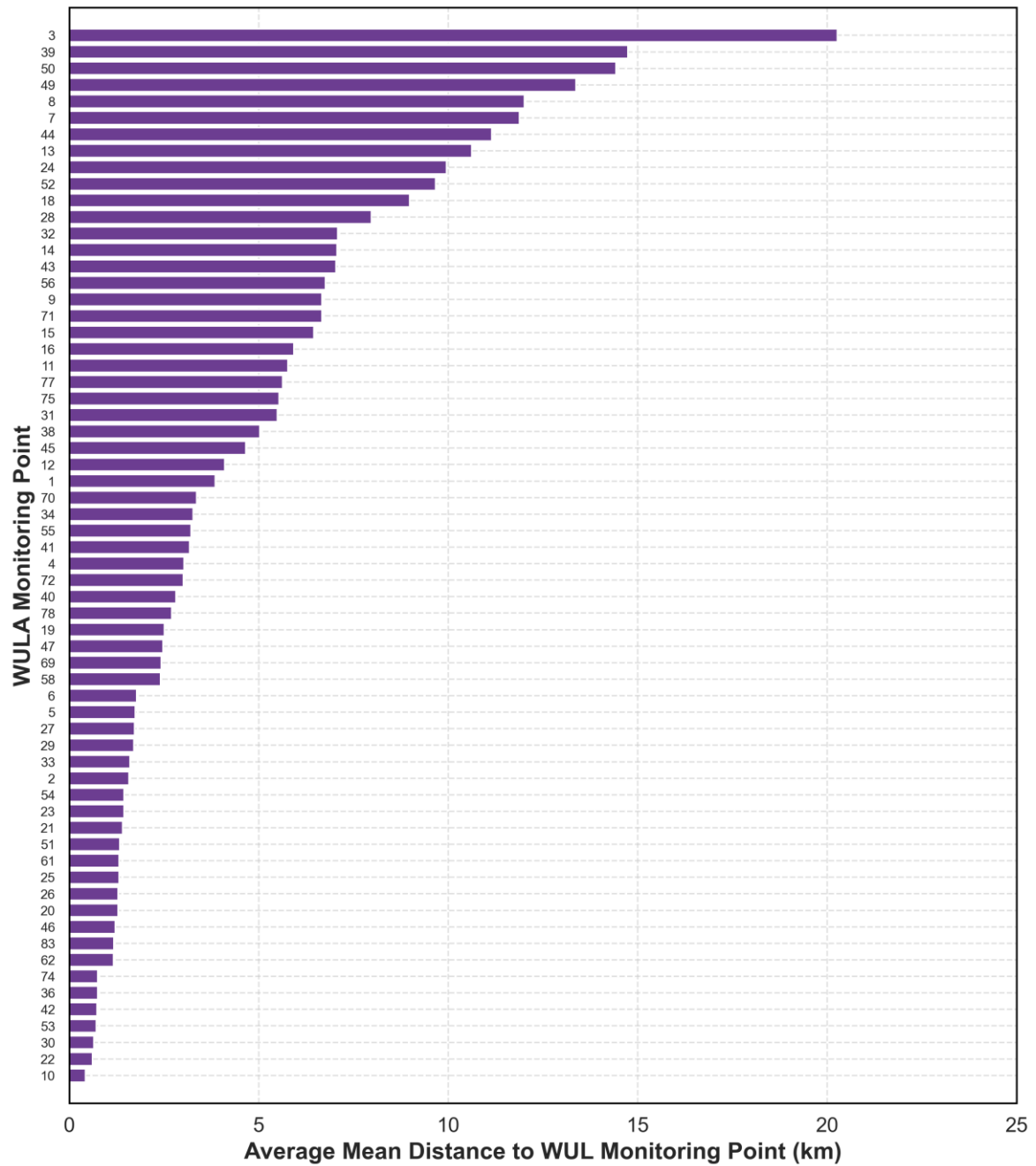
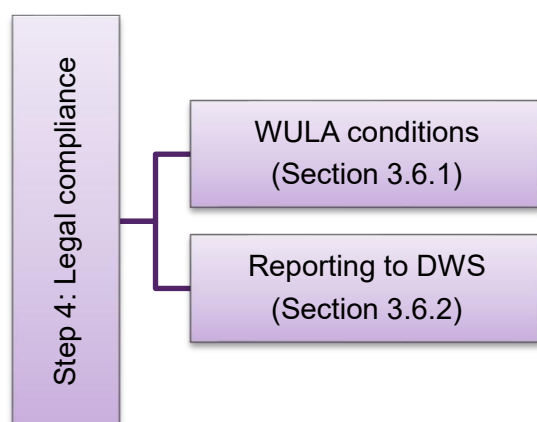


Figure 3.9: Average GW mean distance to each individual WULA monitoring point.

The bar plot shows that while most monitoring points align closely with their prescribed locations, a few consistently exhibit greater deviations. These are typically sites where field access is difficult, demonstrating how mining activity and environmental conditions influence the practical implementation of the monitoring programme.

3.6 Step 4: Legal compliance



3.6.1 WULA conditions

The WULA requires that samples are collected at authorised monitoring points tied to specific geographic coordinates. Deviations from these coordinates therefore represent a compliance risk.

Figure 3.10 and Figure 3.11 illustrate the errors in latitude and longitude observed when comparing in-field coordinates with WULA-approved locations.

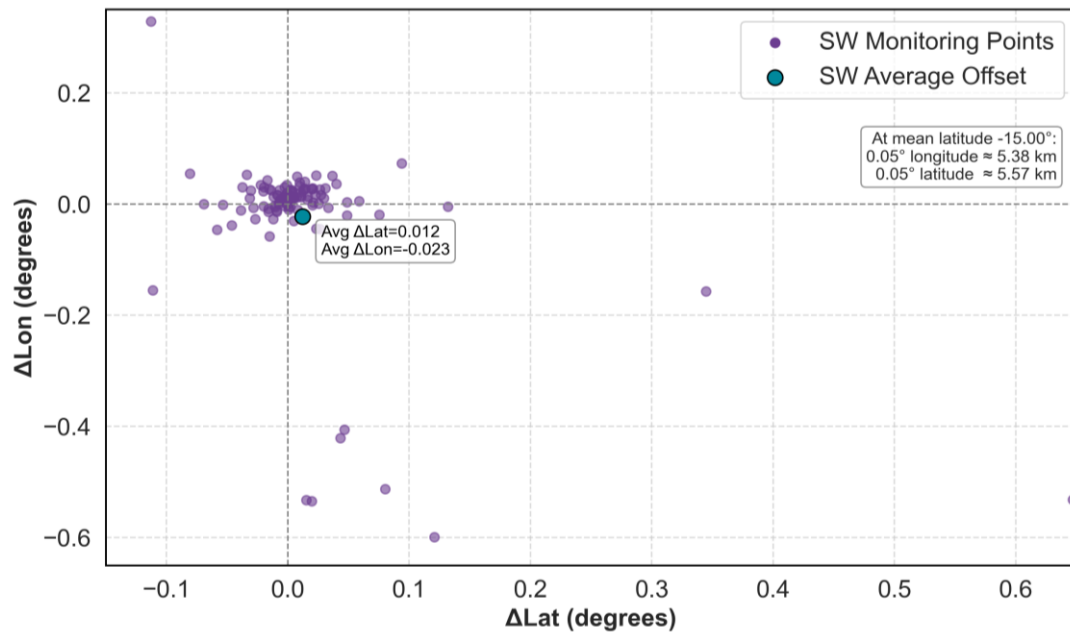


Figure 3.10: Scatter plots of coordinate differences (ΔLat , ΔLon) (Surface water).

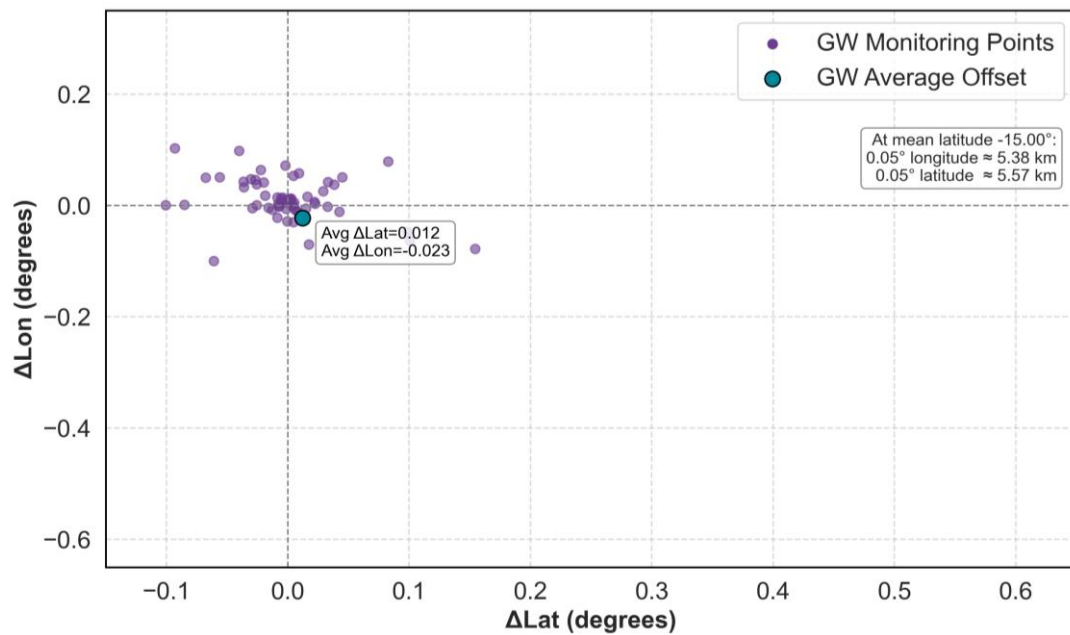


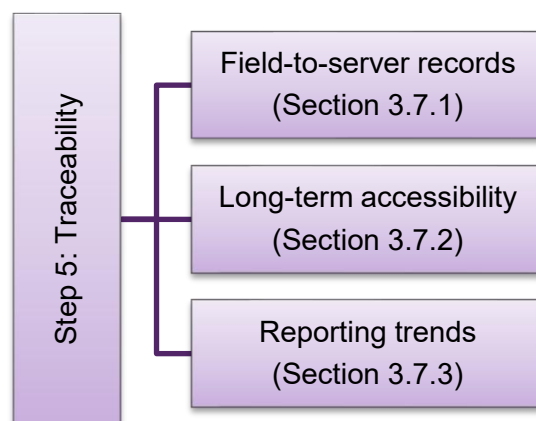
Figure 3.11: Scatter plots of coordinate differences (ΔLat , ΔLon) (Groundwater).

While most sites remain within acceptable limits, repeated or systematic deviations highlight vulnerabilities in compliance reporting. These discrepancies emphasise the importance of automated metadata capture and verification.

3.6.2 Reporting to DWS

The preparation of bi-annual submissions to the DWS was previously hindered by reliance on paper-based forms and manual collation. With server-based storage, datasets can now be exported in structured formats suitable for reporting. This has reduced administrative workload, minimised transcription errors, and supported timely submission of compliance reports.

3.7 Step 5: Traceability



3.7.1 Field-to-server records

All monitoring data captured in the field is uploaded to the web-based server, creating a permanent record of sampling events. Unlike paper forms that could be misplaced, the server provides a reliable archive of field activities.

GW monitoring points in particular highlight the importance of accurate coordinate capture for traceability. As shown in Figure 3.12, GW monitoring points are often minimally visible in the field, typically a narrow PVC casing with a small concrete or steel collar surrounded by dense vegetation. Without precise GPS coordinates, locating specific boreholes can become challenging, especially when monitoring points are dispersed across a wide geographical area.

SW monitoring points, shown in Figure 3.13, present a different type of traceability challenge. These sites are typically located within natural drainage lines, channels, or wetland systems where conditions change seasonally. Vegetation growth, sediment deposition, or fluctuating flow levels can alter the accessibility and visual appearance of sampling points over time. Consistent

GPS tagging and photographic documentation are therefore essential to ensure that samples are collected from the same location during each monitoring event.



Figure 3.12: Example of a GW monitoring point.



Figure 3.13: Example of a SW monitoring point.

3.7.2 Long-term accessibility

Data stored on the server can be exported into Excel or PDF reports and retrieved for historical analyses, audits, or compliance verification. Each entry is traceable to the specific sampler, site,

and date, strengthening accountability and ensuring that sampling activities align with licensed monitoring requirements. In addition, photographs taken during sampling are automatically linked to each record, providing verifiable visual evidence of site conditions on the day of sampling.

Figure 3.14 illustrates an example of the online dashboard used to log and synchronise field sampling data. Each row represents a distinct sampling event, displaying parameters such as sample status, surface-water level, pH, EC readings, and environmental inspection photographs. This digital traceability framework ensures that all sampling actions are time-stamped, location-verified, and permanently stored for future reference during audits, investigations, or operational reviews.



	Date	Location	User	Choose Site	Choose monitoring point (SW)	Save location	Take a field photo	Choose sampling status	Surface water level	Insert pH Reading	Insert EC reading	Visual Environmental Inspection	Take a photo of the environment	Actions
	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
	2023-08-01	-15.0227 ; -150.052			MP SW 47	-14.9988 ; -149.944	SurfaceWater_fieldphoto	Sample not taken	Dry				SurfaceWater_environmentphoto	
	2023-08-01	-15.0142 ; -150.137			MP SW 104	-14.9401 ; -150.166	SurfaceWater_fieldphoto	Sample Taken	Low				SurfaceWater_environmentphoto	
	2023-08-02	-14.9841 ; -150.004			MP SW 106	-14.9841 ; -150.189	SurfaceWater_fieldphoto	Sample Taken	Low				SurfaceWater_environmentphoto	
	2023-08-02	-14.9948 ; -150.004			MP SW 101	-14.9948 ; -150.004	SurfaceWater_fieldphoto	Sample Taken	Full				SurfaceWater_environmentphoto	
	2023-08-02	-14.9839 ; -149.978			MP SW 102	-14.9828 ; -149.978	SurfaceWater_fieldphoto	Sample Taken	Full				SurfaceWater_environmentphoto	
	2023-08-02	-14.9838 ; -149.978			MP SW 99	-14.9828 ; -149.978	SurfaceWater_fieldphoto	Sample Taken	Low				SurfaceWater_environmentphoto	
	2023-08-02	-14.9838 ; -149.978			MP SW 100	-14.9828 ; -149.978	SurfaceWater_fieldphoto	Sample Taken	Full				SurfaceWater_environmentphoto	
	2023-08-02	-14.9838 ; -149.978			MP SW 98	-14.9828 ; -149.978	SurfaceWater_fieldphoto	Sample Taken	Full				SurfaceWater_environmentphoto	
	2023-08-02	-15.1590 ; -149.764			MP SW 14	-15.1518 ; -149.774	SurfaceWater_fieldphoto	Sample Taken	Low				SurfaceWater_environmentphoto	
	2023-08-02	-15.1359 ; -149.803			MP SW 122	-15.1253 ; -149.791	SurfaceWater_fieldphoto	Sample Taken	Low				SurfaceWater_environmentphoto	

Figure 3.14: Example of online dashboard for displaying synced field-sampling logs.

3.7.3 Reporting trends during digital transition

Although not all samples were captured directly through the mobile application, the overall number of laboratory reports increased notably during the period in which the mobile monitoring tool was implemented. This pattern suggests that the digital system improved traceability and data transfer between field sampling and laboratory reporting.

SW records show that the total number of laboratory reports received increased from 875 during the paper-based period (January 2021–April 2022) to 1 090 during the digital period (May 2022–August 2023), equivalent to an increase in monthly averages from 55 to 68 reports (Table 3.2).

Table 3.2: Comparison of paper-based and digital reporting periods for SW.

SW	Paper reporting period	Digital reporting period
Reporting period	January 2021–April 2022	May 2022–August 2023
Total Laboratory reports received	875	1090
Average per month	54.7	67.1
Duration	16 Months	16 Months

For GW, the total number of reports remained relatively consistent, with 385 during the paper period and 360 during the digital period (Table 3.3). This stability is expected because GW monitoring points are scheduled on a four-month rotation, meaning each borehole is sampled only three times per year. In cases where access restrictions or other field constraints occurred, sampling was deferred to the following month, in line with the site’s monitoring protocol.

Table 3.3: Comparison of paper-based and digital reporting periods for GW.

GW	Paper reporting period	Digital reporting period
Reporting period	January 2021–April 2022	May 2022–August 2023
Total Laboratory reports received	385	360
Average per month	24.1	22.5
Duration	16 Months	16 Months

Overall, the steady GW reporting frequency and the increase in SW reports suggest that the introduction of mobile monitoring improved traceability, data completeness, and coordination between field activities and laboratory reporting, even when sampling intervals differed between monitoring types.

3.8 Step 6: Reporting

Step 6: Reporting

Reporting has significantly improved through the adoption of the mobile application and web-based system. Internally, reports can now be generated to support operational planning,

environmental management reviews, and decision-making. The system also enables the identification of redundant monitoring points, for example, where samples are located in close proximity to one another. Such information can support future WULA amendment applications, ensuring that monitoring remains efficient while still fulfilling regulatory requirements.

Externally, structured data exports simplify bi-annual submissions to the Department of Water and Sanitation (DWS) and enhance the reliability of reported information. Compared to the previous paper-based system, the current approach reduces administrative effort, minimises errors, and provides greater transparency.

3.9 Comparison between in-field vs mobile logged

To evaluate the reliability and traceability of the newly implemented mobile monitoring system, sampling dates recorded on the mobile application were compared with those documented on in-field sampling registers for the overlapping period between May 2022 and August 2023. The comparison assessed the extent to which manual written sampling events corresponded to those logged digitally.

The SW sites are monitored more frequently than GW sites and therefore the assessment focused exclusively on the SW dataset. Monthly monitoring provided a robust basis for assessing digital capture validity.

Table 3.4: Comparison of in-field versus mobile logged sampling records.

System view	Matched (n, %)	Only in system (n, %)	Unreconciled (n, %)
In-field (n=1614)	383 (23.7%)	1009 (62.5%)	222 (13.8%)
Mobile (n=880)	392 (44.5%)	259 (29.4%)	229 (26.0%)

A total of 1 614 in-field and 880 mobile sampling records were analysed to evaluate consistency between the in-field sampling records (paper based) and digital monitoring systems. Matching was performed using both the sampling dates and the monitoring point name to determine whether each record represented the same sampling event.

As shown in Table 3.4, only part of the data overlapped between the two systems. From the in-field perspective, 383 samples (23.7%) matched exactly with the mobile dataset, while 1 009 (62.5%) appeared only in the paper register and 222 (13.8%) were unreconciled. From the mobile side, 392 samples (44.5%) corresponded directly with the in-field records, 259 (29.4%) appeared only in the mobile database, and 229 (26.0%) could not be reconciled on the same date.

To understand the extent of the unreconciled records, the sampling dates for the corresponding monitoring points were compared to determine the number of days separating the two entries. Differences were treated as absolute values, since the offset could occur before or after the official date.

As shown in Table 3.5, most discrepancies were small, with more than half of the mismatched records differing by only one day (53% of in-field and 54% of mobile entries). Smaller proportions were two to four days apart, while roughly one-fifth (21–23%) of the records differed by more than five days.

These short-term differences suggest minor delays in data entry rather than missed sampling events. However, the longer offsets (>5 days) indicate irregularities in how sampling dates were captured, either through early collection for the next month's schedule or retrospective data logging.

Table 3.5: Distribution of date differences between in-field and mobile records.

Days out (Difference)	In-field records (n, %)	Mobile (n, %)
1	118 (53%)	119 (54%)
2	13 (6%)	15 (7%)
3	28 (13%)	26 (11%)
4	16 (7%)	16 (7%)
>5	47 (21%)	53 (23%)
Total	222	229

In addition to the date discrepancies observed between systems, several instances of duplicate sampling were also identified, providing further evidence of inconsistent date recording.

Duplicate entries appeared in a few months, including July, August, and September 2022, and again in April, June, and July 2023, with the highest number recorded in December 2022, where 25 samples were logged more than once. These repeats were mostly from the same monitoring points and are likely linked to samples being taken for the upcoming month before the current month's schedule was complete.

In the paper records, duplicates were found in January 2022 (8 samples) and February 2023 (11 samples). These cases suggest that the sampler entered different dates for the same sampling event, possibly when catching up on missed forms or when sites were revisited later in the month.

These results indicate that, while both systems were active during the transition period, the adoption of the mobile platform was not yet complete. A large proportion of samples continued to be recorded manually, while some field data were captured only on the mobile application. The discrepancies between systems highlight gaps in data synchronisation and verification procedures, emphasising the need for a unified entry and validation process that integrates field capture, laboratory submission, and reporting.

Overall, the comparison between in-field and mobile records highlights clear improvements in data availability through digital monitoring but also reveals inconsistencies that affected full traceability. The overlap between systems confirms that the digital application was used alongside the paper process rather than as a complete replacement, resulting in duplication and gaps in record alignment. The small date differences observed in most cases suggest that sampling was conducted as scheduled but that data were captured or entered at slightly different times. However, the larger discrepancies and duplicate entries indicate that procedural habits from the manual system, such as early or delayed logging, carried over into the digital phase. Together, these results show that the main challenge during the transition was not the technology itself but the consistency of field practice and data management. Strengthening coordination between sampling, data entry, and laboratory submission is therefore essential to achieve a fully traceable and reliable monitoring record.

3.10 Validation of study

The aim of this study was to evaluate and improve water quality data management compliance in the gold mining operation. The research was guided by four objectives, and each is reviewed here to validate the applicability and effectiveness of the methodology developed.

Objective 1: Evaluate existing methodologies for developing and integrating a new water quality monitoring data management system.

The literature review and methodology (Chapter 2) provided the foundation for developing suitable solutions, ranging from fully automated to hybrid systems using mobile devices. Based on the study findings, using a mobile application provided a practical and affordable alternative to a fully automated system. This confirms that the chosen methodology was appropriate for integration into the case study operation.

Objective 2: Identify and interpret the requirements set out in the Water Use Licence Application (WULA) framework in gold mining.

The analysis of WULA conditions, together with the geographical comparison of in-field and WULA monitoring points, confirmed that compliance depends on accurate site identification, consistent sampling schedules, and reliable reporting. The mobile application directly addressed these requirements by standardising metadata capture, linking each record to WULA-prescribed coordinates, and supporting structured reporting outputs.

Objective 3: Develop a structured reporting system that ensures traceability of sampling activities and that can be seamlessly transferred to a centralised database.

Traceability was achieved through server-based storage of all field entries, including metadata and photo evidence. The system allowed in-field reports to be exported into Excel and PDF formats, supporting both internal decision-making and external submission to the Department of Water and Sanitation. Retrieving historical data for compliance checks confirmed that the structured reporting system worked well and aligns with the objective of the study.

Objective 4: Incorporate the new data management system into the current monitoring process to validate its applicability and effectiveness.

The one-year test run demonstrated that the mobile application could be integrated into the existing monitoring framework without disrupting field operations. A total of 771 surface water and 133 groundwater samples were captured with complete location data, which enabled verification of geographical accuracy and improved reporting. Compared to the previous paper-based and spreadsheet-driven system, the new mobile application significantly reduced manual data entry, improved traceability, and minimised the risk of transcription errors. Although some challenges remain, such as occasional GPS errors or missing location entries, the system proved effective in enhancing efficiency, accuracy, and legal compliance.

Overall, the study successfully achieved all four objectives, validating the applicability of the methodology.

3.11 Conclusion

Chapter 3 applied the proposed monitoring methodology to a large-scale gold mining operation in South Africa, focusing on data management, data quality, mining context, legal compliance, traceability, and reporting. The results demonstrate how the adoption of a digital, mobile-based monitoring system can strengthen the overall reliability of the programme while also revealing the limitations that persist in practice.

Data management was significantly improved by replacing paper-based systems with mobile application capture and web-based storage, providing more efficient access to field information. Data quality benefited from standardised dropdown selections, automatic metadata recording, and photo documentation, though errors still occurred due to dropdown mis-selections, inaccessible sites, or GPS variability. Geographical comparisons between in-field and WULA coordinates showed that most points aligned closely, but deviations were evident in both surface water and groundwater datasets. These discrepancies were traced to a combination of licence inaccuracies, sampler behaviour, and device error.

From a mining perspective, the results highlighted how operational constraints, such as site access or overlapping monitoring points, influence data collection consistency across the five mines. Legal compliance was strengthened by standardising data capture at prescribed monitoring points and by improving the structure and accuracy of reporting to the Department of Water and Sanitation. Traceability and long-term accessibility were also enhanced through server-based storage, which preserves metadata and photographic evidence for audits and legal purposes.

In alignment with the case study methodology presented in Figure 1.8, Figure 3.15 provides a detailed representation of Chapter 3 phase, illustrating how the results were compared with the theoretical framework and used to refine the monitoring methodology.

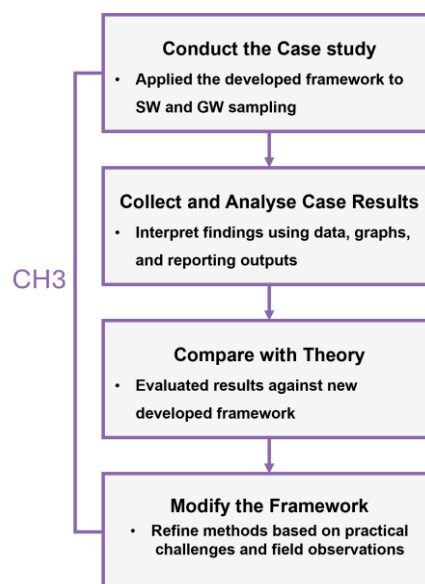


Figure 3.15: Detailed representation of Chapter 3 phase of the case study methodology.

Overall, the one-year test run demonstrated that the mobile application and server-based system provide a practical, scalable solution for improving compliance monitoring in mining operations.

While challenges remain, particularly in addressing coordinate inaccuracies and ensuring complete location metadata, the results show that digital monitoring systems can enhance efficiency, accuracy, and accountability. These findings form the basis for the conclusions and recommendations presented in Chapter 4.

CHAPTER 4 CONCLUSION AND RECOMMENDATIONS

4.1 Preamble

This chapter discusses the key findings and reflects on the significance of the study within the context of water quality monitoring in South African gold mining operations. It revisits the research methodology outlined in Section 1.10 and evaluates the methodology and results presented in Chapters 2 and 3. The chapter concludes by offering recommendations for practice and identifies potential directions for future research.

4.2 Summary

South Africa is a water-stressed country with an unevenly distributed water supply. Although the mining sector accounts for only about 2% of national water use, its activities can have disproportionate impacts on water quality. The National Water Act (Act 36 of 1998) provides the legal framework for regulating water use, with the DWS responsible for overseeing the management of water resources across industries. Within this framework, gold mining companies are required to comply with the conditions of their WULs or WULAs.

To explore ways of strengthening compliance and ensuring that reliable, quality data is readily available for decision-making, a literature review was undertaken. The review examined approaches to water quality monitoring, with particular emphasis on data management, legal compliance, and traceability, to identify practices and methodologies that could support gold mining operations in meeting their WULA obligations.

The results of this study show that digitised and standardised monitoring systems can significantly improve the accuracy, traceability, and accessibility of water quality data in the mining sector. By moving away from paper-based records to mobile capture and web-based storage, data management was streamlined and the risk of human error reduced. Data quality was further enhanced by features such as dropdown menus, automatic metadata recording, and photographic evidence, although limitations remained in relation to GPS variability, sampler behaviour, and physical access to sites. From a legal compliance perspective, the system provided a structured way to align monitoring activities with licensed points, while also highlighting discrepancies between field conditions and WULA coordinates.

Quantitatively, the introduction of the mobile monitoring framework resulted in measurable improvements across several performance indicators. The number of surface water laboratory reports increased from 875 during the paper-based period to 1 090 during the digital period,

representing an average monthly increase of approximately 24%. Although groundwater reports remained relatively stable (24 to 22 per month), this trend aligns with the mandated four-month sampling frequency. Record matching between in-field and mobile datasets improved traceability, while automated uploads ensured that 100% of captured samples were time-stamped, geo-referenced, and user-verified. Collectively, these results demonstrate that the digital transition enhanced data completeness, reliability, and accessibility for regulatory compliance and long-term environmental management.

4.3 Study limitations and recommendations

Although this study was limited to a single gold-mining operation in South Africa, it successfully demonstrated how a digital monitoring framework can enhance the accuracy, traceability, and efficiency of environmental data collection. The nature of the case allowed for a detailed evaluation of implementation challenges and the potential for improvement. The main limitation relates to the relatively short monitoring period, which restricted long-term evaluation of data reliability and system performance. Despite these constraints, the results clearly highlight how targeted procedural and technological adjustments could substantially strengthen monitoring outcomes.

A key finding from this research is that the structure and distribution of sampling responsibilities play an essential role in ensuring data accuracy. In future monitoring programmes, the workload should be distributed among multiple samplers to reduce fatigue and human error, particularly in areas where access is difficult or environmental conditions are unpredictable. The accuracy of recorded information can be further improved by separating the roles of field sampling and digital data entry. When the same person performs both tasks, errors can easily go unnoticed, whereas independent verification between samplers and data capturers provides an added layer of quality control.

The study also revealed that geolocation accuracy remains a critical area for improvement. Earlier monitoring phases lacked precise GPS data, which limited the ability to verify that samples were collected at the exact sites specified in the WULA. Implementing more reliable geotagging and rerunning the monitoring process with this enhancement would make it possible to measure spatial accuracy and assess whether improved location data translates into more representative water-quality results. Establishing a clear link between sampling precision and laboratory outcomes would provide stronger evidence of the effectiveness of digital monitoring and support compliance assurance.

Another important consideration is the consistency of sampling schedules. Comparing the planned monitoring programme with the actual collection dates can reveal where samples were taken late, early, or missed altogether. These timing inconsistencies can influence data quality and compliance reporting. Understanding and addressing the reasons behind them, whether related to logistics, weather, or operational constraints, will help to strengthen the reliability and regularity of future monitoring cycles.

Beyond these operational refinements, a stronger connection should be established between field sampling data, laboratory results, and reporting workflows. Integrating laboratory data with the sampling schedule on a unified digital platform would create a single, traceable record from collection to analysis. By developing automated dashboards that consolidate all available data and highlight discrepancies or non-conformances, stakeholders can be notified promptly of issues that require intervention. This proactive communication loop would ensure that data gaps, sampling errors, or exceedances are addressed directly by the responsible teams, fostering accountability and improving overall programme responsiveness.

Overall, the findings of this study suggest that improving personnel structure, verification practices, geolocation accuracy, and the consistency of sampling schedules can greatly enhance the reliability and compliance value of digital monitoring systems. When combined with automation and predictive tools, these refinements can transform environmental monitoring from a reactive, paper-based process into a proactive, data-driven mechanism for protecting South Africa's water resources and ensuring responsible water use within the mining industry.

4.4 Reflection on implementation

The integration of the new mobile data management system achieved the study's aim of improving accuracy, traceability, and efficiency in water-quality monitoring. One of the major improvements was the automatic recording of date, user, and location, which resolved previous issues with manual entry errors. However, several challenges were encountered during implementation. The sampler initially struggled with the digital platform due to limited technical experience, requiring multiple training sessions and on-site assistance. Safety risks also arose when illegal mining activities prevented the use of mobile devices at certain points, as they could easily be stolen. Technical issues such as GPS signal loss and location settings occasionally switching off further complicated fieldwork. Despite these challenges, the system proved reliable once established and significantly reduced transcription errors, improved data verification, and streamlined reporting across all sites.

In reflecting on the overall implementation several factors contributed to a successful outcome of the improved monitoring framework:

- A clearly defined monitoring problem ensured that the system was designed to address real operational requirements.
- Integrating WULA locations with in-field mobile data created a unified dataset that enabled accurate spatial comparison and traceability.
- Automatic recording of date, time and location enhanced accountability and substantially reduced human error.
- The centralised database structure supports long-term monitoring, compliance verification, and future automation of reporting processes.

4.5 Study Conclusion

In conclusion, the research demonstrates that a digital monitoring framework can significantly strengthen the reliability and accountability of water quality monitoring in gold mining operations. By enhancing data management, improving quality assurance, and supporting regulatory compliance, such systems contribute to more accessible and effective management of South Africa's scarce water resources.

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APPENDIX A SCATTER PLOTS

This appendix presents selected scatter plots comparing WULA monitoring points with their corresponding in-field average coordinates, calculated from multiple sampling events. The plots include annotated distances between the official licence points and the averaged field positions, highlighting deviations in location accuracy. Four representative groups are provided as examples (Figures A.1–A.4).

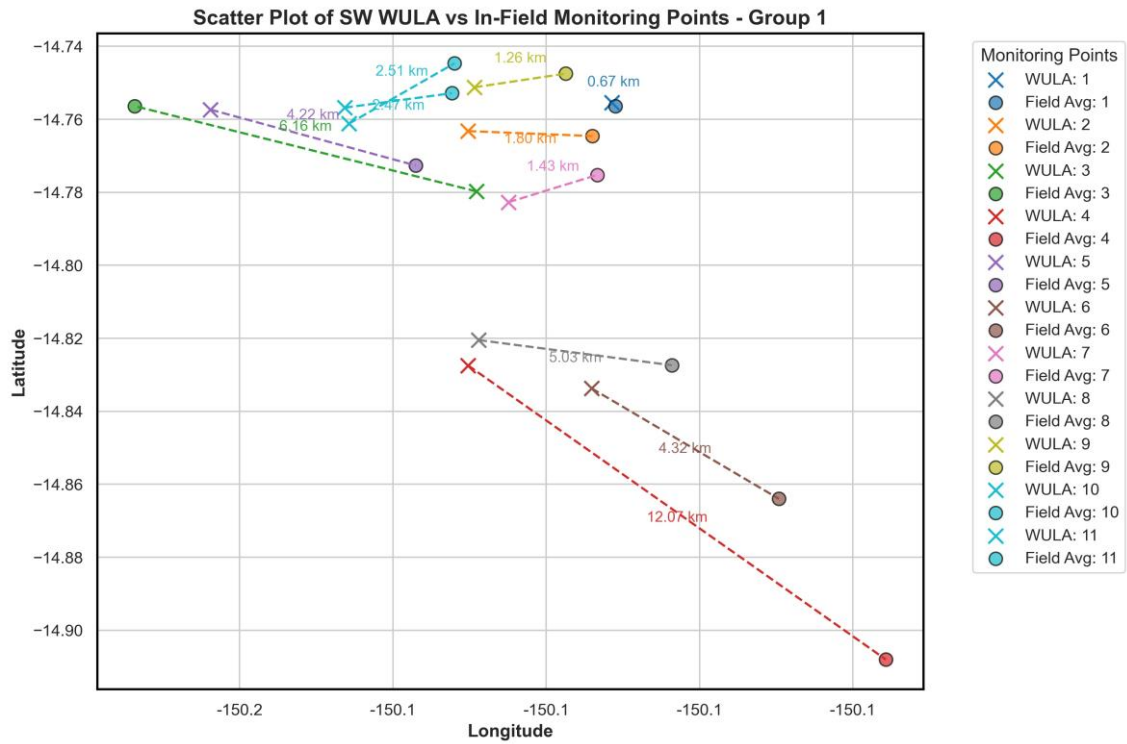


Figure A.1: Scatter plot of SW WULA vs in-field monitoring – Group 1

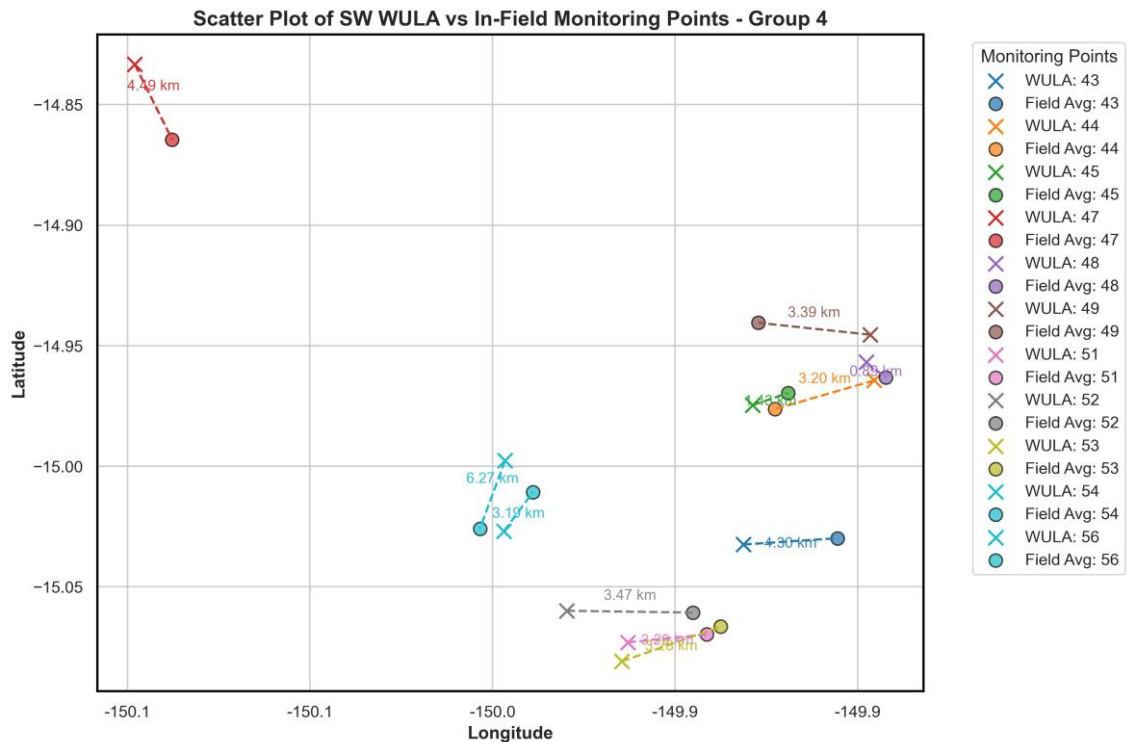


Figure A.2: Scatter plot of SW WULA vs in-field monitoring – Group 4

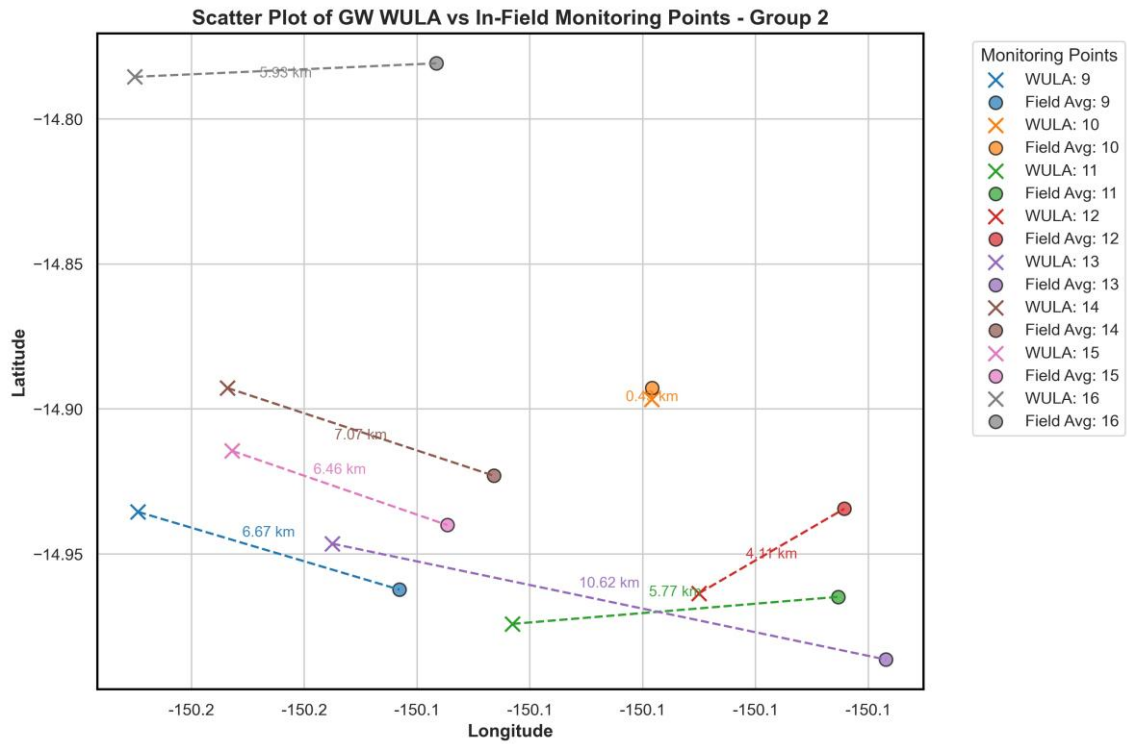


Figure A.3: Scatter plot of GW WULA vs in-field monitoring – Group 4

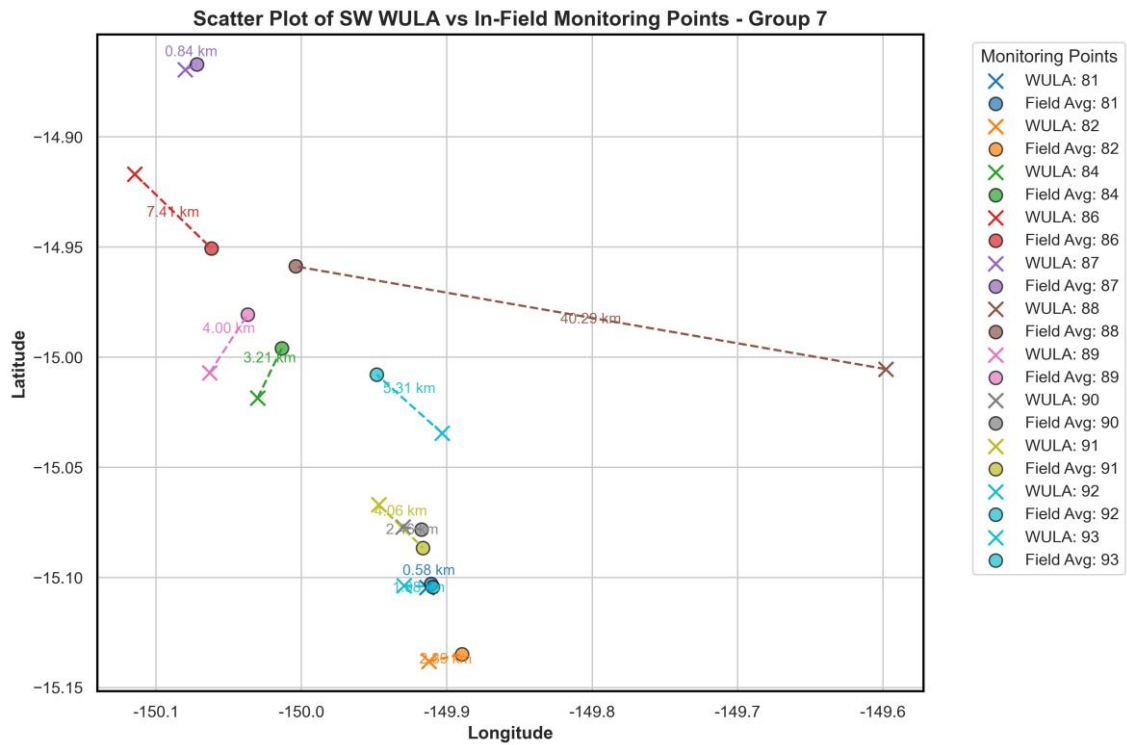


Figure A.4: Scatter plot of GW WULA vs in-field monitoring – Group 7