# Water balance development for legal compliance of gold mines in South Africa

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# Abstract

**Title:** Water balance development for legal compliance of gold mines in South Africa

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South Africa is experiencing water scarcity due to the increase in water demand and decrease in water supply. A predicted shortfall of 17% by 2030 is prompting stricter enforcement of the National Water Act number 36 of 1998, compelling all large-scale water users to obtain a water use license. One of the main requirements for a water use license and the application thereof is a detailed, accurate water balance. For a water balance to be compliant, it should be sufficiently detailed and accurate within 10% over a process unit and 15% per mining operation.

Numerous gold mines in South Africa do not have water use licenses, leaving them vulnerable to possible consequences such as mining activities which are forced to stop. Existing water balances of gold mines are also not compliant with the regulations set out by the Department of Water and Sanitation, making the application process for a water use license difficult.

This thesis focuses on the development of a water balance methodology that can be applied to any water system at a gold mine. The methodology aims to produce water balances that are fully compliant and practical for use in the gold mining industry. Process units of the gold mining process are developed as modules which can then be linked to complete the flow for any water balance system. These process units include shafts, processing plants, tailings storage facilities, water bodies, backfilling plants, and waste rock dumps.

The application of this methodology was done on a gold mining operation in South Africa. After applying this methodology to the mining operation, accurate and detailed water balances were obtained that are all within a 10% variance over a process unit and 15% over the mining operation. These water balances are therefore fully compliant with the requirements for a water use license set out by the Department of Water and Sanitation.

Water use licenses are becoming increasingly important for South African gold mines. Detailed and accurate water balances are a mandatory requirement in the water use license application process. The methodology developed in this thesis proves to deliver water balances that are detailed and accurate and comply with all the requirements for a water use license application.

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# Nomenclature

| | |
|---|---|
| Backfill | Tailings that have been prepared to refill excavated voids underground. |
| Backfilling plant | Where tailings are treated or prepared to be sent underground as a means to fill mined-out voids. |
| Lined dam | A process water dam that has been lined with concrete to prevent seepage. |
| Processing plant | Where raw ore is treated or prepared to extract the gold. |
| Process water dam | Storage of water that has been used within mining operations for reuse. |
| Reclamation plant | Where waste rock is treated or prepared to extract the gold. |
| Return water dam | A dam which stores water recovered from the tailings storage facility until the water can be reused by the processing plant. |
| Shaft | A vertical access hole that stretches underground to the ore. From the shaft miners, supplies, water, and air are conveyed to get access to the ore. |
| Tailings | Waste material left after gold is extracted from ore. |
| Tailings storage facility | A structure built for the purpose of storing uneconomical ore from the milling process. |
| Waste rock | Waste rock is removed with the ore and consists of rock and gold in concentrations too low for economic recovery. |
| Waste rock dump | Large accumulations of waste rock. |
| Water treatment plant | A facility which treats polluted water to make it appropriate for reuse or discharge. |

# List of Abbreviations

| | |
|---|---|
| BPG | Best practice guideline |
| DWAF | Department of Water Affairs and Forestry |
| DWS | Department of Water and Sanitation |
| EMP | Environmental management plant |
| IWWMP | Integrated water and waste management plan |
| NWA | National Water Act |
| ROM | Run of mine |
| RWD | Return water dam |
| SA | South Africa |
| TSF | Tailings storage facility |
| WRD | Waste rock dump |
| WTP | Water treatment plant |
| WUL | Water use license |
| WULA | Water use license application |

# INTRODUCTION AND LITERATURE

## 1.1 Preamble

South Africa (SA) is a water scarce country and consumes water at an increasing rate. It is therefore important to understand the water landscape in SA (Section 1.2).

One of the significant water users is deep-level gold mines. To mitigate the impact of the deep-level gold mining sector on water resources, the effective management of water is important (Section 1.3).

Effective water management will also assist in understanding how water is used and affected by mining operations (Section 1.4).

The South African Government has set out legislation which aims to ensure sustainable use of water in SA. The Department of Water and Sanitation developed various regulations and guidelines to guide mines in knowing what the legal requirements imposed on them are, and how to achieve these requirements (Section 1.5).

From the regulations and legislations, it is evident that a detailed and accurate water balance is an essential requirement to achieve compliance. Existing methodologies in developing and quantifying water balance for gold mines are therefore investigated (Section 1.6).

The gaps in literature were identified, which led to the need for the study as well as the objectives for this thesis (Section 1.7). Finally, an overview of this thesis is given in Section 1.8.

## 1.2 Water landscape in South Africa

South Africa (SA) is ranked as the 30$^{th}$ driest country in the world [1]. Despite being a water scarce country, the average water consumption in SA is around 233 litres per capita per day, compared to the international benchmark of almost 180 litre per capita per day [2]. There is therefore significant strain on the already limited water resources in SA. Askham and Van der Poll [3] predict a water supply shortage of 17% by 2030 if the stress placed on the water resources of SA continues.

To understand the water supply and demand landscape, the water resources in SA were firstly identified and investigated. The distribution is shown in Figure 1.

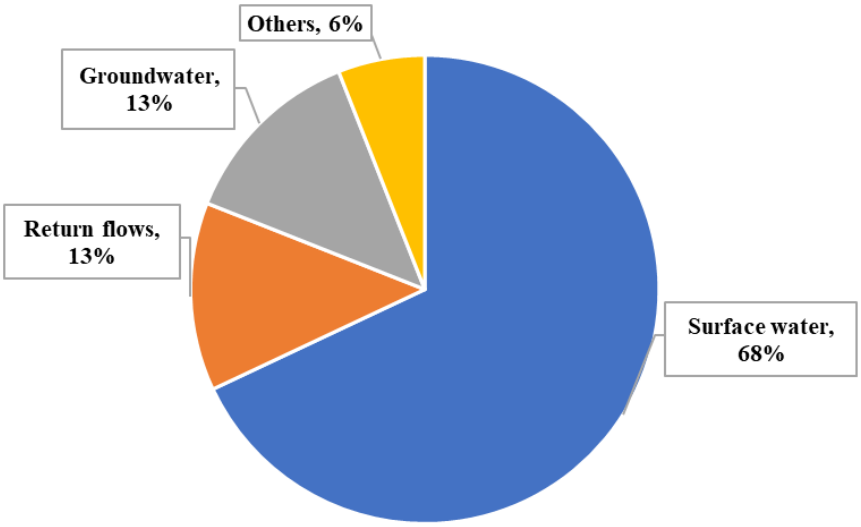


**Figure 1: Water resources in SA [2].**

Surface water, which includes dams and rivers, accounts for roughly 68% of SA's water resources. Return flows include surface and subsurface water that returns to a water source (such as a dam or river) after utilisation. Irrigation, urban domestic uses, and bulk industrial and mining effluents all form part of return flow resources. Return flows make up 13% of the total water resources in SA. Ground water, which mainly includes boreholes, is equally sourced at 13%. Finally, other water resources such as desalination of brackish or seawater accounts for the rest at 6%.

SA currently has a reliable water supply (at 98% assurance of supply) of roughly 15 billion $m^3$ per year from the water resources shown in Figure 1 [2]. The current registered water usage throughout South Africa is, however, significantly higher at 17.3 billion $m^3$ per year. This means that for many supply systems, the water usage exceeds the current reliable water supply [2]. While the water supply can still be met in some cases, the supply assurance decreases and therefore the probability of supply failure increases [1]. The risk of a shortage in water supply throughout the country is therefore imminent.

The water users in SA were secondly investigated to comprehensively understand the water needs of the country. The water users were categorised into seven main sectors which are depicted in Figure 2.

Sectors such as agriculture and farming, and municipal usage face some of the highest risks associated with a shortage in water since these sectors are highly water dependent. These two sectors are the highest consumers of water in SA, as depicted in Figure 2, further emphasising the risk that these sectors are facing.

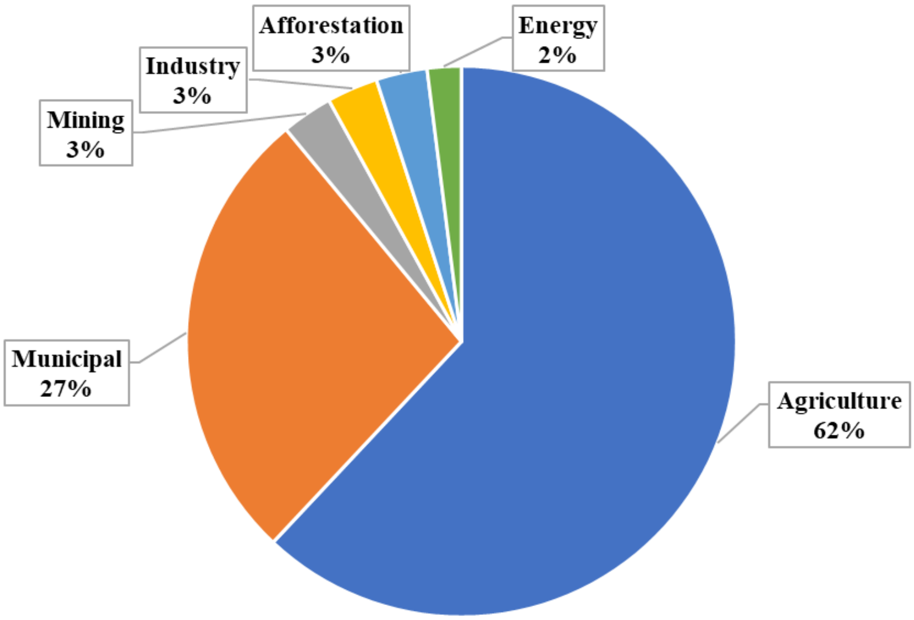


**Figure 2: Water use in South Africa by sector [1].**

The majority (62%) of the water used in SA is by agriculture or farming. Municipal usage is the second largest water user and accounts for 27% of the water used in SA. Municipal water uses includes the distribution of water for private use. Industry, mining and afforestation each consume roughly 520 million m$^3$ per year, equating to 3% of the total water usage respectively. Finally, the energy industry uses the least amount of water with less than 350 million m$^3$ per year (2%).Although the mining sector only accounts for 3% of the water use in SA, mining activities can have a great impact on the integrity of the water resources. Mining operations are at risk of polluting nearby water resources through their operations, even though the mining operations might not be utilising the water resource directly. Therefore, although mining operations only account for 3% of the water used in South Africa, they pose the risk of polluting the available water resources to the extent where it is no longer utilisable by other industries. Effective water management in mining operations will therefore ensure optimal water availability for the mining operations themselves as well as other water users.

The importance of water management in mining is further supported by the critical role that the mining industry plays in the South African economy. Mining also has a significant impact on the country's environmental footprint. The importance of these two areas is highlighted in the following sections.

## 1.3 Importance of water management in the mining industry

In 2020, the mining industry as a whole contributed almost R400-billion to the Gross Domestic Product of South Africa despite challenges faced due to the COVID-19 pandemic [4]. This industry also secures 451 000 jobs throughout SA and contributes R34.7-billion in value-added taxes [5]. Ensuring that mining industries do not face increasing challenges regarding water availability will therefore aid in the preservation of the South African economy.

Despite impeding a decline in the South African economy, effective management of water in mining operations is crucial to ensure sustainable availability for water users in other sectors. The largest concern of ineffective water management in mining operations is the severe impact that mining activities have on water quality and availability. Mining operations affect water quality and therefore pose a significant risk to the integrity of water resources in SA [6]. The contamination of water caused by mining activities results in less water available for other sectors, such as human consumption and environmental processing. Reversing the contamination of the water resources through treatment of the water requires large capital expenditure, which is not always available [7].

Furthermore, mining activities can significantly alter the topographical and hydrological characteristics of mining surface areas, which could lead to a change in surface runoff, soil moisture, groundwater behaviour, as well as evapo-transpiration [8]. All of these effects will have an impact on the water resources in the area.

In addition to ensuring that current mining activities do not negatively impact the available water resources, it is also necessary to ensure that the water requirements for any future mining activities can be met, without placing increased stress on the available water resources.

Mines therefore need to manage their impacts on both surface- and ground-water resources in a sustainable manner, to maintain community and government support for existing and future projects. Management practices which aim to prevent or minimise negative impacts on water resources are fundamental for mining operations to be sustainable [6].

Proactive management of environmental impacts is required from the outset of mining activities. Internationally, principles of sustainable environmental management have rapidly developed in the past few years. Locally, the Department of Water and Sanitation (DWS) and the mining industry have made major strides together in developing principles and approaches for the effective management of water within the industry. This has largely been achieved through the establishment of joint structures where problems have been discussed and addressed through co-operation [8].

To successfully manage water usage, it is critical to understand how water is used within various operations, from where the water is sourced, how it is distributed and how much is used [7].

Different mining industries have different water requirements. Gold mines typically require 2.46 $m^3$ of water per Run of Mine (ROM) ton, where platinum mines and coal mines require 1.68 $m^3$ and 0.79 $m^3$ respectively [9]. Deep-level mines generally have a higher water requirement since water is largely utilised for cooling [10].

More than 95% of the gold generated in SA is sourced through underground mining [11]. Understanding, managing, and improving water systems within the deep-level gold mining sector will therefore be a major stride towards the ultimate objective of ensuring sustainable and reliable water throughout SA. Deep-level gold mines were therefore chosen as the focus of this thesis.

## 1.4 Water use in South African gold mines

Water plays a critical role in the operations of gold processing [12]. Water is used in most gold separation processes and is also the main medium used for the transportation of solids within the processing circuit [13].

Since South African deep-level gold mines are often at great depths such as 3 600 metres below surface level, water is largely utilised for cooling [10]. For example, mines with a cooling requirement of 20 000 kW (the amount of energy that must be removed from the system that will result in adequate cooling) generally require 200 L/s of water to meet this legal cooling requirement. Cooling in deep-level mines is largely obtained through either surface or underground fridge plants. Cooled water is sent underground where the water removes heat from heat sources, preventing these sources from raising the temperature of the air.

Furthermore, water is used to mill the ore and transport the tailings slurry [10]. Milling of gold ore is generally performed with 50 - 70% water by weight [14]. Other uses for water in deep-level gold mines include drilling, dust control, extraction processes of gold, power sources in hydro powered mining operations, and employee amenity areas [10, 15].

Figure 3 shows a typical flow diagram of a deep-level gold mining operation. Distribution between the different process units is indicated with either a blue, grey or brown line. Blue indicates water while grey lines indicate rock. The brown lines represent slurries.

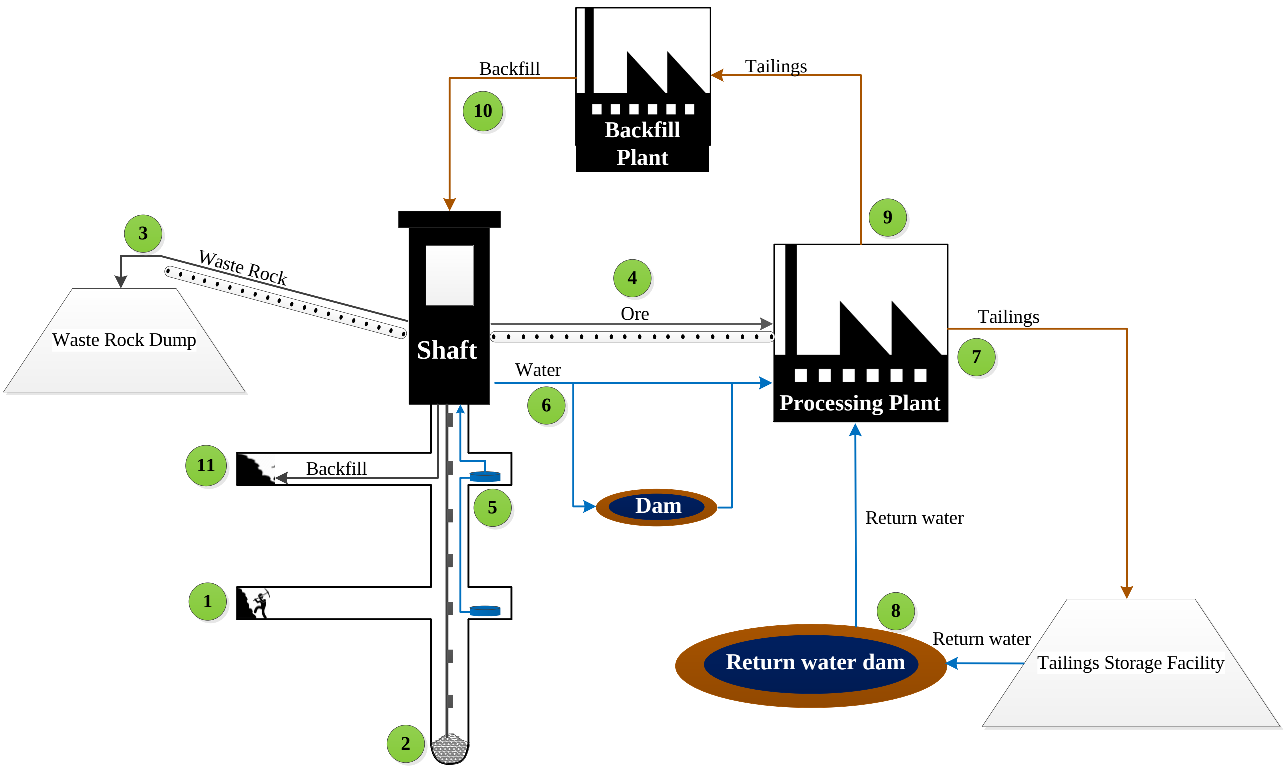


**Figure 3: Typical flow diagram of a deep-level mining operation.**

Generally, deep-level mining operations consist of one or more shafts, where rock is mined and hoisted to the surface. Ore is mined in the stopes (indicated in Figure 3 as point 1). From here, the ore is transported to shaft bottom (point 2), where it is hoisted to the shaft surface. Waste rock, which does not contain a significant concentration of gold, can be sent to a waste rock dump (point 3). Ore, which has a higher concentration of gold, is sent to a processing plant (point 4).

As a result of mining activities and the fissure water entering the mining areas, water accumulates underground and is generally pumped to surface. For very deep mines, it is inefficient to pump the water directly to the surface since the pumping requirements will be too high. The water is therefore pumped in stages, first to higher levels (point 5), and then to surface. The water is then either pumped to a holding dam, or to a processing plant as a water supply (point 6).

After the ore has been processed, the tailings are pumped as a slurry to a tailings storage facility (point 7), after which a percentage of the water in the slurry water can be recovered and gathered in a process water dam (point 8). This water is then pumped to the plant for re-use. When mines send backfill underground, a portion of the tailings is sent to the backfill plant (point 9), after which it is sent to the shaft (point 10) and pumped back into underground cavities (point 11).

Some mining operations have water treatment plants which treat processed water for re-use or disposal. In some cases, processing plants reprocess previously treated tailings or waste rock and are called reclamation plants. New and improved technologies make it economical to extract the value contained in tailings which was deemed not feasible in earlier processing. Rock, with a low ore grade which was considered waste in the past, might also now be economical to process [13].

Each of these specific units within a mining operation acts as its own process and is therefore referred to as a process unit. A list of the process units that can be found in a gold mine operation is therefore:

- Shaft,
- Processing plant,
- Reclamation plant,
- Waste rock dump (WRD),
- Tailings storage facility (TSF),
- Water treatment plant (WTP),
- Backfill plant,
- Unlined water body, and
- Lined dam.

These process units all have individual water requirements which are interlinked to form the water requirements for the complete mining operation. It is therefore important to investigate the water usage for each individual process unit as well as the mining operation as a whole.

## 1.5 Regulations and legislation of water use in South African gold mines

### 1.5.1 Overall water management

After the restructuring of the DWAF in 2009, and the establishment of the DWS in 2014, the DWS became the custodian of SA's water resources. The DWS is primarily responsible firstly for formulating the policies governing this sector, and secondly for facilitating the implementation of these policies [16].

The DWS aims to ensure reliable and sustainable water supply to ensure economic and social development. The DWS also leads and regulates the water and sanitation sectors in SA [2]. They therefore aspire to protect the limited water resources available in the country, ensure that these water resources are managed in an effective way, and align all relative stakeholders towards a vision of integrated water resource management [17]. The DWS is the custodian of two Acts: The National Water Act (NWA) of 1998 and the Water Services Act of 1997.

NWA 36 of 1998 [18] elaborates on the rights and requirements specified in the Bill of Rights in the Constitution of the Republic of South Africa, 1996 (Act 108 of 1996) and is the primary statute providing the legal basis for water management in SA. NWA 36 of 1998 is intended to ensure ecological integrity, economic growth and social equity when managing and using water.

The Act gives the national government the overall responsibility for authority over the nation's water resources in order to: manage the use of water, protect water quality, allocate water, and promote the integrated management of water resources. The Minister of Water and Sanitation is the public trustee of water resources on behalf of the national government and has overall responsibility for all aspects of water resource management in SA.

Chapter 4 of the NWA focuses on the use and authorisation of water. Water uses that require a license are identified in Section 21 of the NWA and the permissible water uses are discussed in Section 22 [19]. In Section 21 a water use that requires a license is defined 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 of water in any manner 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.

A water use must be licensed, unless it is specified under Schedule 1 as an existing lawful use or permissible under general authorisation, or if a responsible authority such as the DWS waives the need for a license. The applications for these licenses, permits, and authorisations are evaluated by the DWS to evaluate the possible impacts on water resources [6].

With respect to Section 21 water uses, mines were required to register their existing lawful uses where these occurred before October 1998 (including old 1956 Water Act exemption permits where applicable). This will involve translating the existing lawful use registrations and permits into new style water use licences. Where new mining developments occur, a new WUL must be applied for at the same time as the mining authorisation application [20].

Part 10 of Chapter 4 of the NWA clearly sets out the consequences to be faced if water users are non-compliant with licensing obligations. These consequences include recovering costs from the unlicensed user or suspending their right to water use. Both these consequences can result in severe economic penalties for the water user [19].

In 2017, the DWS stated that the water use license application can take up to 300 days to process [21]. In February 2021, during the State of the Nation Address, President Cyril Rhamaphosa announced that water use licenses would now be issued within 90 days [22]. This follows a notice by the DWS in 2018 to practise stricter enforcement of water use license compliance, and increasing investigation into mining companies without water use licenses [23].

Consequently, there is increasing pressure on water users to obtain their water use licenses. The Broad-Based Socio-Economic Empowerment Charter for the Mining and Minerals Industry, 2018, amended (“Charter”), was published on 27 September 2018 and commenced on 1 March 2019. This amendment resulted in the industry being required to comply with any obligations imposed on them [24], which includes applying for and maintaining a water use license.

The legal framework guiding the use of water for mining and related activities in SA is contained in Government Notice No. GN704 dated 4 June 1999 [6]. These regulations set out what is required from a mine, but do not provide guidance on how these requirements can be achieved. In an attempt to enable mining operations to achieve these requirements, the DWS developed the Water Resource Protection and Waste Management Strategy. The documentation which set out to describe the water resource protection and waste management in South Africa was developed on different levels, as shown in Figure 4.

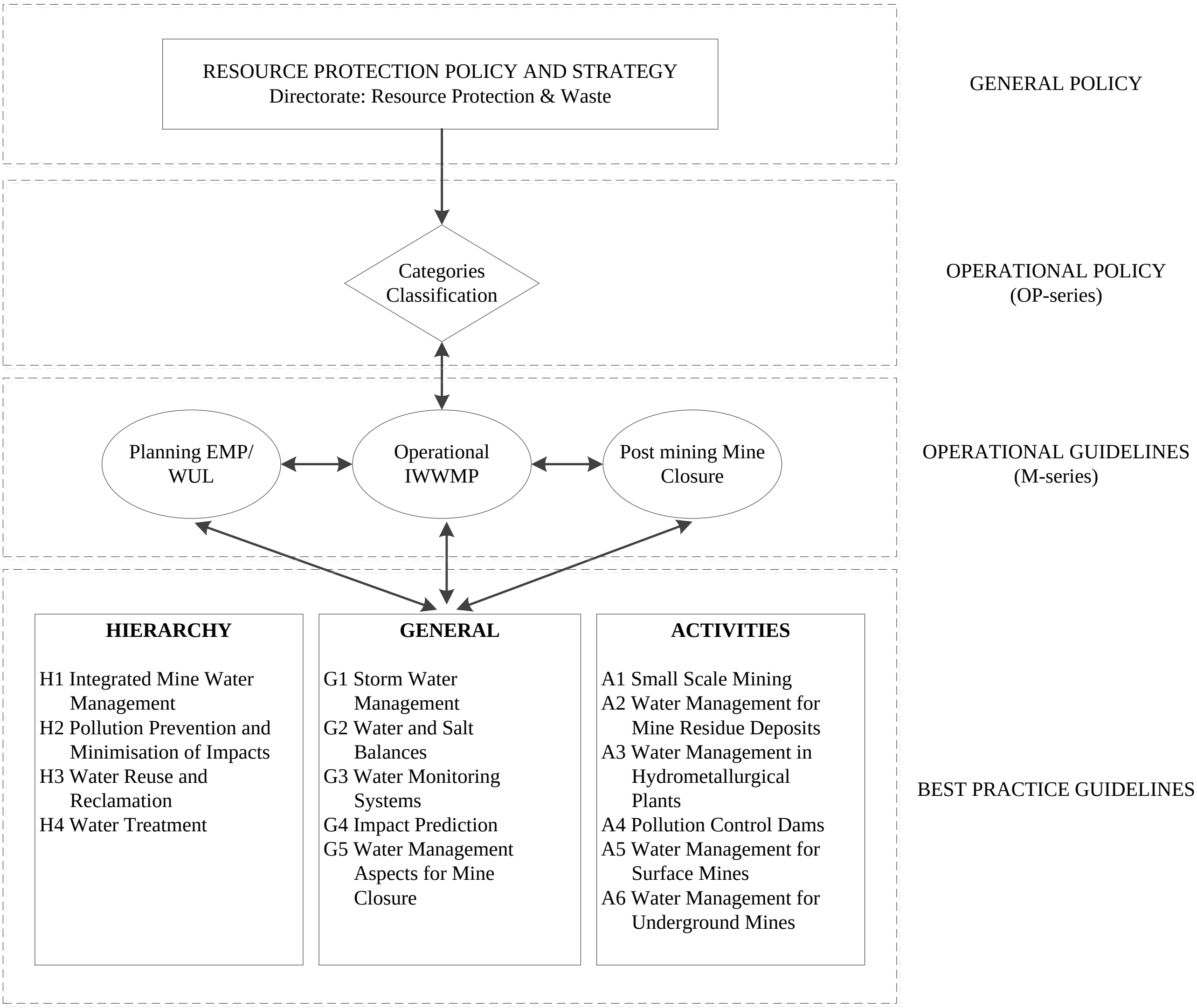


**Figure 4: Schematic diagram of the Mining Sector Resource Protection and Waste Management Strategy [6].**

The Resource Protection and Waste Management Strategy describes the interpretation of policy and legal principles and sets out organisational and functional preparatory measures for resource protection and waste management in South Africa. The four levels of the Strategy in Figure 4 are General Policy, Operational Policy, Operational Guidelines, and the Best Practice Guidelines.

Operational Policy describes the rules applicable to different categories and aspects relating to waste discharge and disposal activities. These activities are categorised based on the potential risk that they pose to the environment. Operational Guidelines describe the requirements for specific documents and are developed for the three phases of the life of mine. Firstly, there is a planning phase in which the mining effects of the planned mining activities are investigated and assessed. An operational phase follows in which the effects of active mining activities are assessed. The final phase is the post-mining closure phase. The planning phase includes Environmental Management Plans (EMPs) and Water

Use Licenses (WUL). These should generally be submitted and approved before any actions which might have an impact on the environment or water resources are commenced.

The Integrated Water and Waste Management Plan (IWWMP) forms part of the operational phase of the Operational Guidelines. The IWWMP was developed to assist industries including mines with the WUL application process in terms of Section 40 (1) of the National Water Act 36 of 1998. The IWWMP assists mines in setting up a water management plan and must be submitted to the DWS together with the Water Use License Application (WULA). The main purpose of the IWWMP is to provide the regulatory authorities with the required information in a structured way, and also to guide and direct the users of the IWWMP on water and waste management [8].

When a mine is nearing its end of mine, appropriate planning regarding the mine closure is critical in ensuring all long-term risks of the mining activities have been mitigated.

Best Practice Guidelines document and describe the best practices for both waste and water management [6].

### 1.5.2 Legal responsibilities

As discussed in the preceding section, where water uses as defined in the NWA [18] are triggered, water use licenses should be applied for and maintained.

A water balance is one of the minimum information requirements for a water use license application [21, 25]. These water balances should be accurate and detailed [6]. To take measurement errors into account, the DWS considers 5 - 10% variance over a process unit and 10 - 15% variance over the mining operation to be adequate. A study by Mckenzie, et al. [26] estimated that the average share of water lost by various municipalities in South Africa was almost 37%. Although this level of variance in a water balance is typical in many industries, these municipalities are seen as non-compliant in terms of water use regulations. These municipalities would benefit by increasing water management since the level of water lost was attributed to leaks, metering errors as well as undocumented consumption. A variance of 15% per region will therefore be achievable if effective water management strategies are in place.

In addition to the ensuring the accuracy of the water balance, these water balances should also be dynamic in nature and should therefore reflect the changes over time throughout the process. The water balances may therefore change frequently in accordance with changes at the site [6].

There are 531 mining projects in SA, 86 of which are gold mining projects (16%). Using the #MineAlert platform [27], in July 2021 it was found that there were only about 33 approved water use licenses for gold mining companies. It is therefore estimated that more than 60% of gold mining projects did not have approved water use licenses at that time, and are therefore non-compliant with the regulations set out by the DWS. These mining operations are at risk of monetary fines or suspension of water use activities [4].

## 1.6 Review of existing water balance systems

The DWS [6] developed Best Practice Guideline (BPG) G2 to aid water users in the development of their water balances. The proposed steps to follow to develop a water balance are shown in Figure 5 to Figure 7.

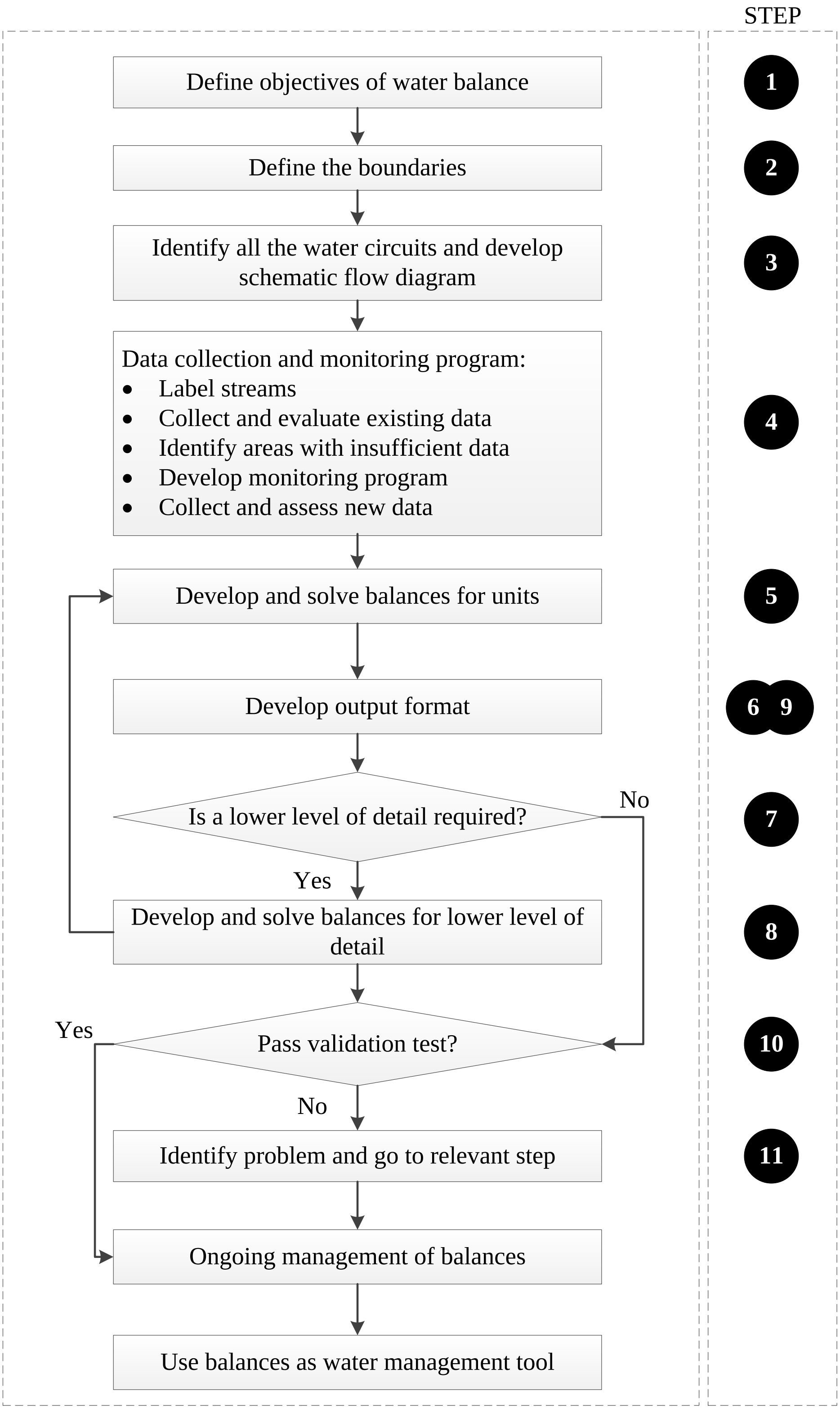


**Figure 5: Flow diagram of water balance development process from BPG G2 [6].**

**Step 1** as shown in Figure 5 is one of the most important steps in the water balance development process. This step will determine what the boundaries, level of detail, and type of water balance is required [6]. The defined objectives should address the purpose of the water balance, which is generally either to be used as a management tool or as an auditing tool to assess legal compliance. If the purpose of the water balance is well defined, the balances' boundaries and level of detail will be evident. The objective of the water balance should also define the areas that the water balance will evaluate, for example underground workings, the mining operation, or only a shaft or plant [6].

To develop a water balance for a mine, boundaries of the system under investigation need to be defined and understood and is therefore considered to be **Step 2** of the process. Generally, boundaries can be defined according to manmade processes such as underground mines or surface plants, or natural phenomena such as catchment and geography [6]. Each of the different boundaries chosen will require a separate water balance. The interconnection between the different balances should be taken into consideration, therefore these water balances should not function in isolation.

The third step (**Step 3**) in the process is to understand the water layout of the systems under investigation. To do this, all process units and flow paths within the boundaries need to be identified. A detailed and accurate schematic flow diagram of the system is required to ensure that all the streams and process units have been accounted for [6].

Furthermore, existing data regarding flows and dam volumes need to be collected. From the existing data, a gap analysis can be done to determine where data is not available, outdated, insufficient, or unreliable. The integrity of a water balance is heavily reliant on the accuracy of the data used, therefore **Step 4** in the process is very important [6].

Once all the available data has been collected, mathematical equations can be used to quantify streams that cannot be measured. This forms part of **Step 5** as shown in Figure 5. The equations of a water balance are based on the conservation of mass theory: *the mass of water that enters the system should be equal to the mass of water that exits the system, assuming that no chemical reactions with the water takes place.* This balance enables the user to solve unknown variables which cannot be measured or easily calculated.

After equations have been set up, the iterative process of developing a balance can be initiated. A preliminary water balance should be developed, after which the accuracy can be assessed. If the accuracy is not acceptable (less than 90% over each unit), the causes of the imbalance should be identified and addressed. A revised water balance can then be calculated, and the accuracy should be assessed again. This process should be repeated until an acceptable level of accuracy is achieved. This iterative process forms part of the initial flow diagram of Step 5 in Figure 5. The additional actions within Step 5 (5.1 to 5.6) are illustrated in Figure 6.

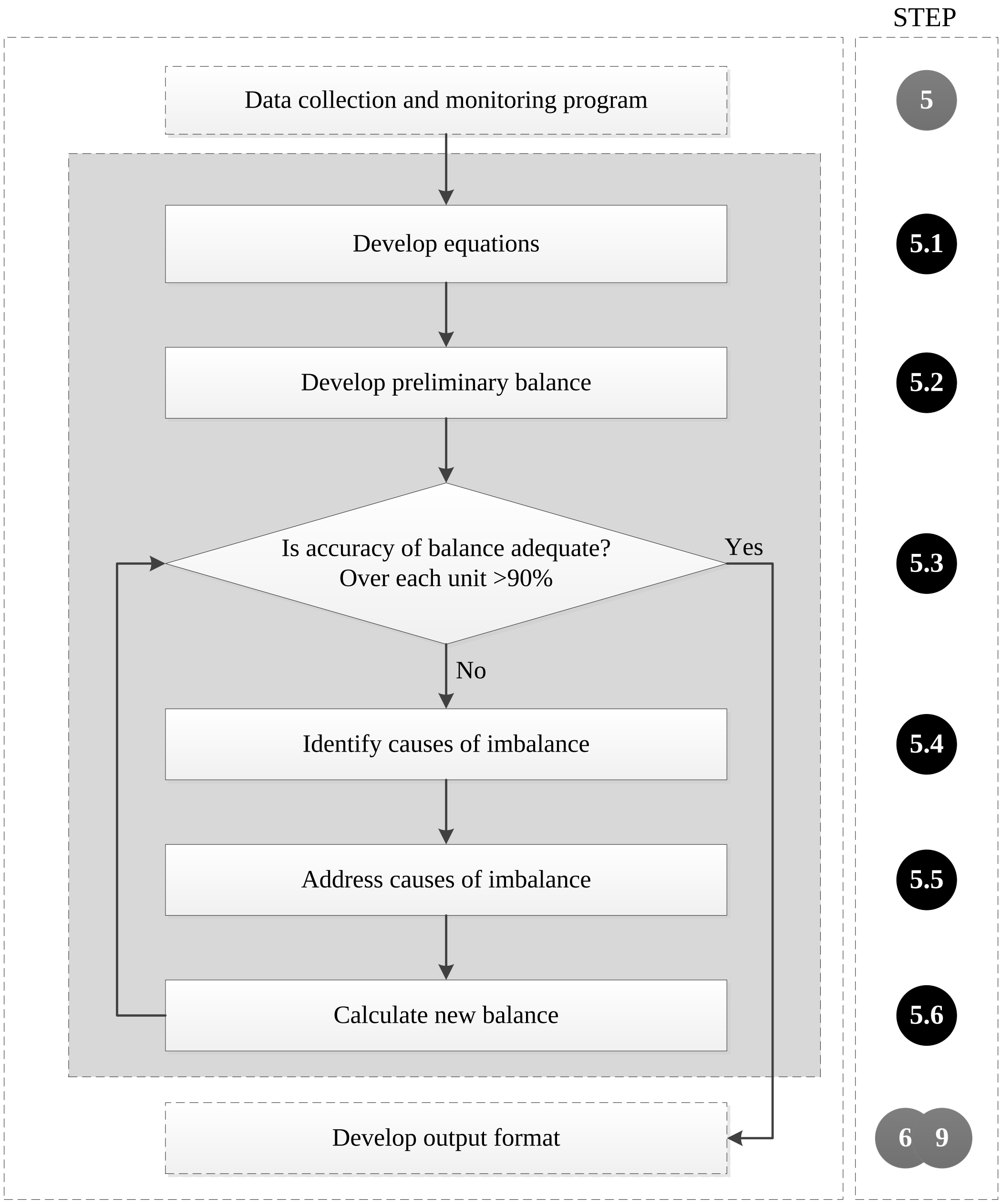


**Figure 6: Flow diagram of process for Step 5 [6].**

The output of Step 5 follows to **Step 6** which is to define an output format. The DWS [6] proposes that schematical and graphical representation of water balances are the most appropriate way of representing the results.

The level of detail of the water balance should be assessed in **Step 7**. The objectives set out in Step 1 should aid the user in the level of detail required. For a lower level of detail, smaller water balances will need to be integrated and calculated in Step 8 of the process. **Step 8** is described in more detail in Figure 7. Converting water balances to a lower level involves linking the high-level water balances, identifying and addressing any inconsistencies, and using an iterative process to get a final lower-level water balance with an acceptable accuracy level [6].

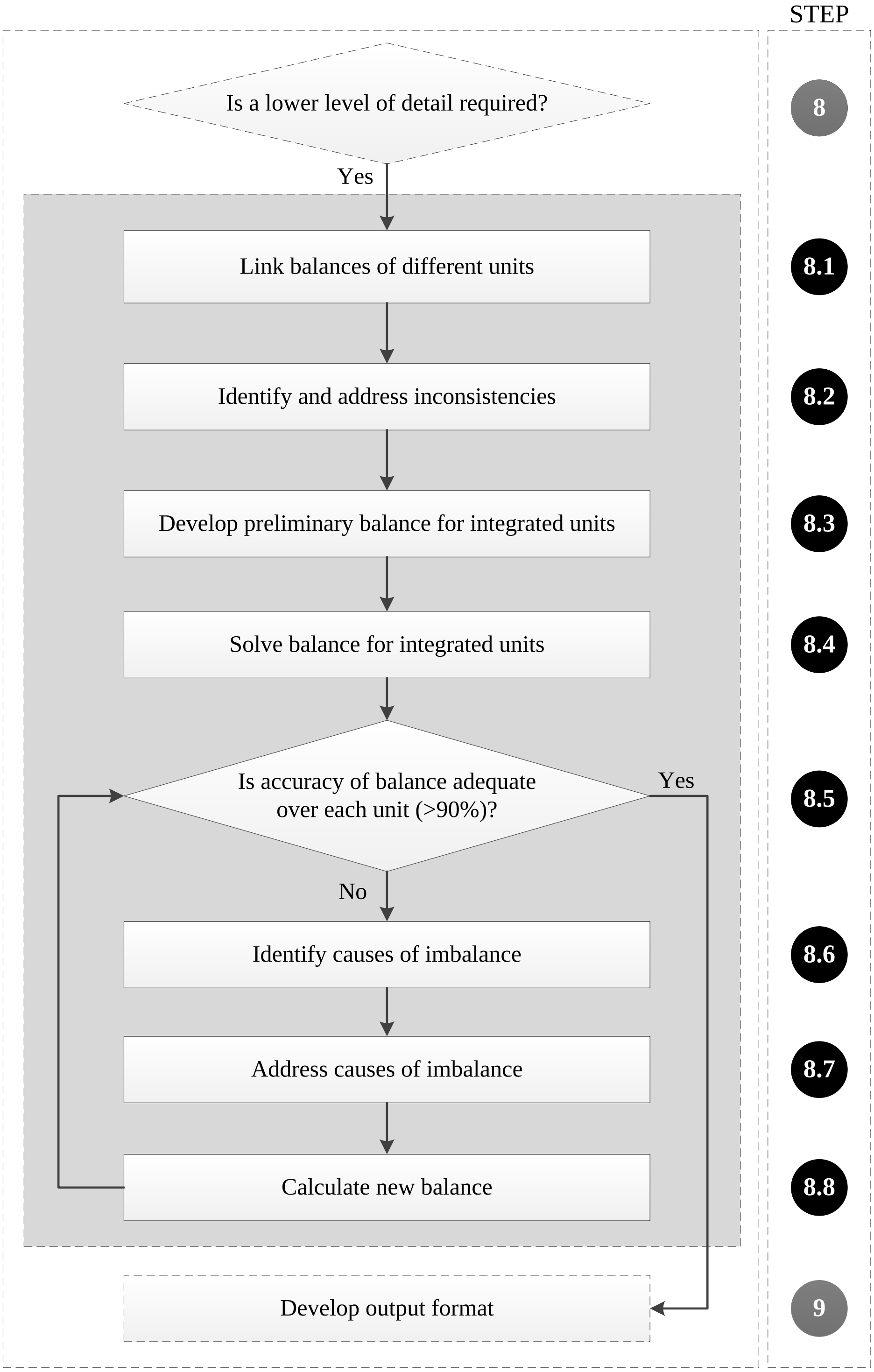


**Figure 7: Flow diagram of process for Step 8 [6].**

**Step 9** in the process is the same as Step 6. After the level of detail has been identified and water balances have been updated, the output format of the water balances should be defined. **Steps 10 and 11** in the process are critical steps in ensuring that the results obtained from the water balances are accurate. To validate the water balance model, data should be verified and meters should be calibrated [6] or the accuracy of the meters should be verified.

The DWS [6] provides a simple framework that can be used to set up a water balance as shown in Figure 5 to Figure 7. Although the framework discusses quantifying the flows for a coal mine water balance, very little discussion regarding how to quantify these flows takes place, apart from evaporation. The DWS proposes using Equation 1 to Equation 3 to calculate the water lost through evaporation.

$$P'_{WS} = 0.6105^{17.27 \times \frac{t_{wb}}{237.3 + t_{wb}}}$$ **Equation 1**

$$r = \frac{0.622 P_w}{P - P_w}$$ **Equation 2**

$$E = F_A \times r$$ **Equation 3**

Where: $P'_{WS}$ = vapour pressure (in kPa)

$t_{wb}$ = wet bulb temperature (°C)

$r$ = moisture content of air (kg/kg)

$P$ = atmospheric pressure (kPa)

$F_A$ = air flow ($m^3$/day)

$E$ = water lost through evaporation ($m^3$/day)

Other studies concerning water balances have also been evaluated with respect to their approach on water balances and quantification of flows to assist with the current uncertainties in legislation.

Makamure and Klimczak [28] investigate the water balance of a Manganese mine in South Africa. The main focus of the study was to develop water balances for the mine during peak dry and peak wet seasons. Various assumptions were made regarding the input parameters of the water balance, most of which are not substantiated through scientific methods. Evaporation from the process water dams was assumed to be 10% of the total inflows into the dam. An annual return flow from the TSF of 50% of the tailings inflow was assumed and 10% of all inflows into the TSF as well as all direct rainfall was considered as losses. Furthermore, it is assumed that the sewage treatment plant has a 90% recovery rate, and that runoff rates at the process water dam is 5% in wet seasons and 0% in dry seasons. While the methodology followed by Makamure and Klimczak [28] delivered water balances that are seemingly accurate (no variance between inflows and outflows), the generalised assumptions made could not be substantiated scientifically.

The water balance of an open-pit gold mine in Ghana was investigated by Tiile and Nicholas [15]. The study focused on identifying and comparing inflows and outflows of the water balance to estimate the storage capacity of water storage facilities by using the relationship shown in Equation 4.

$$Change\ in\ storage = Input - Output \qquad \textbf{Equation 4}$$

A final summary of the water balance obtained during the study by Tiile and Nicholas [15] is presented, but no detail regarding the exact methodology followed to identify inflows and outflows and quantification of these inflows and outflows is discussed. It is mentioned that average environmental factors such as rainfall is used within the model, but the calculations used are not identified.

Solgi [29] researched the water balance for a metal mining TSF in great detail with the purpose of comparing available methods of approaching the water balance of a TSF. Equation 5 is the proposed way of calculating the volume of water present in tailings.

$$Water\ with\ tailings = Daily\ ore\ throughput\ \times Days\ in\ month\ \times \frac{1 - tailings\ \%\ solid}{tailings\ \%\ solid} \qquad \textbf{Equation 5}$$

Assumptions regarding the area climatic conditions were made, the most significant of which is a pond evaporation pan factor of 0.8 and a pit runoff factor of 0.5. Solgi [29] developed a relationship to estimate the pond area on top of the TSF based on the tailings solids content and climatic conditions of the area, as shown in Table 1.

**Table 1: TSF pool area based on climate conditions and tailings solids content**

| | Tailings solids content (%) | Pond area (% of TSF area) |
|---|---|---|
| **Wet climate area** | 45 | 25 |
| | 60 | 25 |
| | 70 | 0 |
| | 80 | 0 |
| **Dry climate area** | 45 | 25 |
| | 60 | 15 |
| | 70 | 0 |
| | 80 | 0 |

A wet climate area is considered as a climate area where the water balance can only be maintained if water is discharged into the environment [30]. A dry climate area is therefore an area where water from external water resource should be imported to maintain the water balance of the area.

Solgi [29] proposes that rainfall and runoff onto a TSF can be calculated by using Equation 6 and Equation 7, respectively, while evaporation from a TSF can be calculated using Equation 8.

$$Rainfall = \frac{Rainfall\ recorded}{1000} \times Pond\ area$$ **Equation 6**

$$Runoff = \frac{Rainfall\ recorded}{1000} \times Area \times Runoff\ factor$$ **Equation 7**

Where: Rainfall recorded is in mm

Pond area is in $m^2$

Area is the area over which the rainfall is recorded in $m^2$

Runoff factor is dimensionless

$$Evaporation = Pond\ area \times Pond\ evaporation\ fator \times Evaporation\ rate$$ **Equation 8**

Where: Pond area is in $m^2$

Evaporation rate is in m/month

Estergaard [31] also investigates the water balance for a TSF. In the study is it proposed to calculate rainfall and evaporation using the same equation as proposed by Solgi [29] shown in Equation 6 and Equation 8, while Equation 9 is discussed as the preferred method for calculating the volume of water lost through seepage.

$$Seepage = Seepage\ rate\ \times Operating\ days\ in\ month \times 24$$ **Equation 9**

Where: Seepage rate is in $m^3$/hr

Table 2 shows existing water balance studies and their approaches to water balances and quantification. The limitations of these studies are also discussed.

**Table 2: Existing water balance studies.**

| Literature Source | Water balance approach | Process units included | Quantification of variables | Limitations |
|---|---|---|---|---|
| **The DWS [6]** | Simple approach to water balances. Very high level of detail included. | Dams, TSFs, WRDs, WWTP, Processing Plant, Shaft. | Very detailed quantification of evaporation. | Psychrometric properties required to estimate daily water loss through evaporation. Focus is on coal mines. |
| **Makamure and Klimczak [32]** | Two separate models for wet and dry seasons. | Shaft, Processing Plant, RWD, TSF, WWTP, Dam | Rough estimations on evaporation rate, return water from the TSF. | Flows quantified through available data or assumptions. No calculations or validation of assumptions discussed. |
| **Tiile and Nicholas [15]** | Annual water balance. Very low level of detail. | Dam, TSF, WWTP, Processing Plant. | Average environmental factors (evaporation, rainfall) for the area assumed. | Open pit mine. No methodology regarding quantification of flows is discussed. |
| **Solgi [29]** | Very detailed water balance. | TSF. | Simple calculation for water with tailings. Discusses methods to calculate rainfall, evaporation and runoff. | Level of detail discussed requires various parameters which might not be available such as hydraulic conductivity, curve number, etc. |
| **Estergaard [31]** | Simple approach. | TSF. | Simple calculation for rainfall, evaporation, runoff, seepage. | The simple equations require parameters which might not be available such as fraction of runoff diverted, seepage rate, etc. No explanation on how to derive or assume these parameters. |
| **Wels and MacG [30]** | Very complex model. | TSF. | Complex calculations for evaporation, seepage, rewetting. | Complex models require parameters which might not be available. |
| **Stanley and Metallurgy [33]** | General overview of a TSF water balance. | TSF. | No quantification. | No quantification of flows discussed. |

While the list of literature reviewd in Table 2 is not exhaustive, it indicates that there is a clear gap in quantification of water balance flows, especially in studies which focus on more than one process unit. Where quantification is discussed, it is largely based on broad assumptions or very complex equations. These equations also largely require parameters that might not be available within most mining operations. Studies look at the overall steps that need to be followed to set up a water balance, but very little information on data sourcing, calculations, and necessary assumptions is available. Accurate quantification of a water balance is a crucial step in water balance development.

Most studies also do not have a holistic approach to water balances, but rather focus on a single process unit. For a water balance to be fully compliant with the regulations set out by the DWS, the water balance should be sufficiently accurate and detailed and should therefore incorporate all process units within the respective operation. To comply, all process units should be considered both as an individual process unit and as interconnected with other process units in the mining operation. Therefore, a holistic approach to water balances is required.

## 1.7 Need for the study and objectives

There is increasing pressure on the gold mining industry to obtain their water use licenses. One of the minimum information requirements for the application of these licenses is a detailed and accurate water balance.

When examining existing water balance studies, general methods on how to develop a water balance is discussed, but very little research regarding methods to quantify the flow streams of a water balance is available. Where quantification is discussed, it is often very complex and will require parameters that might not be available in all mining operations.

Generally, the area of investigation of existing water balance studies only includes a few, if not a single, process unit. Very few studies considered the mine as a whole and the interaction between the different process units.

The need for a practical methodology to quantify water balances which comply with the regulations set out by the DWS for a mining operation therefore exists. The primary objective of this thesis is to develop a methodology for the development of water balances within the gold mining industry. A few additional objectives are needed to assist in the thesis and to provide a functional water balance methodology. These objectives are:

- Evaluating existing methodologies for the development of water balances from literature and identifying how these methodologies can be applied to this thesis.
- Identifying and understanding the requirements from standards and regulations.
- Developing a water balance methodology to deliver detailed and accurate water balances for gold mines.
- Validating the methodology through industrial implementation.

Consequently, the thesis will assist in the development of a water balance methodology to ensure legal compliance for gold mines in SA.

## 1.8 Thesis overview

### 1.8.1 Chapter 1

Chapter 1 gives a background on the water landscape in South Africa and introduces the importance of water management in deep-level gold mines. The impact that these mines have on the country's water resources is investigated. Legislation and regulations applicable to water use in SA are discussed. The legal requirements imposed on the gold mining industry are highlighted with a focus on water use licenses and water balances. Existing water balance methodologies regarding the development and quantification of water balances are investigated and the research gap in literature is discussed.

### 1.8.2 Chapter 2

In Chapter 2 a methodology is developed which ensures the development of accurate and detailed water balances with the use of literature and guidelines. Modular units are developed for all the possible process units within a deep-level gold mine, and the quantification of the relevant flows is discussed in detail. The interconnectivity between these process units is reviewed and a methodology to connect these modular units is developed. The overall water balance for the mining operation is further expanded.

### 1.8.3 Chapter 3

Chapter 3 looks at the implementation of the methodology developed in Chapter 2 on a mining operation. The mining operation was evaluated in detail while a summary of two nearby mining operations was presented. The integration of these mining operations to form a regional water network is discussed briefly.

### 1.8.4 Chapter 4

In Chapter 4 the conclusion and findings of the research are recapped. From Chapter 4 it is also clear that the objectives of the thesis were met, and that the methodology proved to be successful. Recommendations for future research are also discussed.

# METHODOLOGY

## 2.1 Preamble

Chapter 1 highlighted the importance of a water balance within the mining industry. The need for a methodology to develop and quantify these water balances was identified. The main objective of this chapter is therefore to develop a modular framework which can be applied to any gold mining water balance system to fully develop and quantify water balances for legal compliance.

A modular approach is followed to develop the overall framework. Firstly, water balances for identified process units will be developed. Calculations and assumptions to quantify the water streams will be provided (Section 2.2). In Section 2.3 the limitations and uncertainties identified in the development of the modular water balance units are discussed. In Section 2.4, a procedure to develop a water flow diagram is identified, after which the integration of the process units is discussed. This will ultimately form the complete regional water balance which can be adjusted to fit the desired operation.

Criteria to validate the methodology are discussed in Section 2.5, which enable the user to test and verify the accuracy of the water balances. Lastly the practicality of the methodology is investigated in Section 2.6 to ensure that the methodology developed in the preceding sections could be easily implemented in the gold mining industry. The outline of Chapter 2 is illustrated in Figure 8.

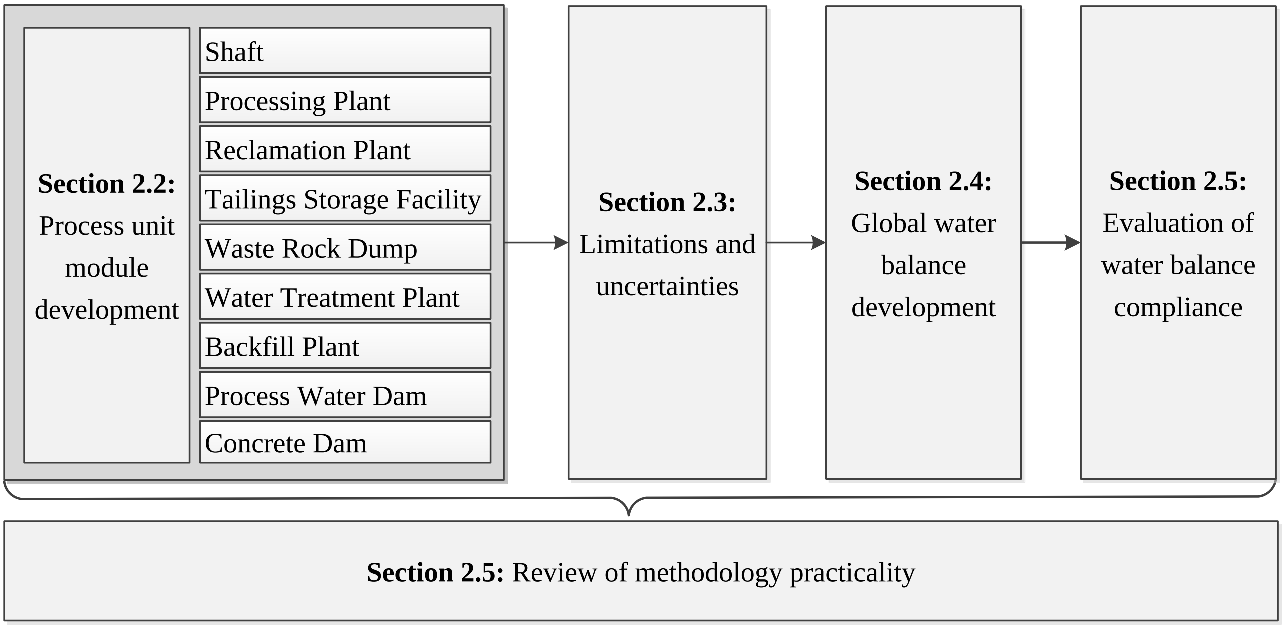


**Figure 8: Outline of Chapter 2**

## 2.2 Process unit module development

The aim of the water balances is to quantify the volume of water applicable to the water uses listed in Section 1.5. Therefore, the scope of this research only focuses on surface water balances since this will ensure that all the required information is obtained.

Generic process unit water balances were developed which can be applied to any operation to obtain a comprehensive balance. Waters [34] proposed using a decision tree as an effective method in discovering, understanding, and communicating decisions in a decision based methodology. Kamiński, et al. [35] states that decision trees consist of three node types namely decision nodes, chance nodes, and end nodes. Decision nodes are nodes where the outcome is based on a decision, whereas chance nodes consider the probability of certain outcomes. End nodes show the final outcome of a decision path. A decision tree was developed which lists the steps followed to develop these generic modular units for the generic process units and is shown in Figure 9. The methodology visualised in the decision tree however does not contain any chance nodes since none of the outcomes are based on probability. The decision tree therefore consists of decision nodes, end nodes, and action nodes where action nodes represent an action to be taken.

Felder and Rousseau [36] discusses the law of conservation of mass and how this law can be applied in solving unknown variables in material balances. Since a water balance is essentially material balances, these principles have been applied throughout the methodology to solve unknown flows.

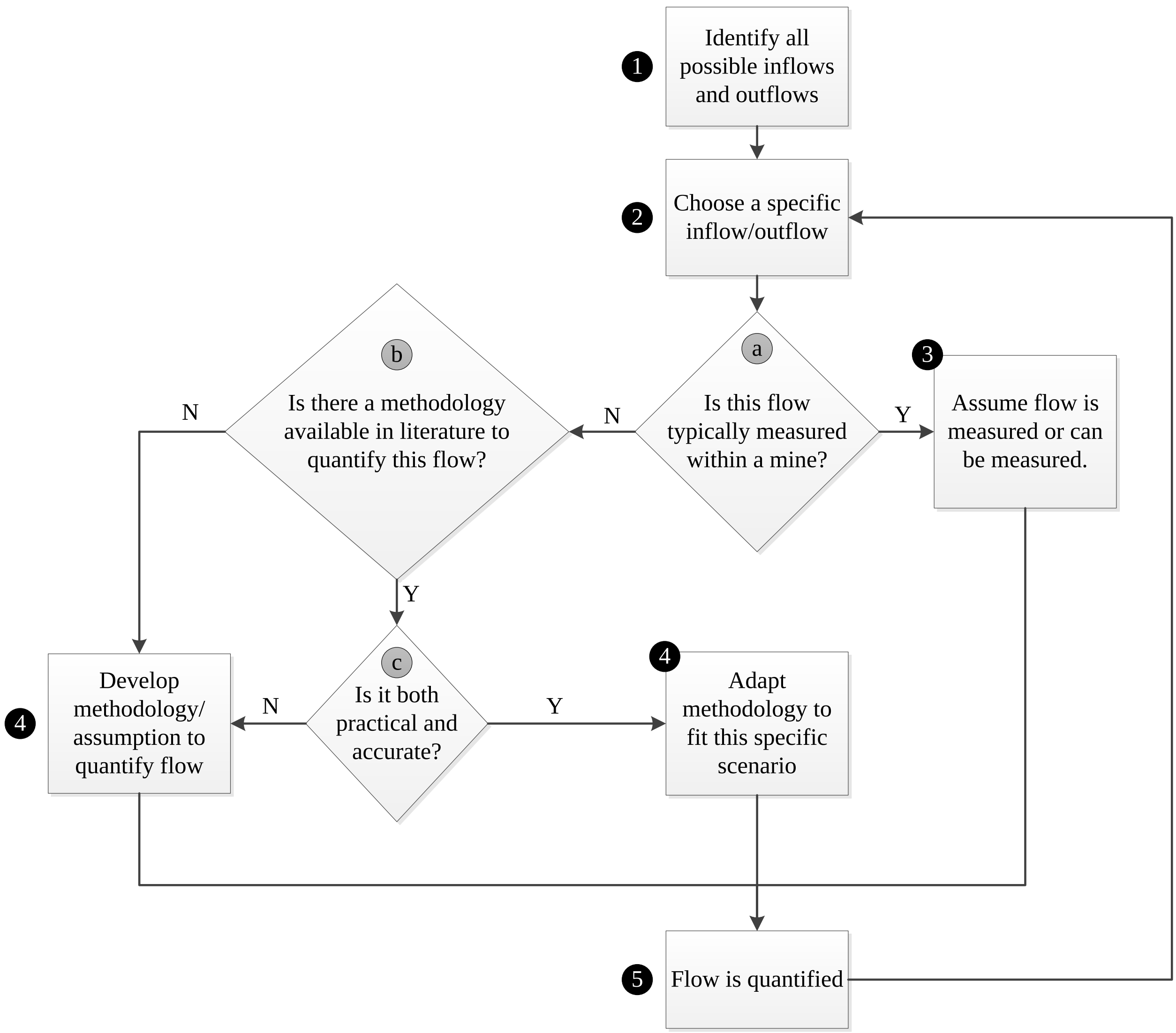


**Figure 9: Modular process unit water balance development steps.**

The first step in developing the generic water balance for a process unit was to identify all the possible inflows and outflows of the identified process unit boundary. Once all the inflows and outflows have been identified, the flows could be quantified. Considering a specific flow, it was first evaluated whether this flow is typically measured (or should be measured) in the mining industry (decision *a* in Figure 9). If the flow is not typically measured, the flow needs to be quantified either through a calculation or through an assumption. Literature was examined to identify existing methodologies to quantify these flows. Where methodologies existed, they were used to quantify the flow or adapted to fit the specific scenarios where required. Where methodologies did not exist, procedures were developed through the support of literature. After the specific flow has been quantified (Step 5), the process can be repeated for all the specific flows under investigation.

To achieve a water balance with an acceptable degree of detail, flows should be considered down to an accuracy level of approximately 1 - 5% of the total flow [6]. For example, for a process unit circuit with a total flow of 10 000 m$^3$ per day, all individual flows of 100 – 500 m$^3$ per day should be considered when developing the water balance. The following subsections discuss the water balance development for each of the eight modular process units in a gold mining operation. For all variables it has been assumed that there are no leakages on pipelines transporting water and slurry. These process units were identified in Chapter 1, Section 1.5.1.

### 2.2.1 Shaft water balance

The first water balance is developed for the shaft of the mine. The term *shaft* in this thesis includes all the surface commodities related to where mining occurs. The shaft typically has a very integrated water flow system which supports production, ventilation, cooling etc. A simplified illustration of the shaft area and the important streams for a water balance is depicted in Figure 10.

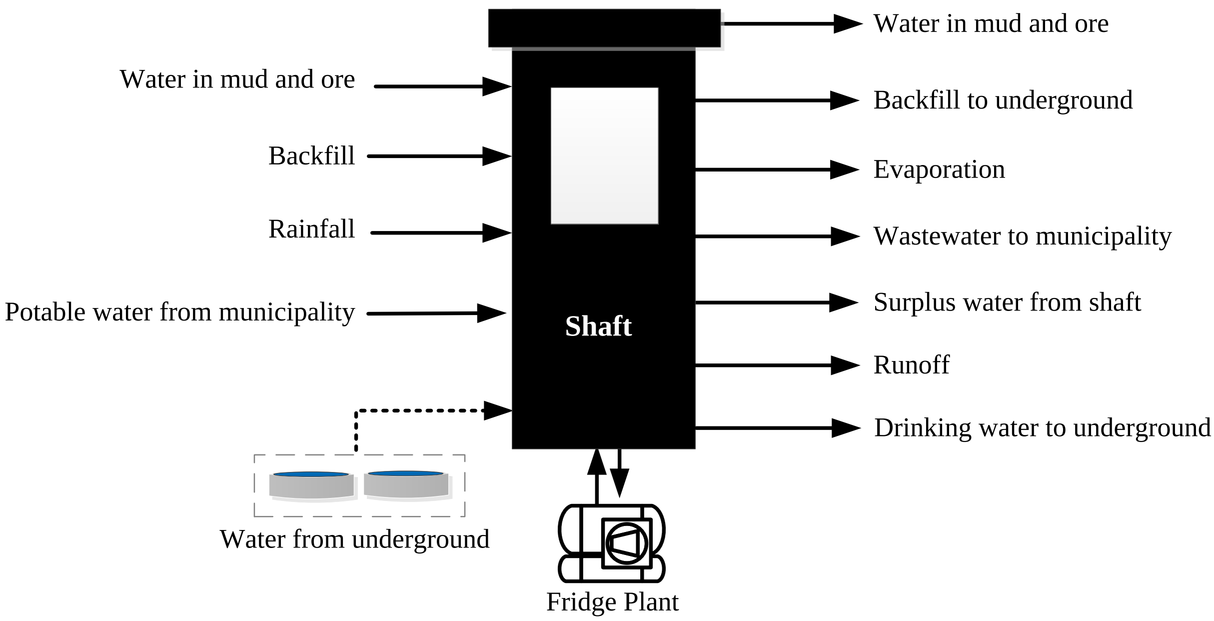


**Figure 10: Standard water balance over a shaft area.**

From the illustration in Figure 10 it can be seen that the standard water balance over a shaft includes water abstracted from underground, as well as the pumping of this abstracted water to the designated area. Where backfill is applicable, backfill from the plant, as well as backfill sent to underground is included. There is also water present in the mud and ore that is hoisted from underground and sent to the plant.

Environmental factors such as direct rainfall and evaporation are considered, as well as potable water from the municipality and the resulting wastewater sent back to the municipality. Generally, the shaft process unit includes fridge plants, bulk air coolers, compressors, change houses, and offices.

***Inflows***

*Water in mud and ore*

In deep-level mines there is generally an accumulation of water in the underground levels. This is mainly due to fissure water from crevices in the rocks, as well as service water that is sent underground [37]. This water is typically contaminated with mud and other particles. These suspended solids must be removed from the water before it can be pumped to surface. This is mainly done by making use of settlers. The mud that is removed from the water in gold mines is typically enriched with gold and is therefore seen as a valuable product. This mud accumulates in mud dams underground from where it is pumped to the processing plant. [8]

There is also a degree of moisture present in the ore that is hoisted from underground. Deep-level mines generally use water as a cooling medium for drilling equipment. Ore that is hoisted from underground therefore usually contain a layer of moisture. The moisture may be present in varying degrees; samples must therefore be taken to accurately measure the moisture content [13].

Water in mud is measured at the shaft, while the moisture content in ore is measured at the plant, as both of these variables are important for reporting purposes. The amount of water in the mud can therefore be used from the measurement while water in ore can be calculated by using Equation **10** or Equation 11 [29].

$$Mass\ of\ water\ in\ ore = \frac{T_D}{1-x} - T_D \qquad \text{Equation 10}$$

$$Volume\ of\ water\ in\ ore = (\frac{T_D}{1-x} - T_D)/\rho_W \qquad \text{Equation 11}$$

Where: $T_D$ = dry tonnage of ore (tonnes)

$x$ = moisture content by weight

$\rho_W$ = density of water (tonnes/$m^3$)

Some shafts have other mud dewatering systems such as filter presses. The mud is hauled out of the mine with the ore and not pumped to the processing plant separately [8]. In these cases, the combined water volume (in ore and mud) is estimated at the shaft.

*Backfill*

Certain deep level mines place processed material (tailings) underground to add support to mined out stopes [8, 38]. The process is known as backfilling and the slurry that is sent underground for this purpose is termed backfill. Backfill is usually mixed with a binder and sent underground as a slurry where it is pumped into the voids. By backfilling processed material instead of sending it to the tailings storage facility, the mine also decreases the negative environmental impacts of tailings storage on surface [39]. By backfilling tailings, ore volumes extracted can also be maximised when room or pillar mining is considered. Backfilling produces the structure required to mine the areas around the original cavity [40].

The tonnes and the density of the backfill placed underground are typically variables measured and recorded by the plant to audit the tailings. These variables are measured by the backfill plant to ensure that the backfill settles in the intended manner. Equation 12 and Equation 13 can be used to determine the volume of water in the backfill (in $m^3$) [41].

$$x_{Sl} = \frac{SG_S(SG_{Sl} - 1)}{SG_{SL}(SG_S - 1)} \qquad \text{Equation 12}$$

$$Water\ in\ slurry = \frac{1 - x_{Sl}}{x_{Sl}} \qquad \text{Equation 13}$$

Where: $x_{Sl}$ = fraction of solids within the slurry

$SG_S$ = specific gravity (SG) of the solids (tailings) in the slurry

$SG_{Sl}$ = SG of the slurry mixture.

These SG values are used to determine the fraction of water in the slurry mixture. The water in the slurry equals the volume of water in the backfill.

*Rainfall*

Rainfall affects process units when it enters the boundary of the process unit. Once the rainfall enters the boundary, it can exit the boundary in a number of ways. If it falls on a permeable medium such as soil, most of the rainfall seeps away and the rest of the rainfall evaporates. However, if rainfall is received on a water body such as a dam or a tank, it merges with the current water in the water body by increasing the volume. In many shaft or plant areas, rainfall which falls on the concrete surfaces of the operations is routed to trenches and storm water sumps. From here it is routed to storm water dams, evaporation ponds, or any other water storage facility.

Most processing plants have rainfall meters where rainfall is measured and reported. Certain Tailings Storage Facilities (TSFs) and shafts also have rainfall meters. Where rainfall meters are not available, monthly rainfall for the specific process units can be determined through interpolation between areas that are measured. Equation 14 shows the calculation through which rainfall (in $m^3$) is calculated [31].

$$Rainfall = \frac{Rainfall\ reported}{1000} \times (A) \qquad \text{Equation 14}$$

Where: Rainfall reported = rainfall recorded in millimeters (mm)

A = surface area in $m^2$

Surface area refers to the area over which the rainfall was recorded.

*Potable water from municipality*

Mining operations require potable water for various processes. At mining shafts, potable water is mainly used by employees in offices, change houses, and hostels for drinking and sanitation [42]. In rare cases, potable water is sent underground as make-up water for the underground cooling systems if there is not enough service water available [43].

Potable water is either sourced from the local municipality or from water treatment plants at the shafts. Where the potable water is received from the municipality, the water received is typically measured by both the municipality and the mine. The meter readings taken by the mine can then be compared with the invoices from the municipality as a validation step.

Where there is surplus service water in the system (usually from a substantial influx of fissure water), the shafts can choose to set up a water treatment plant which will then treat this water to potable water standards. The potable water produced by these water treatment plants is typically measured by the water treatment plant operators.

*Water abstracted from underground*

Deep-level mines typically have a surplus of water underground due to fissure water in the system. Water must be pumped to surface to prevent flooding of the underground levels. In some cases, the shafts also have surface fridge plants. Hot water is then pumped from underground to the surface fridge plant, where it is cooled before being pumped back underground where it is used to manage the underground temperatures [44]. The water that is pumped from underground to surface is generally measured at the shaft.

***Outflows***

*Water in mud and ore*

The water in mud and ore that is described as an inflow moves through the shaft and is directly diverted to the processing plant. It is assumed that no losses of water will occur while the mud and ore is transported. The volume of water present in mud and ore into the shaft (calculated with either Equation 10 or Equation 11) therefore equals the water in mud and ore out of the shaft.

*Backfill to underground*

The backfill that is received from the processing plant is pumped underground, where it is mixed with concrete before it is pumped into the mined-out stopes. The concrete is mixed with the backfill at the point of delivery underground to prevent the backfill from setting in the pipelines. It is assumed that there are no losses of water while the backfill is transported to its final destination. Therefore, the water in backfill sent to underground is the same as the water in the backfill inflow which is determined with Equation 12 and Equation 13.

*Evaporation*

It is difficult to determine the exact evaporation rate for each of the process units with psychrometric principles, since the air flow rate at each point is unknown. The air flow rate is also not a constant, making it difficult and uneconomical to determine an average air flow rate. It would also not be cost effective to measure and monitor evaporation at each of the process units. It was decided to calculate the overall evaporation in the mine with psychrometric principles [6]. Evaporation rates have been derived from historical data and are shown in Table 3.

**Table 3: Evaporation rates**

| **Month** | **Evaporation rate (mm)**[i] |
|---|---:|
| January | 206.25 |
| February | 162.96 |
| March | 145.59 |
| April | 110.13 |
| May | 86.40 |
| June | 69.02 |
| July | 78.37 |
| August | 107.14 |
| September | 146.70 |
| October | 183.63 |
| November | 201.75 |
| December | 212.65 |

[i] *Based on 48 years (1961-2009) of data from The DWS*

Equation 15 represents the calculations required to determine the evaporation.

$$Evaporation = Pool\ area \times (\frac{Evaporation\ rate}{1000}) \qquad \text{Equation 15}$$

Where: Pool area = the surface area of a body of water

In a conventional dam, the pool area would be the same as the surface area of the dam. In a shaft or tailings storage facility, the pool area would be the area where the water accumulates to form a body of water. In a shaft, this would be the storm water dams, or trenches. In a tailings storage facility this would be the surface area of the pool that forms on top of the TSF. There is also evaporation from water underground due to the high temperatures, but this is not included within the boundary chosen for the shaft water balance, as discussed in Section 2.2.

*Wastewater to municipality*

Wastewater is another difficult variable to measure. Sewage pipelines are typically buried and the flow of sewage is mainly driven by gravity [45]. General instruments therefore have difficulty in directly performing flow measurements. The water properties of wastewater also greatly differ between sources, and solid impurities often block flow measuring equipment. Chemical erosion by the wastewater components may also decrease the service life of measuring equipment [46]. Due to the large costs involved in measuring wastewater sludge, it is generally not measured as it exits the shaft area and enters the municipal sewerage system.

Potable water at a mining shaft is mainly used in offices, change houses, and hostels. A certain portion of water is sent underground. The water used within offices, change houses and hostels includes water use for drinking and food preparation, water use for sanitation such as cleaning and washing, and ablutions, and collectively are referred to as domestic use [42]. Generally, potable water sent to the offices, change houses, hostels, underground, condenser dams, cooling towers etc. is measured, which are collectively referred to as industrial water. This makes it easy to distinguish between the potable water used for domestic use and potable water used for industrial purposes (cooling towers, compressors, etc.). It is therefore an acceptable assumption that all water that is not used for industrial purposes is used for domestic uses. It is assumed that all potable water used for domestic use exits the system as wastewater.

Potable water distribution within the process unit is not always measured. In this case, the wastewater generated can be based on the number of personnel present on the shaft as well as a general assumption of how much water is used per person per day. Mckenzie, et al. [26] studied the water consumption throughout SA and calculated the average water consumption per person per day for various areas throughout the country. Although these average focus on potable water for domestic purposes, it is assumed that the difference between these reported averages and the average consumption at a mining operation will be negligible. These reported averages can be used to estimate the total volume of wastewater generated. However, this should be used only as a last option if there is no metering of potable water within the process unit.

*Surplus water from shaft*

Water that is abstracted from underground to surface is sent to process water dams or directly to processing plants. In cases where shafts have surface fridge plants, the water abstracted from underground is typically sent to the precooling dams of the surface fridge plant. Assuming that there are no losses when water is abstracted from underground, the surplus water from the shaft will be the same volume as the water abstracted from underground.

*Runoff*

All water entering the shaft boundary as rainfall is expected to run off into trenches which flow to the nearest process water dam. Therefore, shaft runoff is considered to be equal to the volume of rainfall received over the shaft area.

*Drinking water to underground*

At mining shafts, a certain portion of the potable water that is received is sent underground. This water is used by mine workers underground as drinking water. The potable water sent to underground for this purpose is generally measured.

***Summary***

Table 4 gives a summary of the variables used within the water balance calculations for the shaft area.

**Table 4: Shaft water balance summary**

| Variable in water balance | | Type of variable (*measurement / calculation / assumption*) |
|---|---|---|
| ***Inflows*** | *Water in mud and ore* | Calculation (Equation 10 and Equation 11) |
| | *Backfill* | Calculation (Equation 12 and Equation 13) |
| | *Rainfall* | Calculation (Equation 14) |
| | *Potable water from municipality* | Measurement |
| | *Water abstracted from underground* | Measurement |
| ***Outflows*** | *Water in mud and ore* | Calculation (Equation 10 and Equation 11) |
| | *Backfill to underground* | Calculation (Equation 12 and Equation 13) |
| | *Wastewater to municipality* | Measurement & assumption |
| | *Surplus water from shaft* | Measurement |
| | *Runoff* | Calculation |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

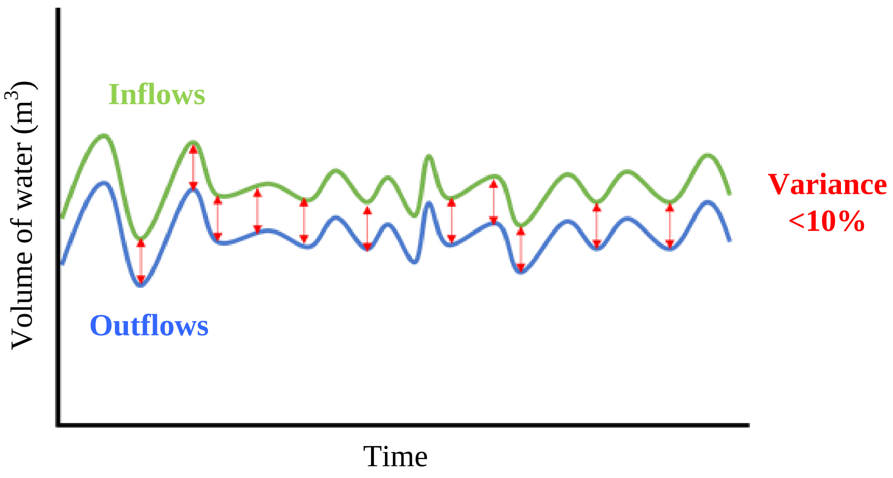


**Figure 11: Evaluation of inflows and outflows of a process unit.**

By comparing the inflows and outflows, the variance of the water balance for every specific time unit can be evaluated. If the variance remains 10% over a period of time, it is an indication that the water balance is acceptably accurate. This check can be applied to all the process units.

### 2.2.2 Processing plant water balance

Processing plant is the second modular unit for which a water balance is developed in this thesis. A simplified illustration of a processing plant and a summary of the important water streams to consider is depicted in Figure 12.

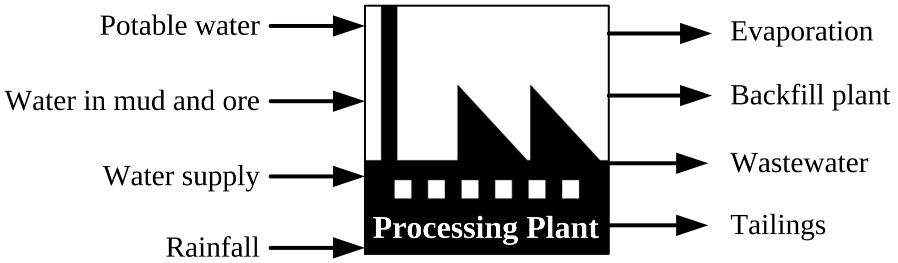


**Figure 12: Standard water balance over a processing plant.**

The major contributors to the water balance in Figure 12 are water supply (whether from the return water dam or other resources), water in tailings sent to the TSF, and backfill. Also included is potable water from the municipality, water in mud and ore from the shaft, wastewater to the municipality, and environmental factors such as rainfall and evaporation.

The water that exits the plant with the tailings includes the water that entered the plant with the mud and ore, and water which is added during the milling phase. The water added during milling is generally return water that is recovered from the TSF [29]. These variables are discussed in more detail in the following paragraphs.

***Inflows***

*Potable water*

Potable water in processing plants is mainly used during the elusion process. Service water cannot be used in this process because it requires deionised water of a specific pH [47]. Potable water is also used as a top-up for the milling process in cases where insufficient water is recovered from the return water dams [4].

Processing plants can either source potable water from the local municipality, or from nearby water treatment plants. In both cases, these flows are typically measured and can be directly included in the water balance.

*Water in mud and ore*

Water enters the processing plant through mud from the underground settlers and as a percentage moisture with the ore. The water volume present in the mud and ore should correspond to that reported at the shaft but can also be calculated by using Equation **10** and Equation **11**.

*Water supply*

Water supply is the term used for service water that is used in the gold extraction process. The service water is mainly sourced from recovered water from the TSFs which accumulated in the return water dams. Water from nearby dams and streams can also be utilised in some cases. Water supply to the plant is typically measured since a certain ratio of water to ore is required for the milling process [14].

*Rainfall*

Processing plants generally have rainfall meters. The rainfall received by the plant can be calculated using Equation 14.

***Outflows***

*Evaporation*

Evaporation at a processing dam will occur at open processing water dams. If the surface areas of these dams are known, Equation 15 can be used to calculate the evaporation. If surface areas are not known, estimations for the surface areas can be obtained using interfaces such as Google Earth.

*Backfill plant*

Certain mining operations send backfill underground. The tailings obtained after processing of ore can either be pumped to the TSFs, sent underground as backfill, or a combination of the two. Backfill can be calculated using Equation 12 and Equation 13.

*Wastewater*

Wastewater in processing plants is generated by the offices. Wastewater is assumed to be the total potable water that is used for domestic purposes within the plant. Since potable water in a plant is used for both domestic and industrial use, these streams should be measured to ensure an accurate water balance.

*Water in tailings*

The amount of water present in the tailings slurry is dependent on the tonnage throughput and the tailings' solids content. A fraction of this water gets trapped in the pores of particles after the tailings settle and cannot be recovered. The rest of the water is termed supernatant water and collects in the tailings dam pool. [29]

Tailings is a slurry just like backfill, therefore Equation 12 and Equation 13 can be used to determine the volume of water that exits the plant boundary with the tailings. The tonnes treated by the plant as well as the density of the slurry are typically measured by the plant, and will be required to calculate the water in the slurry.

***Summary***

Table 5 gives a summary of the variables used within the water balance calculations for the processing plant.

**Table 5: Processing Plant water balance summary**

| **Variable in water balance** | | **Type of variable** *(measurement / calculation / assumption)* |
|---|---|---|
| ***Inflows*** | *Potable water* | Measurement |
| | *Water in mud and ore* | Calculation (Equation 10 and Equation 11) |
| | *Water supply* | Measurement |
| | *Rainfall* | Calculation (Equation 14) |
| ***Outflows*** | *Evaporation* | Calculation (Equation 15) |
| | *Backfill plant* | Calculation (Equation 12 and Equation 13) |
| | *Wastewater* | Assumption & measurement |
| | *Tailings* | Calculation (Equation 12 and Equation 13) |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.3 Reclamation plant water balance

Due to an improvement in gold extraction technologies and improved gold prices, it is now economical to extract a higher percentage of gold from rock [33]. Therefore, old tailings storage facilities are being reprocessed (or reclaimed) by reclamation plants. The important water streams that need to be considered for the water balance over a reclamation plant are illustrated in Figure 13.

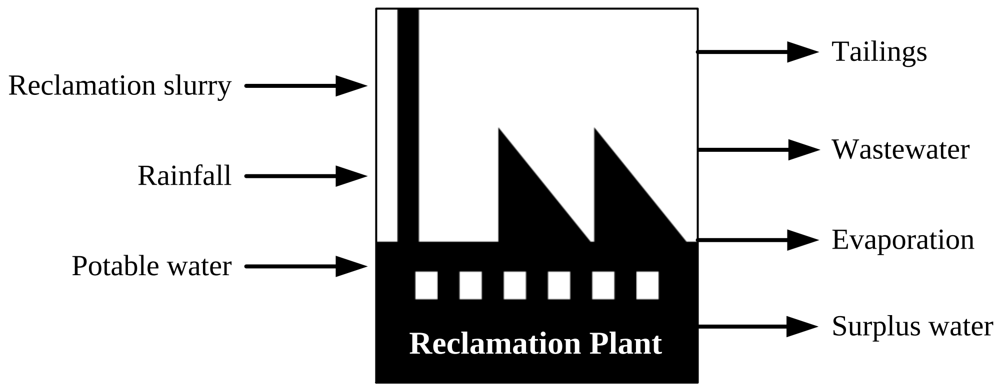


**Figure 13: Standard water balance over a reclamation plant.**

Hydraulic reclamation uses high pressure water to break up the tailings on the tailings dams and is the most commonly used method for tailings reclamation [33]. Reclamation plants are very similar to processing plants with the main difference being that reclamation plants do not have mills. This is because the solids that have to be processed have already been milled in the previous extractive process.

***Inflows***

*Reclamation slurry*

After the tailings on the old TSF have been broken up through hydraulic reclamation, the tailings are transported with the water as a slurry to the reclamation plant. The water in this slurry can be calculated by using Equation 12 and Equation 13.

*Rainfall*

The rainfall received by the reclamation plant can be calculated using Equation 14. It is assumed that all rainfall received on the open dams of the plant will form part of the process water, while runoff received on other plant surfaces will run off into trenches and to the plant storm water dam.

*Potable water*

Potable water at reclamation plants is mainly used in employee amenities and should either be measured by the plant or the municipality, or both. A certain portion of potable water is, however, required during the elution phase of gold extraction and will exit the system as process water. The volume of water used for elution should be measured by processing plants.

***Outflow***

*Tailings*

After gold has been extracted from the tailings or waste rock, the remaining tailings are sent to a TSF as a slurry. The water that is present in the slurry can be calculated using Equation 12 and Equation 13.

*Wastewater*

The portion of potable water that is not used for elution will exit the system as wastewater. To distinguish between potable water used for industrial use and potable water used for domestic use, these flows need to be measured by the plant.

*Evaporation*

Evaporation occurs from the open dams in the plant. The evaporation over the open dams can be calculated by using the evaporation rate listed in Table 3 and Equation 15.

*Surplus water*

Reclamation plants may have a surplus of water in the system if the reclamation slurry has a high water percentage. This water will then be removed from the slurry and sent to a nearby dam. The amount of surplus water is typically measured by the plant and can therefore be used without additional calculations in the water balance.

***Summary***

Table 6 gives a summary of the variables used within the water balance calculations for the reclamation plant.

**Table 6: Reclamation Plant water balance summary**

| Variable in water balance | | Type of variable<br>*(measurement / calculation / assumption)* |
|---|---|---|
| ***Inflows*** | *Reclamation slurry* | Calculation (Equation 12 and Equation 13) |
| | *Rainfall* | Calculation (Equation 14) |
| | *Potable water* | Measurement |
| ***Outflows*** | *Tailings* | Calculation (Equation 12 and Equation 13) |
| | *Wastewater* | Assumption & measurement |
| | *Evaporation* | Calculation (Equation Equation 15) |
| | *Surplus water* | Measurement |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.4 Tailings storage facility water balance

A standard TSF water balance consists of inflows such as water deposited through tailings, rainfall, dust suppression, and runoff and outflows such as interstitial water, seepage, and evaporation [6]. A basic layout with the important streams over a TSF is illustrated in Figure 14.

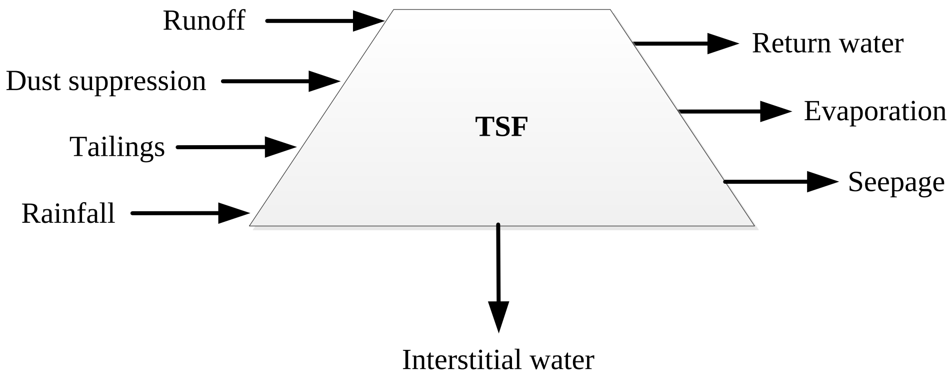


**Figure 14: Standard water balance over a tailings storage facility.**

The amount of water inflow with the tailings deposition is dependent on the tonnes that are being deposited, as well as the solid content within the tailings slurry [29]. The water entering the system via the tailings can either be trapped in the pores of the tailings after settling or be turned into supernatant water which collects in a pool on top of the TSF. The water trapped in the pores of the solids usually cannot be recovered, and is referred to as interstitial water [9].

Makamure and Klimczak [32] proposes that the total losses over a TSF can be as significant as as 50% of the tailings inflows during wet seasons, and 65% of tailings inflows during dry seasons [15].

***Inflows***

*Dust suppression*

Mines are required to comply with the National Dust Control Regulations Act [48] and the National Environmental Management Air Quality Act 36 of 2004 [49], which makes provision for dust-control management or air-quality control. Since the tailings dumped on a TSF consist of fine particles, dust suppression on a TSF forms part of these requirements.

Dust suppression can either be applied by using water bowsers or a piping system. The water used for dust suppression is generally monitored as it is a legal requirement for mining operations, and it should therefore be reported on a monthly basis. The monitored value can therefore be used within the water balances.

*Tailings*

Tailings on a TSF can either come from a general processing plant, or a reclamation plant. The water in these tailings streams should correspond with that reported by the plant, assuming that there are no leaks on the pipeline.

*Rainfall*

Rainfall is received on the TSF surface as well as on the TSF pond. Rainfall received on the TSF pond is considered as a direct rainfall inflow.

*Runoff*

Runoff results mainly from the rainfall on undisturbed regions on the TSF [29], although a small percentage of runoff results from the rainfall on disturbed regions on the TSF. Welch [50] assumes that all the rainfall that falls on the TSF surface and pond enters the ponds. It is therefore assumed in this thesis that all rainfall on the TSF surface, which is not directly on the pond, will be seen as runoff to the pond, as proposed by Welch [50].

***Outflows***

*Interstitial water*

Interstitial water is water trapped in the pores of the saturated tailings particles during sedimentation. Interstitial water is not lost, like evaporated water, but can also not be recovered [29]. It is therefore considered an outflow.

The volume of water trapped in the tailings pores depends on the final dry density after sedimentation. Finer tailings will result in a higher volume of water lost through interstitial water [30, 51]. Daniel Fontaine [52] developed a series of equations which can be used to calculate the interstitial water. Equations 16 to 19 provide the relationship.

$$V_T = \frac{M_{S-INIT}}{\rho_D} \qquad \text{Equation 16}$$

$$V_S = \frac{M_{S-INIT}}{\rho_S} \qquad \text{Equation 17}$$

$$V_V = V_T - V_S \qquad \text{Equation 18}$$

$$V_{IW} = S \times V_V \qquad \text{Equation 19}$$

Where: $V_T$ = total volume of tailings deposited (in $m^3$)

$V_S$ = volume of the tailings solids (in $m^3$)

$V_V$ = volume of the tailings voids (in $m^3$)

$M_{S-INIT}$ = total mass of the tailings solids (tonnes)

$\rho_D$ = average dry density of the tailings (in $m^3$/tonne)

$\rho_S$ = average solids density of the tailings (in $m^3$/tonne)

$V_{IW}$ = total interstitial water

$S$ = degree of saturation of the tailings

The degree of saturation of the tailings is measured by the plant but can be assumed to be 1 if it is not given [52].

*Seepage*

Seepage is an intricate phenomenon and very difficult to quantify. A comprehensive study of the behaviour of tailings after deposition is required to accurately model seepage. Seepage loss, however, represents a small portion of the total water lost on a TSF when compared to evaporation and interstitial water losses [29]. It is also assumed that seepage will only occur at unlined TSFs.

Previous studies observed that 8 - 10% of all water entering the pond on the TSF is lost through seepage [53]. In this thesis an average of 9% was considered. Pond seepage on the TSF can therefore be calculated by using Equation 20.

$$Seepage = 0.09 \times \sum Inflows \qquad \text{Equation 20}$$

Rewetting is seepage that occurs at the beaches formed at the active discharge points of the TSF [30]. Since rewetting losses are very subtle and can be considered negligible [30], rewetting losses were not considered in this thesis.

*Return water*

Return water (also known as reclaimed water, decanted water, or water recovery) is the supernatant water that is drawn from the pool on top of the TSF. This water can be re-used, evaporated, or treated and discharged to natural dams or streams. Return water is typically routed to return water dams by using barge pump systems or penstocks. From here, the processing plants can abstract the water and re-use it in the gold extraction process [29].

Considering the boundary of the TSF process unit, the return water outflow refers to the water that is routed from the TSF to the return water dam. Since the volume of water that flows to the return water dam is generally not measured, this volume is generally solved as the unknown variable in the water balance system.

*Evaporation*

Evaporation from the TSF pond and other surfaces can be estimated by using Table 3 and Equation 15. To simplify the model, only evaporation from the pond surface will be considered.

Solgi [29] developed a standard comparison for pool area based on tailings solids content. The comparison is done for two climate area conditions: dry climates and wet climates. Welch [50] describes a wet climate as an area where extra accumulated water must be released into the environment to maintain the annual water balance for the TSF. Once the climate area condition of the mining operation has been identified as either a wet climate area or a dry climate area, the relationship derived by Solgi [29] can be used to estimate the pond area of the TSF. The relationships are shown in Table 7.

**Table 7: TSF pool area based on climate conditions and tailings solids content**

| | **Tailings solids content (%)** | **Pond area (% of TSF area)** |
|---|---|---|
| **Wet climate area** | 45 | 25 |
| | 60 | 25 |
| | 70 | 0 |
| | 80 | 0 |
| **Dry climate area** | 45 | 25 |
| | 60 | 15 |
| | 70 | 0 |
| | 80 | 0 |

From the relationships shown in , the pool area for the TSF can be derived. Equation 15 can then be used to calculate the evaporation for a TSF.

***Summary***

Table 8 gives a summary of the variables used within the water balance calculations for the TSF.

**Table 8: TSF water balance summary**

| Variable in water balance | | Type of variable (measurement / calculation / assumption) |
|---|---|---|
| *Inflows* | *Runoff* | Calculation & assumption |
| | *Dust suppression* | Measurement |
| | *Tailings* | Calculation (Equation Equation 12 and Equation Equation 13) |
| | *Rainfall* | Calculation (Equation 14) |
| *Outflows* | *Return water* | Calculation (solved as unknown) |
| | *Evaporation* | Calculation (Equation Equation 15) |
| | *Seepage* | Calculation (Equation 20) |
| | *Interstitial water* | Calculation (Equations 16 to 19) |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.5 Waste rock dump water balance

Waste rock dumps (WRD) are storage facilities where low grade ore is stored. The waste rock dump will either be a permanent storage solution for the low grade ore, or may be processed at a later stage by a nearby processing plant. Figure 15 represents the standard water balance over a WRD.

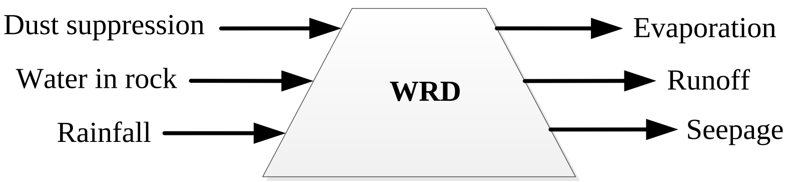


**Figure 15: Standard water balance over a waste rock dump (WRD).**

The major water inflow for a WRD includes dust suppression and rainfall. A small volume of water may also be deposited on the WRD with the rock. Most of the water inflows for a waste rock dump exit the system as evaporation and seepage, with a small percentage of the water being lost through runoff. The quantification of these flows is discussed in the section to follow.

***Inflows***

*Dust suppression*

Dust suppression is a legal requirement for mining operations. The dust suppression applied to waste rock dumps should be measured and recorded.

*Water in rock*

Rock hoisted from underground contains a small percentage of moisture, generally below 7%. The moisture content of the rock is generally measured by the shaft. The volume of water present in the rock can be calculated using Equation **11**, before it is applied to the water balance.

*Rainfall*

The rainfall received by the waste rock dump can be calculated using Equation 14. Generally, there are no rainfall meters located at the waste rock dumps. However, waste rock dumps are typically in close vicinity to shafts and are assumed to receive the same rainfall in this thesis.

***Outflows***

*Evaporation*

Water lost through seepage and runoff should be prioritised over water lost through evaporation. This is because water loss through evaporation occurs over time where seepage and runoff are more instantaneous. Since there is no obvious pool area on a WRD, the evaporation can be calculated by balancing out all the other inflows and outflows over the WRD.

*Runoff*

Runoff from a WRD is a result of rainfall on the WRD. Solgi [29] proposes Equation 21 to be used to determine the surface runoff.

$$Runoff = R_C \times \frac{R_I}{1000} \times A_D$$ Equation 21

Where: $R_C$ = runoff coefficient

$R_I$ = rainfall intensity (in mm)

$A_D$ = drainage area (in $m^2$)

As mentioned above, Welch [50] proposes a runoff coefficient of 65 - 75% for watersheds with no vegetation cover. A coefficient of 70% is therefore chosen for the calculations in this thesis.

*Seepage*

Water used for dust suppression or rainfall received by the WRD that does not exit the system through evaporation or runoff will seep into the ground below the WRD. The seepage can be calculated using Equation 20.

***Summary***

Table 9 gives a summary of the variables used within the water balance calculations for a WRD.

**Table 9: WRD water balance summary**

| | Variable in water balance | Type of variable (*measurement / calculation / assumption*) |
|---|---|---|
| ***Inflows*** | *Dust suppression* | Measurement |
| | *Water in rock* | Calculation (Equation **11**) |
| | *Rainfall* | Calculation (Equation 14) |
| ***Outflows*** | *Evaporation* | Calculation (Equation 15) |
| | *Runoff* | Calculation (Equation 21) |
| | *Seepage* | Calculation (Equation 20) |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.6 Water treatment plant water balance

Water treatment plants can include wastewater treatment plants, reverse osmosis plants which treat the water abstracted from shafts, or any other water treatment plants that take dirty water either effected from mining processes or natural processes and treat it to a better quality. This water can then either be reused in the system or discharged to nearby rivers or dams. Figure 16 shows the water balance over a typical water treatment plant.

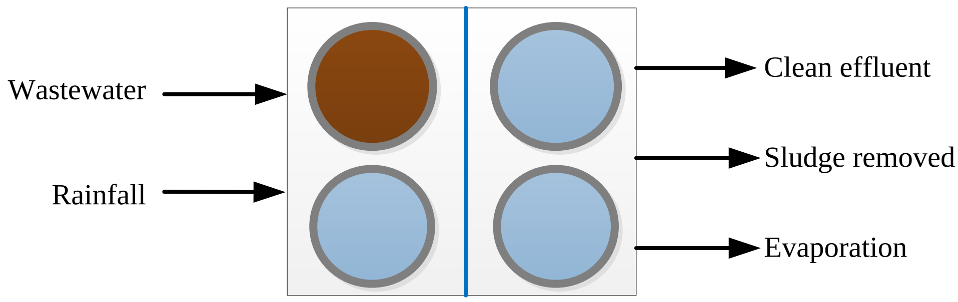


**Figure 16: Standard water balance over a wastewater treatment plant.**

The five streams indicated in Figure 16 are discussed in more detail in the following paragraphs.

***Inflows***

*Wastewater*

Water treatment plants can receive water from nearby dams, wastewater from nearby operations or communities, or dirty process water from mining operations. The total water inflow to a water treatment plant is generally measured by the plant.

*Rainfall*

Rainfall on open dams or water catchment areas within the water treatment plant boundary will enter the system and should be measured. The volume of water from rainfall can be calculated using Equation 14.

***Outflows***

*Clean effluent*

Clean effluent from the water treatment plant can either be sent to nearby mining operations for reuse within their system or be discharged to nearby water sources. The effluent produced by the water treatment plant is generally metered.

*Sludge removed*

Impurities in the wastewater received by the plant are removed as a sludge. If the wastewater contains sewage, the sludge removed will have a much higher volume in relation to dirty process water sourced from nearby dams. The sludge removed is generally measured by the plant. If the volume of sludge is not measured, it can be estimated. Assuming the mass of the solids does not change during the process, the mass of solids within the sludge removed is the mass of solids present in the wastewater inflow to the water treatment plant. Assuming that the density of the clean effluent is effectively 1 and the density and volume of the wastewater inflow is measured, the mass of solids that was removed can be estimated as the difference in mass between the two streams by using Equation 22.

$$Mass\ of\ solids = \rho_I v_I - v_O \qquad \text{Equation 22}$$

Where: $\rho_I$ = density of incoming stream (kg/m$^3$)

$v_I$ = volume of incoming stream (m$^3$)

$v_O$ = volume of clean effluent (kg/m$^3$)

In cases where the wastewater treatment plant is a reverse osmosis plant, impurities are removed as a brine stream. In this case, the volume of the brine stream will be measured.

*Evaporation*

Evaporation of water occurs at all open water bodies. The evaporation can be estimated by Table 3 and Equation 15.

***Summary***

Table 10 gives a summary of the variables used within the water balance calculations for a water treatment plant.

**Table 10: Wastewater Treatment Plant water balance summary**

| Variable in water balance | | Type of variable (*measurement / calculation / assumption)* |
|---|---|---|
| ***Inflows*** | *Wastewater* | Measurement |
| | *Rainfall* | Calculation (Equation 14) |
| ***Outflows*** | *Clean effluent* | Measurement |
| | *Sludge removed* | Measurement |
| | *Evaporation* | Calculation (Equation 15) |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.7 Backfill plant water balance

Certain mines perform backfilling where tailings are sent underground to fill mined-out cavities. This assists with underground support and also decreases the surface footprint of the mining operation since less tailings are deposited on the TSF. After ore is processed by the processing plant, a portion of the tailings can be sent to a backfill plant. Here, the tailings are further processed to obtain the correct slurry density and mixed with a binding agent before they are sent to the shaft for backfilling. Figure 17 represents the standard water balance over a backfill plant.

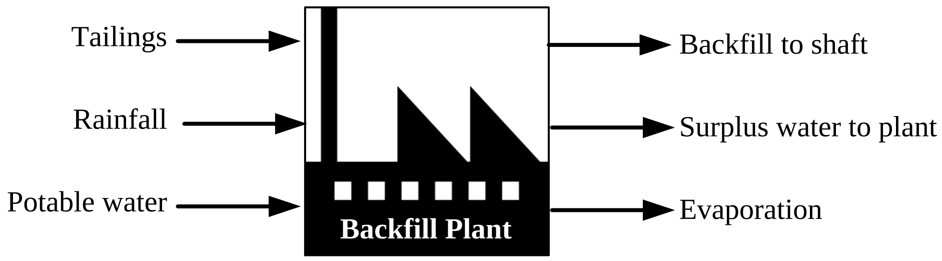


**Figure 17: Standard water balance over a backfill plant.**

The main water inflow for a backfill plant is the water in the tailings slurry that is received from the processing plant. Other water resources include rainfall and potable water used by the staff. Water exits the backfill plant in the backfill slurry that is sent to the shaft to be placed underground. Where the density needs to be lowered, water is removed from the incoming slurry. The water removed is generally pumped back to the processing plant. A small volume of water is also lost through evaporation from open processing tanks. The inflows and outflows are discussed in more detail in the sections that follow.

***Inflows***

*Tailings*

Backfill plants receive tailings from nearby processing plants. The water present in the tailings slurry stream should correspond to that reported by the plant, assuming that there are no leaks in the pipelines.

*Rainfall*

Rainfall received on open dams and water tanks can be estimated by using Equation 14.

*Potable water*

Backfill plants typically only use potable water for employee amenities. The potable water received is measured as it is obtained either directly from the municipality or from a different process unit within the mining operation.

***Outflows***

*Backfill to shaft*

The backfill sent to the shaft for underground deposition is transported as a slurry. The water present in this slurry can be calculated using Equation 12 and Equation 13.

*Surplus water to plant*

Surplus water within the backfill plant is generally sent to the plant to be used as process water. This water volume is measured by the plant.

*Evaporation*

Evaporation occurs over all open dams and water tanks. The evaporation can be estimated by using Table 3 and Equation 15.

*Wastewater*

None of the processes within a backfill plant require potable water. A reasonable assumption is therefore that all potable water used in a backfill plant is used for domestic purposes. Assuming no water is lost through any of these domestic uses, the wastewater generated is equal to the potable water inflow into the plant.

***Summary***

Table 11 gives a summary of the variables used within the water balance calculations for the backfill plant.

**Table 11: Backfill plant water balance summary**

| Variable in water balance | | Type of variable *(measurement / calculation / assumption)* |
|---|---|---|
| ***Inflows*** | *Tailings* | Assumption |
| | *Rainfall* | Calculation (Equation 14) |
| | *Potable water* | Measurement |
| ***Outflows*** | *Backfill to shaft* | Calculation (Equation 12 and Equation 13) |
| | *Surplus water to plant* | Measurement |
| | *Evaporation* | Calculation (Equation 15) |
| | *Wastewater* | Assumption |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.8 Bodies of water

Two types of water bodies are typically present at a gold mine. The first is ponds that occur naturally by means of heavy rainfall. Ponds are not lined and will therefore lose a portion of water through seepage. The second is dams, which are man-made structures. Dams can either be lined, preventing seepage, or unlined, resulting in water loss through seepage. Since the water balance over an unlined dam and a pan consist of the same inflows and outflows, they will be collectively referred to as an unlined body of water. A lined dam will be referred to as such.

Bodies of water have an additional parameter to consider other than inflows and outflows: change in storage. Change in storage is defined as the change in the volume of water present in the water body and should be considered since it may have a significant affect on the water balance over the water bodies.

***Unlined bodies of water***

Figure 18 shows the basic water balance over an unlined body of water.

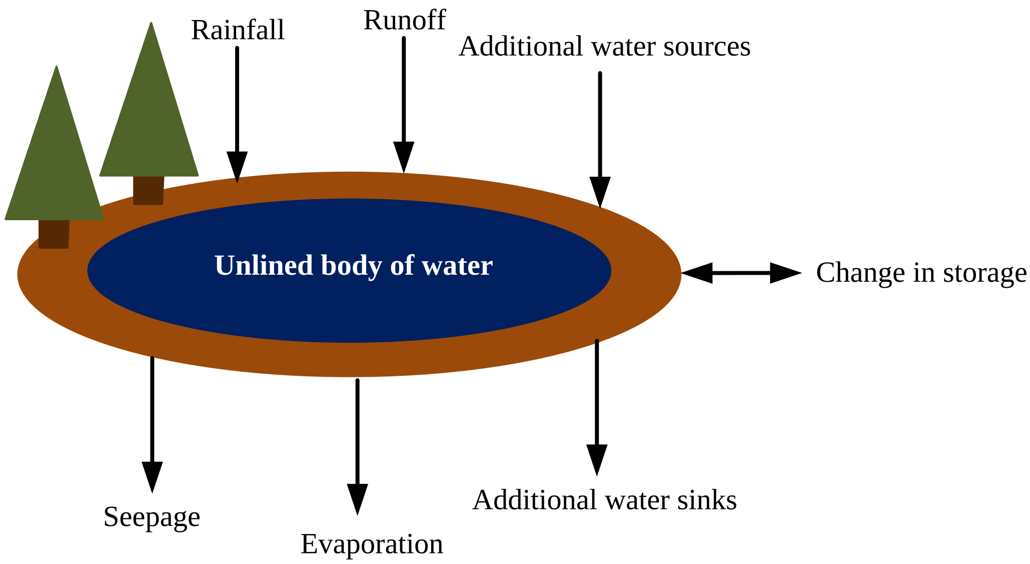


**Figure 18: Basic water balance over an unlined body of water.**

*Inflows*

**Rainfall**

The rainfall received by the pan/dam can be calculated using Equation 14.

**Additional water sources**

Additional water sources into the pan/dam include overflow from other water bodies or discharges from nearby operations. Where possible, these inflows should be measured. If these flows are not measured, they can be solved as the unknown variable of the water balance given the assumption that inflows should be equal to outflows and the change in storage of the water body is known. Special care should be taken to ensure all possible inflows and outflows are accounted for to ensure that the water balance remains as accurate as possible

**Runoff**

Pans/dams generally have large catchment areas. Rainfall received on the catchment area will flow into the pan/dam as runoff. The runoff into the pan/dam can be calculated using Equation 21. Welch [50] proposed that runoff might be about 50% of the rainfall received for larger watersheds such as natural water bodies. This assumption can be used if no variables are known.

*Outflows*

**Seepage**

Seepage may not be accurately quantifiable unless a detailed hydrogeological assessment of the area has been carried out [50]. For this thesis, seepage is calculated using Equation 20.

**Evaporation**

Evaporation will only occur from the surface of the pan/dam. Using Table 3 and Equation 15, the water losses through evaporation can be estimated.

**Additional water sinks**

Additional water sinks or outflows include overflow to nearby streams or dams, water abstracted by nearby operations for use in their systems, or water pumped to other streams or dams.

Measuring overflow of pan/dam is generally not feasible, especially since there is generally no obvious dam wall. Overflow can be solved as the unknown variable within a water balance.

Water abstracted by nearby operations is generally metered. If the volume abstracted is not measured, this volume can be solved by solving it as the unknown together with the overflow, but this would lead to a less accurate water balance. It is advised that any abstractions be measured.

*Change in storage*

Change in storage of a water body can be calculated as the difference between the inflows and outflows of the water body [29]. Parameters such as overflow into and out of a pan is, however, not feasible to be measured, and is not easily quantifiable. By monitoring the water levels as well as surface area of a water body, the change in storage can be estimated by using Figure 19 and Equation 23.

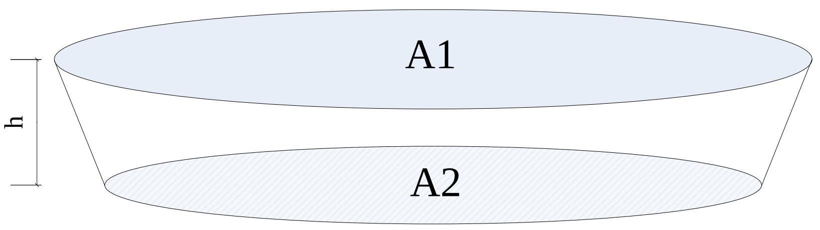


**Figure 19: Cone section diagram used to estimate change in storage of a water body**

$$S = \frac{1}{3}h\left(A1 + \sqrt{A1\,A2} + A2\right) \quad \textbf{Equation 23}$$

Where: S = change in storage of water body (in $m^3$)

h = change in level of water body (in m)

A1 = Surface area at the start of the monitoring period (in $m^2$)

A2 = Surface area at the end of the monitoring period (in $m^2$)

The change in storage in a water body is very dependent on climatic events and may change rapidly. The levels of a water body should therefore be monitored regularly and at least weekly to ensure that the change in storage throughout a month is accurately monitored.

***Lined dam***

Figure 20 shows the basic water balance over a lined dam.

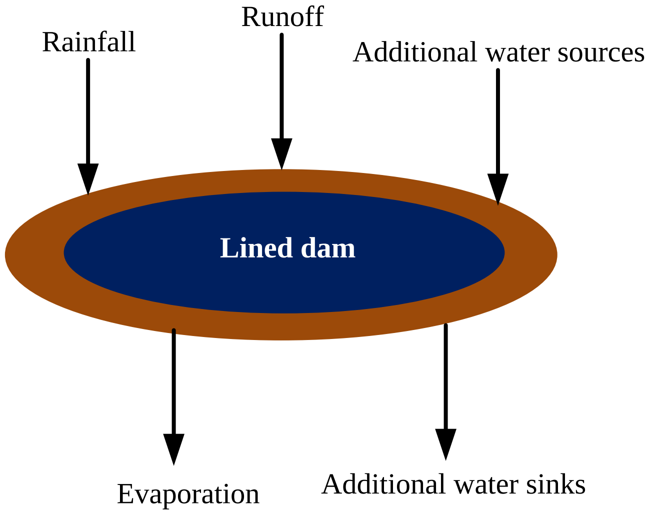


**Figure 20: Basic water balance over a lined dam.**

The four inflow and outflow streams that are considered with the lined dam water balance are discussed further with more detail.

*Inflows*

**Rainfall**

Rainfall received as direct rainfall on the dam surface can be calculated using Equation 14.

**Additional water sources**

Additional water sources or inflows include water pumped into the dam from different water resources such as mining operations, water treatment plants or other dams. These inflows are typically measured.

**Runoff**

Runoff forms from rainfall received on the catchment area of the dam. Equation 21 can be used to calculate the runoff.

*Outflows*

**Evaporation**

Evaporation will occur from the surface of the dam and can be estimated by using Table 3 and Equation 15.

**Additional water sinks**

Additional water sinks or outflows include overflow to nearby trenches, streams, or dams and water abstracted by nearby operations. Although overflow generally cannot be measured, all other measurable outflows should be measured. Overflow can then be estimated by solving it as the unknown variable in the water balance with the assumption that inflows equal outflows.

***Summary***

Table 12 gives a summary of the variables used within the water balance calculations for the two types of water bodies.

**Table 12: Water bodies water balance summary**

| Variable in water balance | | Type of variable (measurement / calculation / assumption) |
|---|---|---|
| **Inflows** | *Rainfall* | Calculation (Equation 14) |
| | *Runoff* | Calculation (Equation 21) |
| | *Additional water sources* | Measurement & assumptions |
| **Outflows** | *Seepage* | Calculation (Equation 20)<br>Only applicable to lined dams |
| | *Evaporation* | Calculation (Equation 15) |
| | *Additional water sinks* | Measurement & assumptions |

The accuracy of the inflows and outflows can be evaluated by using a chart similar to that shown in Figure 11.

### 2.2.9 Process unit water balance development

Generic modular water balance units for all the gold mining process units identified in Section 2.2 were developed in Section 2.2.1 to Section 2.2.8. A summary of the types of variables used to quantify the inflows and outflows for every process unit is shown in Table 4 to Table 12. These generic modular units can be used to develop accurate water balances for each of the processing units. Figure 21 shows the steps required to develop the water balance for a process unit. The sensitivity analysis and the interpretation of the results thereof is discussed in Section 2.3.1.

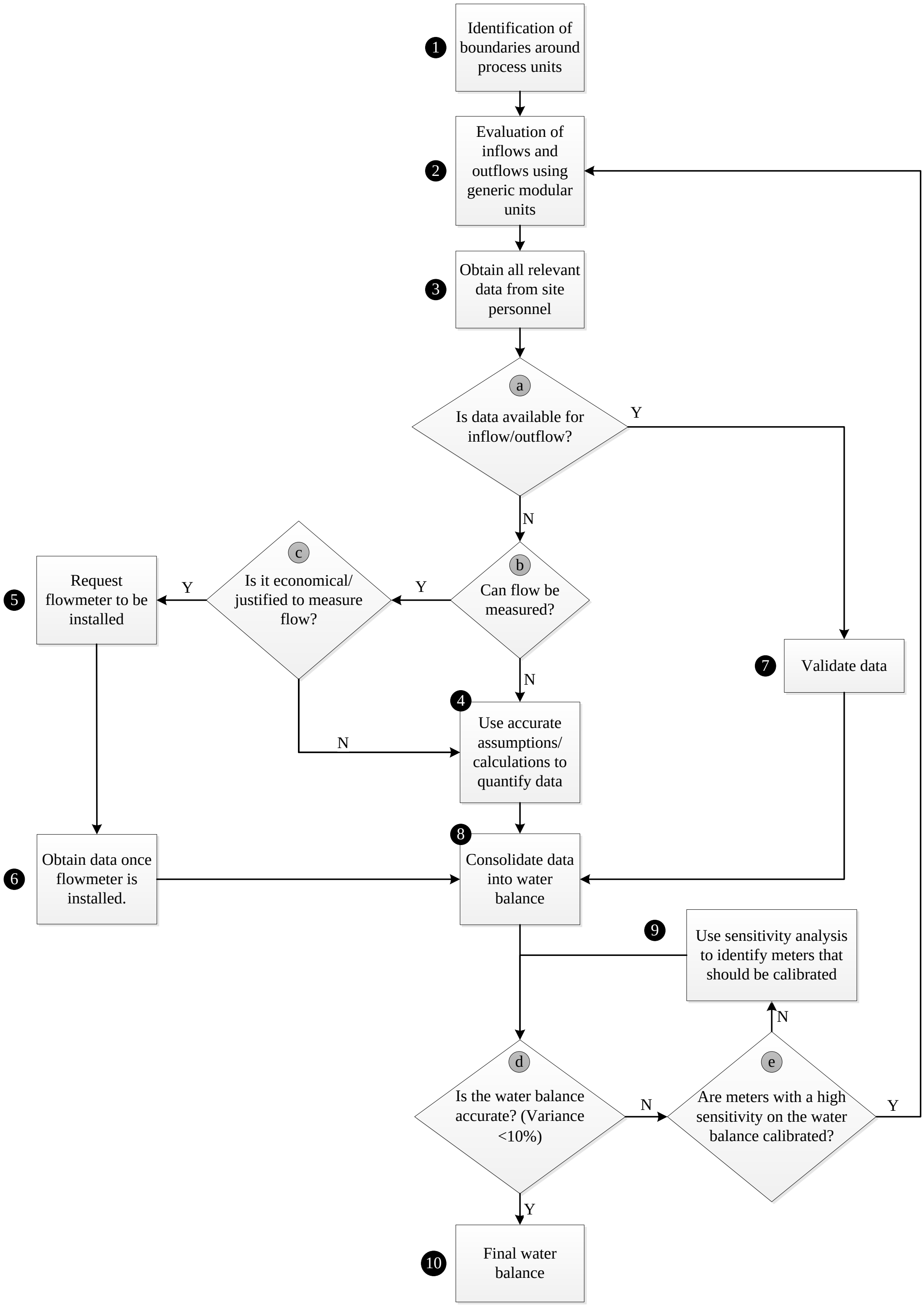


**Figure 21: Steps for the water balance development of a process unit.**

The first step is to identify the boundary for the process unit. After the boundary has been identified, the inflows and outflows can be evaluated by using the generic modular units developed in Section 2.2.

After all the inflows and outflows have been identified, existing water data can be obtained from site personnel (Step 3 in Figure 21). Where data is available for the specific flow, the data must be validated (Step 7). The validation process developed is shown in Figure 22.

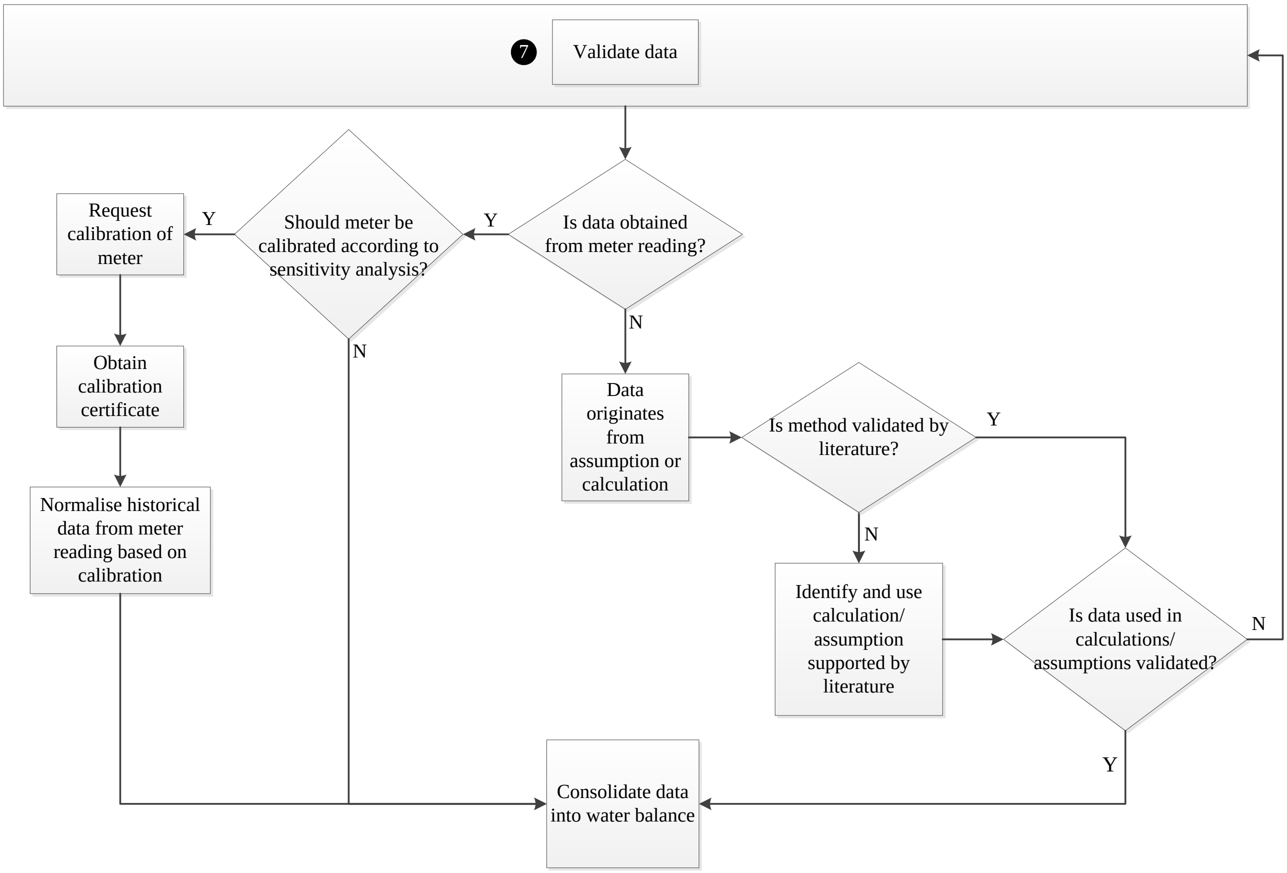


**Figure 22: Data validation steps.**

The first step in validating data is determining if the data originates from a meter reading. Meter readings are the most accurate way to obtain flow data, if the meter is accurate. A sensitivity analysis can be done to determine the importance of calibrating a specific meter. This is discussed in detail in Section 2.3.1. If the meter should be verified, a calibration certificate should be obtained. Once the calibration certificate is obtained, the historical data can be normalised according to the variance in meter accuracy before and after calibration. The data can then be consolidated into the water balance. When there is no need to calibrate the meter (i.e. the sensitivity of the flow is below 10%, as discussed in Section 2.3.1) the existing data can be consolidated into the water balance.

If the data is not obtained from a meter reading, the data originates from either a calculation or an assumption. The calculation or assumption used should be supported by literature. If not, the calculation or assumption developed in Section 2.2 should be used. The data on which the calculation or assumption is based should also be validated before the final data can be consolidated into the water balance.

Once the data is validated, Step 7 from Figure 21 is complete. If there is no existing data for a specific flow, the possibility of measuring the flow should be investigated (decisions b and c). Flow can easily be measured if it flows through a pipeline. If the flow can be measured economically, the installation of a meter is justified. When it is determined that the water balance is highly sensitive to the accuracy of this flow, and the installation, cost and maintenance of the flowmeter are acceptable, it is advised that a meter is installed. However, if there is an accurate way to quantify the flow through an assumption or calculation, or the materiality of the flow is not significant, the installation of a meter is not justified.

Where the flow cannot be measured or the installation of a meter is not justified, the assumptions and calculations discussed in Section 2.2 can be used to quantify the flow (Step 4).

Once all the data has been consolidated into the water balance, the variance (in %) of the water balance can be determined by using Equation 24.

$$Variance = \frac{(Total\ inflows - Total\ outflows)}{Total\ inflows} \times 100 \qquad \text{Equation 24}$$

The variance over a period of time can be evaluated using a graph similar to Figure 11. If the variance over a period of time is less than 10%, the water balance is considered adequately accurate. If the imbalance of the water balance exceeds 10%, the cause should be investigated.

It should firstly be confirmed that the flows with a high sensitivity on the model are measured and the meters are calibrated (decision e). If these meters have been calibrated, the inflows and outflows of the process unit should be re-evaluated to ensure no flows have been overlooked.

The steps shown in Figure 21 should be iterated until an accurate water balance for the process unit is obtained (less than 10% variance). If the steps are followed correctly, accurate water balances should be obtained for all the process units. A graph similar to that shown in Figure 23 can be used to validate the accuracy of the water balances by plotting average variances for all the process units.

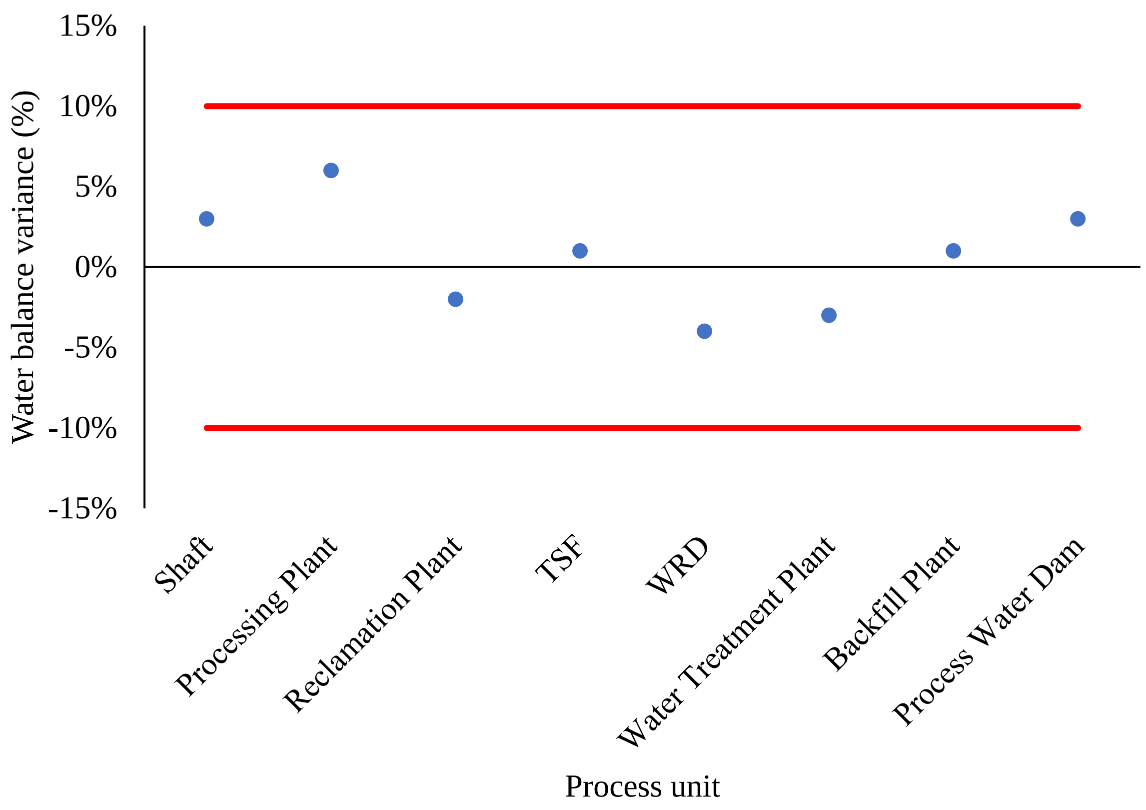


**Figure 23: Compliant process units in a mining operation.**

Although an average variance might obscure inaccuracies within the water balances for specific months, Figure 23 can be used as a final check to ensure that all the process units have been considered and is accurate.

## 2.3 Limitations and uncertainties

Duckstein and Plate [54] lists two uncertainties for water resource issues: (1) data uncertainty and (2) parameter uncertainty. Data uncertainty originates from errors in measurement and the sampling of hydrological variables which are dependent on other factors such as climate or runoff characteristics. Parameter uncertainty (such as runoff or evaporation rates) is due to uncertainties regarding physical parameters in hydraulic phenomena such as wind effects.

Some of the limitations faced by mining operations in terms of their water balances are:

- Metering of streams is not always available.
- Most process water meters are manual meters – this limits the interval in which meter readings can be taken and increases the risk of human error present in the measurements. Most manual meter readings are taken by hand, making verification of these meter readings impossible.

- Meters are not always calibrated, therefore leaving uncertainty in the accuracy of these meters. It is advised to do a sensitivity analysis on the flows in a water balance to identify measures that must be calibrated. A sensitivity analysis method is discussed in the sections that follow.
- Calculations for parameters such as seepage, evaporation, wastewater and runoff need to be simplified since all the parameters required for accurate, comprehensive equations are not always available or measured.
- Rainfall meters are not available or measured throughout mining operations – therefore interpolation is required from time to time. Although this provides a good estimate on the rainfall received, it is not completely accurate.

The listed limitations cause uncertainty in the overall water balance process. To assist with identifying the highest influenceable flows, which will assist in managing uncertainty, a sensitivity analysis of the streams is suggested.

### 2.3.1 Sensitivity analysis

A one-way sensitivity analysis can be used to estimate the influence that a specific variable has on a model (i.e. how sensitive the model is to a change in the specific variable). This is done by varying the variable individually and independently, while other variables within the model remain unchanged [55, 56].

Gous [57] describes a method for a sensitivity analysis that was modified for this specific scenario. The first step of the analysis is to decrease the selected variable by a previously determined or decided percentage and calculate the variance of the water balance. The variable is then increased by a previously determined or decided percentage, and the variable of the water balance is determined again. The variable is then set to its initial value before this process is iterated for other variables.

After the sensitivity analysis for all the selected variables have been completed, a distribution of the results can be obtained from the calculated values. Figure 24 shows an example of a sensitivity analysis distribution plot.

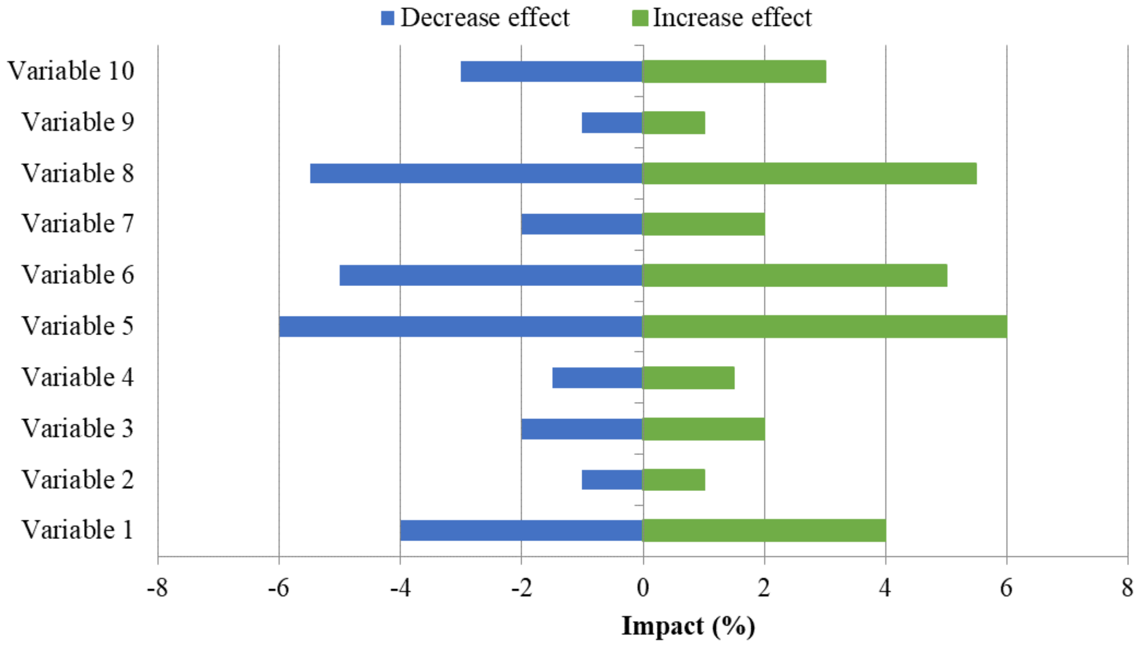


**Figure 24: Example of a sensitivity analysis distribution.**

Figure 24 illustrates the impact of each individual variable on the model. This distribution can be used to determine which inflows or outflows of the model has the highest sensitivity. Variables which have a sensitivity of 5% or more are at risk of creating an imbalance of more than 10% in the water balance. Since water balances are only considered adequately accurate when the imbalance is less than 10%, the accuracy of these variables should be ensured. These flows should be measured wherever possible, and the meters should be calibrated regularly. Where these flows cannot be measured, special attention should be given to the calculations that are used as well as the parameters that are used within these calculations. Where assumptions are required to quantify these flows, these assumptions should be developed meticulously.

### 2.3.2 Accuracy vs time

According to the Global Sustainability Standards Board [58], a balance between the time it will take to complete a task and the reliability of the outcomes needs to be achieved. Therefore, the time required to obtain the parameters required for very complex and extensive equations to quantify flows such as seepage and runoff is not justified when simpler (although slightly less accurate) assumptions and calculations are available.

### 2.3.3 Materiality of streams

Assumptions regarding the materiality of streams should also be considered, for example, rainfall on salvage yards (which will then lead to evaporation/runoff on these areas), water in air from ventilation fans, etc. Streams with a low sensitivity (below 10%) on the total figure do not need to be considered [6]. The sensitivity analysis described in Section 2.3.1 can be used to determine the sensitivity. However, instead of analysing the sensitivity of the parameter on the variance of the water balance, the sensitivity on the total inflows or total outflows should be considered. Where the sensitivity is below 10%, these streams are considered immaterial. They can be included in the water balance if they can be quantified without a great deal of effort; however, they do not need to be considered.

## 2.4 Regional water balance development

All the process units of a possible water system within a gold mining operation have been identified and discussed in detail in Section 2.2. These process units can now be integrated to form a larger water balance system over the entire gold mining operation. Figure 25 shows a procedure developed that can be followed to obtain an accurate water flow diagram for a mining operation. This will assist in determining the specific process units present within the mining operation.

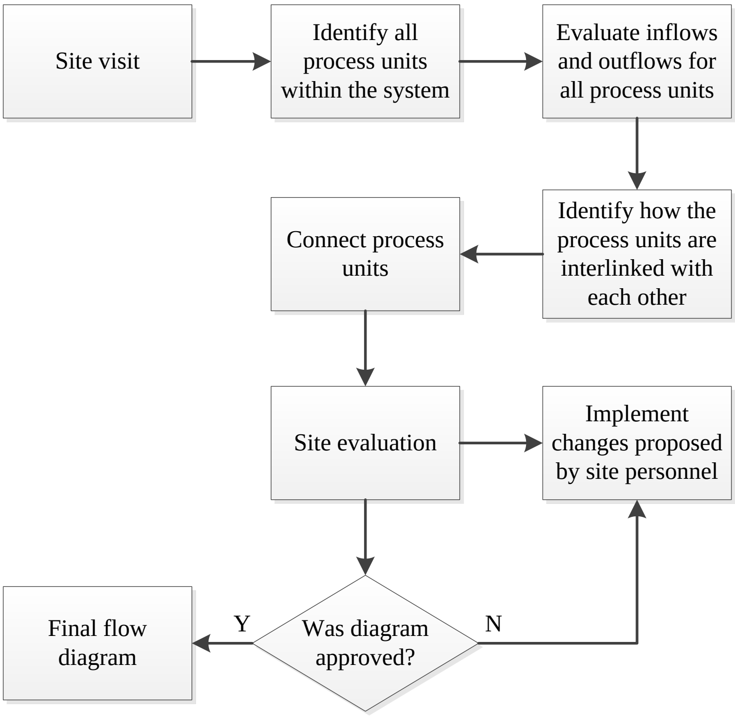


**Figure 25: Regional water flow diagram development tree.**

Firstly, a site visit should be conducted to identify all the process units within the operation. From here the inflows and outflows for all these process units can be evaluated. The interaction between these process units can then be determined with assistance from the process unit inflows and outflows. For example, where a processing plant has tailings as an outflow, the tailings must be deposited on one of the identified TSFs. The ore that the processing plant uses must also originate from one of the identified shafts.

After all the process units have been connected, the water layout should be presented to the relevant site personnel. Changes as proposed by the relevant personnel should be implemented. These steps should be reiterated until the water flow diagram has been approved.

Once the final diagram is developed, the steps illustrated in Figure 26 can be followed to develop the regional water balance. These steps were identified.

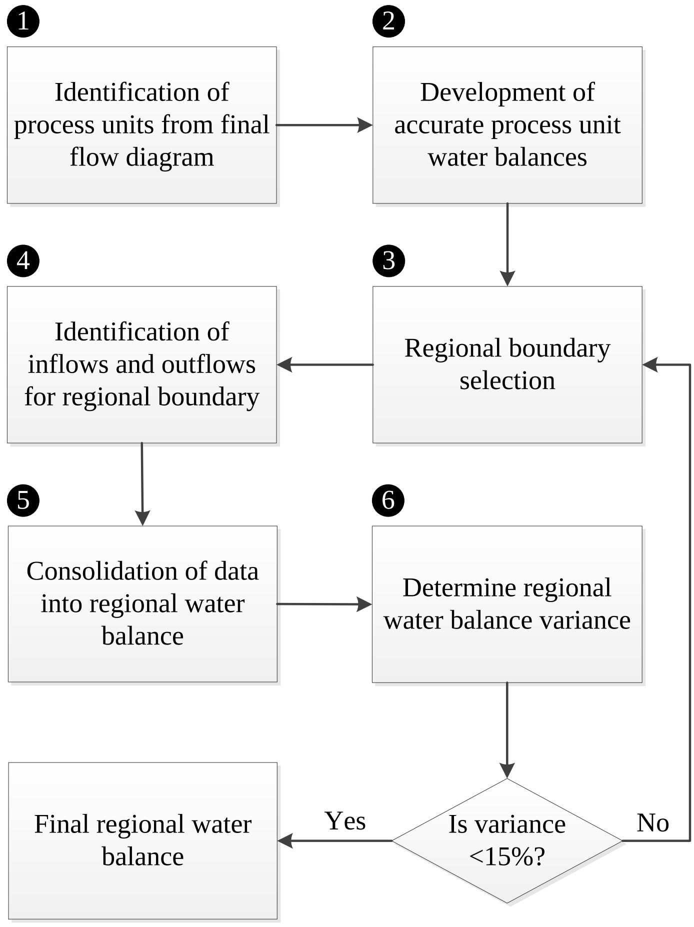


**Figure 26: Regional water balance development steps.**

The procedure discussed in Section 2.2 should then be applied to develop accurate water balances for every process unit. Once all the process units have accurate water balances (less than 10% variance), the regional water balance can be developed. The mining operation is seen as one boundary for the regional water balance. Only water entering or exiting this regional boundary should be considered for the regional water balance. Interactions between process units are therefore not considered. Examples of flows to consider in the regional water balance are:

- Rainfall,
- Seepage,
- Evaporation,
- Interstitial water (even though this water never exits the boundary, it cannot be recovered and is therefore seen as a water loss),
- Water imported from an external source,
- Water pumped to an external source,
- Water pumped from underground, and
- Water pumped to underground (both service and potable water).

All these flows should already be considered within one of the process unit water balances. Therefore, after identifying these flows, the data can be consolidated into the water balance. The variance of the water balance can then be determined. These steps should be re-iterated until the variance of the regional water balance is less than 15% (10% on an individual process unit level) since this is the threshold given by the DWS as discussed in Section 1.5. If the variance is acceptable (less than 15%), the water balance is considered to be adequately accurate.

## 2.5 Verification of water balance compliance

Sections 2.2 to 2.4 explain the steps required to develop accurate and detailed water balances for individual process units within a mining operation as well as the overall water balance. To ensure that the developed water balances comply with all the regulations set out by the DWS, criteria were developed as a validation step. Firstly, to ensure that the water balance is accurate, it should be ensured that all the process units are accounted for and that all the relevant flows for each of these process units have been considered. To further justify the accuracy of these water balances, the variance per process unit should not exceed 10% and the variance for the operation should not exceed 15%. This will ensure that the water balances are considered as accurate by the DWS, as explained in Section 1.5.2. A sensitivity analysis should be done to ensure that the data within the water balances are reliable and accurate. Lastly it should be ensured that the assumptions made have been substantiated and are traceable.

These criteria are shown in Table 13.

**Table 13: Criteria for the validation of the water balance methodology.**

| Criteria | Yes/No |
|---|---|
| Are all process units accounted for? | |
| Are all relevant streams accounted for? | |
| Is the variance over all process units lower than 10%? | |
| Is the variance over the mining operation lower than 15%? | |
| Has a sensitivity analysis been done to identify flowmeters that require calibration? | |
| Are all assumptions validated? | |

Firstly, it is important that all the process units are accounted for. Once all the process units are known, the relevant streams for every process unit should be considered. Therefore, all streams with a materiality of more than 10% should be considered (Section 2.3.3). Once the streams have been identified and quantified, the variance per process unit should be less than 10%. Once this is achieved, the process units can be interlinked to create the regional water balance (Section 2.4), which should have an overall variance of less than 15%.

A sensitivity analysis should be conducted to identify flows with a high sensitivity towards the water balances. The sensitivity analysis in essence indicates the most important flows for which meters should be calibrated. A request to calibrate these meters should then be sent. Whether these meters get calibrated is outside the scope of this thesis.

If faulty meter readings are to blame for an imbalance of the water balances, this will lead to non-compliance with the DWS and will therefore have adverse effects. In this case it is essential to have these meters calibrated.

Lastly, it should be ensured that all the assumptions made have been validated through literature. If all the criteria (with the possible exception of the meter calibration) have been met, the water balances can be considered as compliant.

## 2.6 Review of methodology practicality

Sections 2.2 to 2.5 explain the steps required to develop accurate and detailed water balances that comply with all the required regulations set out by the South African government. A comprehensive methodology was developed to assist with the development process. It is critical that the methodology is practical, since an overly complex model will fail in the mining sector. It is therefore necessary to evaluate the practicality of this methodology. Hustrulid, et al. [59] suggests that water balances should consist of the following properties:

- Simple and easy to use and should have identifiable input data.

- Easy to understand and validate.
- Be set up in such a way that the input data can be varied to implement changes within the system.
- Easy to be used by both mine personnel as well as regulators.

If a methodology meets all four of the terms listed above, it is considered to be practical. Considering the methodology discussed in the preceding sections, the development of water balances has been simplified with clearly laid out steps. The inputs of the water balances will be easily identified throughout the development process.

Validation steps have been incorporated to ensure continuous validation of the water balances. Options and alternatives have been discussed to adjust the water balance inputs according to data availability. Any changes within the system can be easily implemented by retracing the steps followed to develop the initial water balance. The water balances are accompanied by water flow layouts, making the water system of the mine, as well as the interconnectivity thereof, easy to understand.

The methodology developed therefore meets all the requirements listed above and is considered to be practical. Accurate, detailed water balances that comply with all the required regulations should be easily obtainable if the methodology discussed in Sections 2.2 to 2.5 is followed.

## 2.7 Conclusion

Water balance within the deep-level gold mining industry is a critical requirement in ensuring compliance with the legislation and regulations regarding water uses in South Africa.

General modular units for all the possible processing units within the deep-level gold mining industry were developed in Section 2.2, and the quantification of all the relevant flows is discussed in detail. The limitations and uncertainties affecting these generic modular units are highlighted in Section 2.3.

A methodology to link the process units within the mining operation is discussed in Section 2.4, providing the steps necessary to develop the regional water balance for the mining operation. Section 2.5 provided a detailed evaluation of water balance compliance and criteria were created to validate the accuracy of the developed water balances.

Lastly, the practicality of the developed methodology was investigated in Section 2.6 to ensure that the methodology will be easily implementable in the gold mining industry.

# IMPLEMENTATION AND RESULTS

## 3.1 Preamble

In chapter 2, a methodology that will enable mining operations to develop accurate and detailed water balances was developed. In this chapter, this methodology will be applied to a mining operation to verify whether the methodology delivers the required level of detail and accuracy.

The mining operation includes most of the relevant process units within a gold mining company. An expansion of the mining operation to two nearby mining operations ensures that the methodology will be evaluated. The water balances developed will be evaluated based on their accuracy and level of detail. Figure 27 illustrates the outline of Chapter 3.

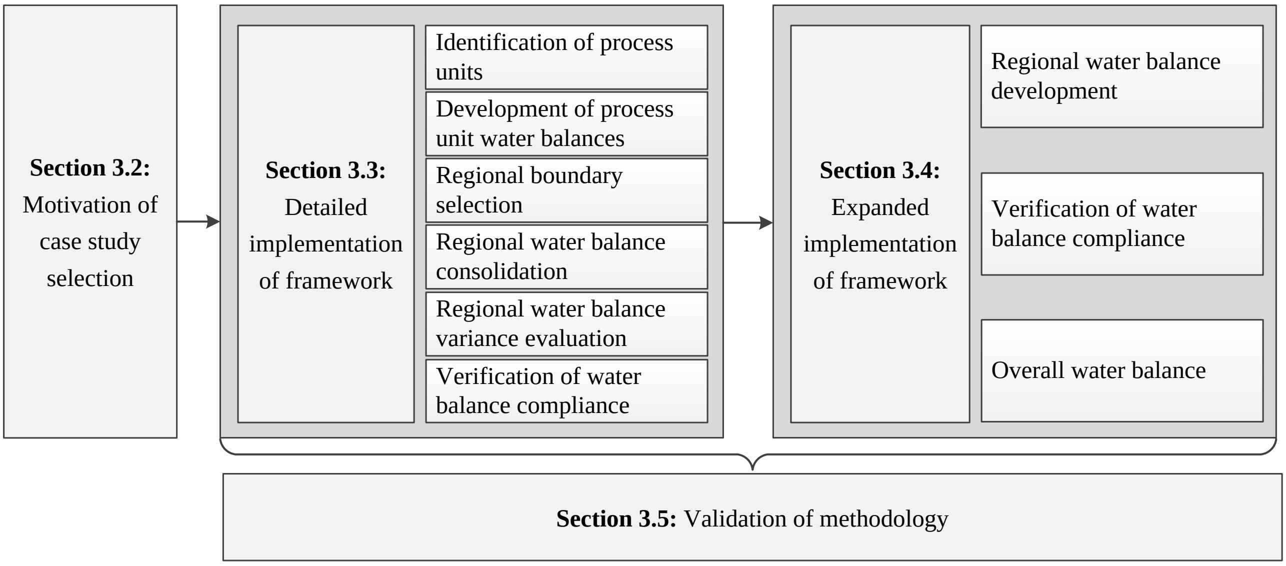


**Figure 27: Outline of Chapter 3.**

## 3.2 Motivation for case study selection

The methodology developed in Chapter 2 was tested on a gold mining operation in SA (hereinafter referred to as mining operation A). The mining operation includes the majority of process units discussed within Chapter 2 and displays the expected interactions between these different process units. This mining operation therefore provides for comprehensive validation of the developed methodology.

The mining operation, however, interacts with nearby mining operations and therefore forms part of a larger integrated regional water network. The methodology was expanded to two of the nearby mining operations, ensuring that all aspects of the methodology are tested.

The summarised methodology that will be followed throughout the mining operations is indicated in Figure 28 and Figure 29 for ease of reference. Figure 29 lists the sub-steps required for Step 2 in Figure 28. The steps have been renumbered accordingly in Figure 29.

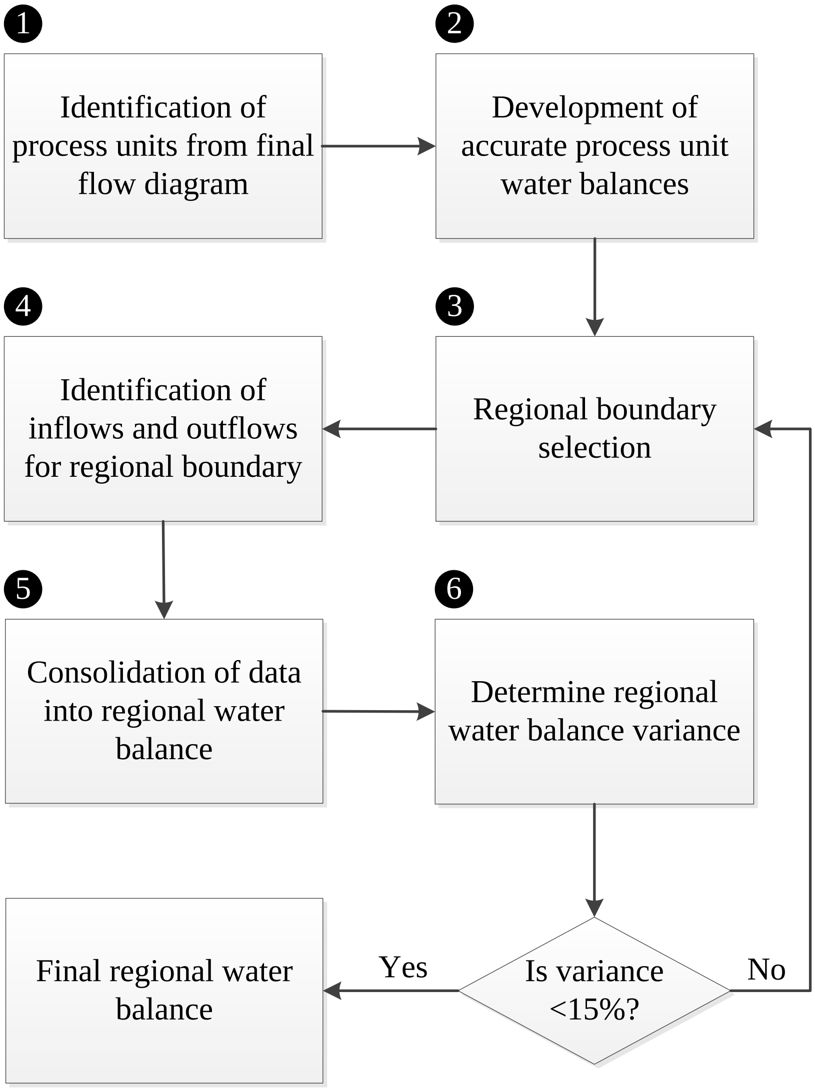


**Figure 28: Regional water balance development procedure**

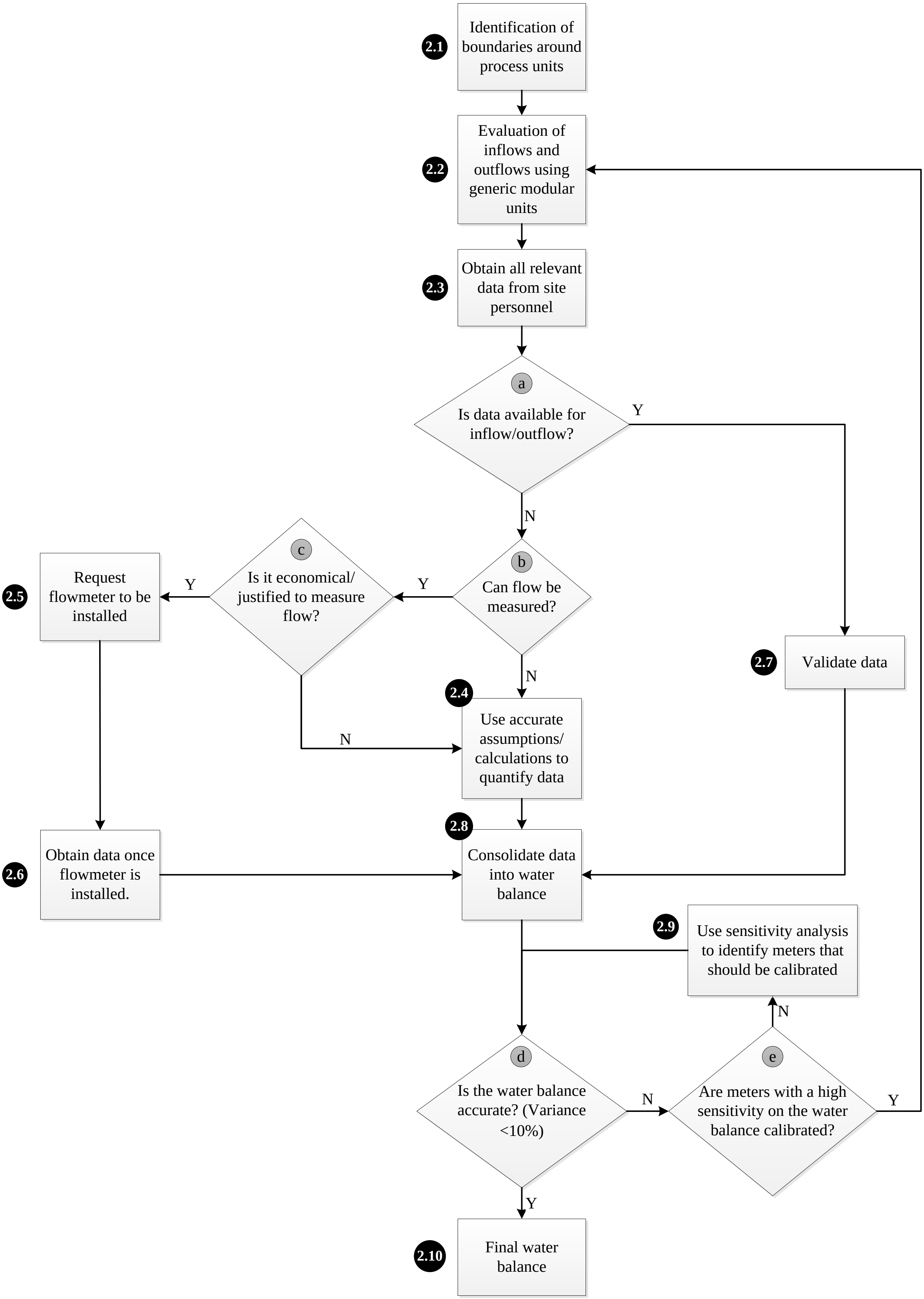


**Figure 29: Steps for the water balance development of a process unit**

## 3.3 Detailed implementation of framework on gold mining operation A

### 3.3.1 Step 1: Identification of process units from final flow diagram

Mining operation A represents a typical gold mining operation in SA. After evaluation of the mining operation during a site visit as proposed in Figure 25, it was established that mining operation A consists of three mining shafts, a processing plant, seven waste rock dumps (WRDs), three tailings storage facilities (TSFs), a water treatment plant (WTP), and a backfill plant. There is also one unlined dam and two lined dams that form part of the mining operation. The process units are summarised in Table 14 along with some additional information.

**Table 14: Process units within mining operation A.**

| **Process unit** | **Number of process units in operation** | **Additional comments** |
|---|---|---|
| Processing Plant | 1 | The ore from the active mining shaft is sent directly to the processing plant. There is no waste rock currently being produced. |
| Shaft | 3 | Active mining only occurs at one of the shafts. The other shafts are used for ventilation or dewatering purposes. |
| Waste rock dump | 7 | There are 6 dormant waste rock dumps that form part of the mining operation. One of the waste rock dumps is being reprocessed by the processing plant. |
| Tailings storage facility | 3 | There is one active tailings storage facility within this mining operation. It is made up of two sections, which function as different units. They will therefore be viewed as two separate process units. The third tailings storage facility is dormant. |
| Wastewater Treatment Facility | 1 | Wastewater from the dewatering shaft is treated at the wastewater treatment facility. |
| Backfill Plant | 1 | Backfill is sent underground at the active mining shaft. |
| Unlined Dam | 1 | There is one unlined dam within the mining operation. |
| Lined Dam | 2 | There are two lined dams within the mining operation. |

After all the process units were identified, their respective inflows and outflows as well as the interconnectivity between them were investigated. After all the required information was obtained, together with input from site personnel, the final water flow diagram was developed.

By using the methodology indicated in Figure 28, the next step is to develop accurate water balances for every process unit in the mining operation. This is compiled in the next section in accordance with the developed balances in Chapter 2 (Section 2.2).

### 3.3.2 Step 2: Development of accurate process unit water balances

The methodology detailed in Figure 29 was used to develop the water balances for the respective process units. The first step (Step 2.1) was to identify boundaries for the process units. The boundaries are indicated with blue dashed lines in Figure 30. Greyed out areas indicate that these process units do not fall within the boundary of the mining operation. The water balances of these process units will not be evaluated. Dotted lines indicate underground water paths and also do not form part of the relevant boundaries.

The next step requires the evaluation of all the inflows and outflows for the selected boundaries. All streams entering the boundaries shown in Figure 30 are therefore seen as inflows and all streams exiting these boundaries are outflows, for every process unit respectively.

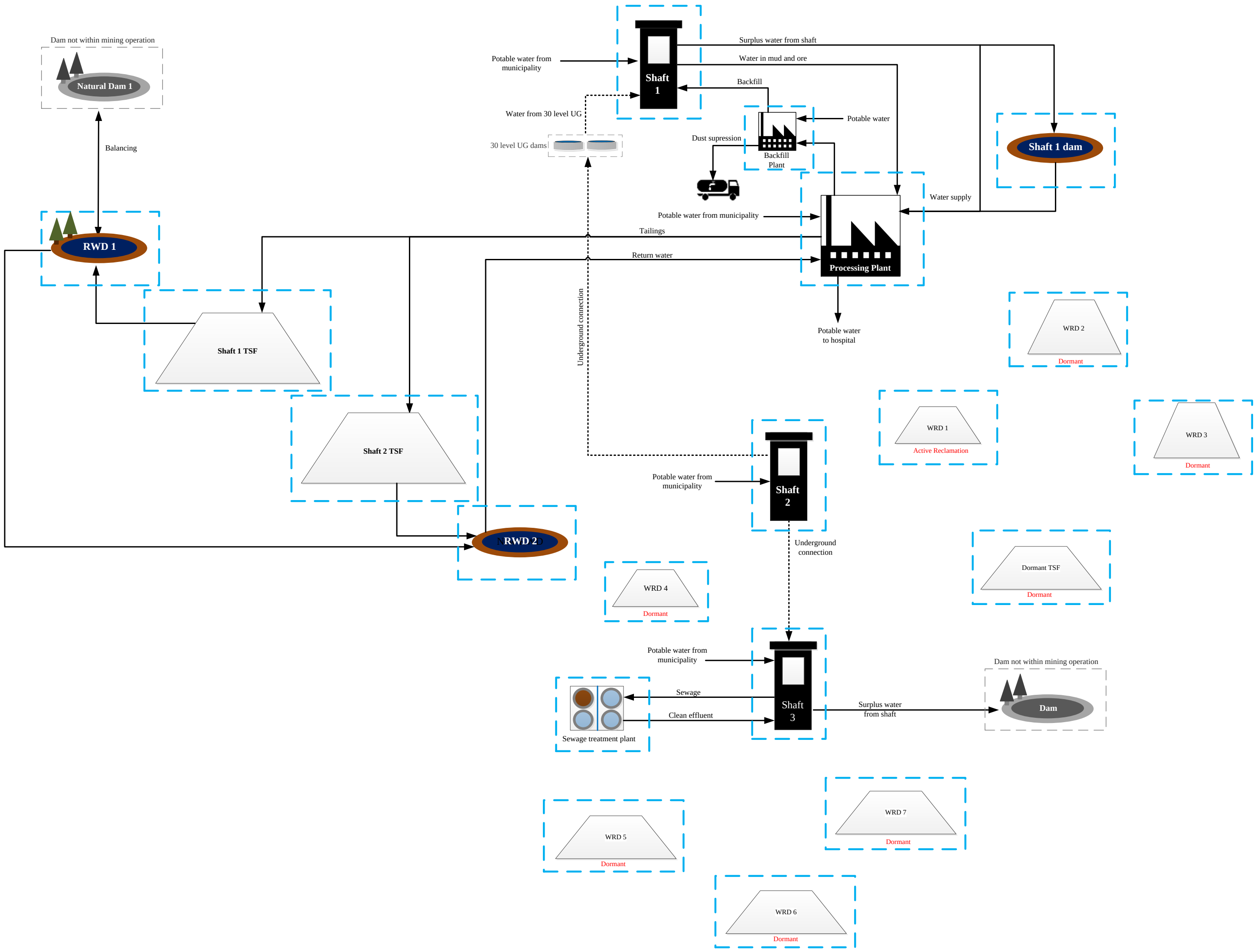


**Figure 30: Final flow diagram for the mining operation A.**

***Step 2.2: Evaluation of inflows and outflows***

The evaluation of the inflows and outflows of the processing plant will be discussed in detail within this chapter. The same method was applied to evaluate the inflows and outflows of the remaining process units within the mining operation. A summary of the outcomes will be discussed within this chapter. The detailed evaluation of inflows and outflows for all of the processing units can be seen in Appendix A.

*Processing Plant (detailed)*

Considering the generic modular unit shown in Figure 12, all inflows and outflows relevant to the processing plant in this mining operation were identified. The inflows and outflows for the processing plant are shown in Figure 31.

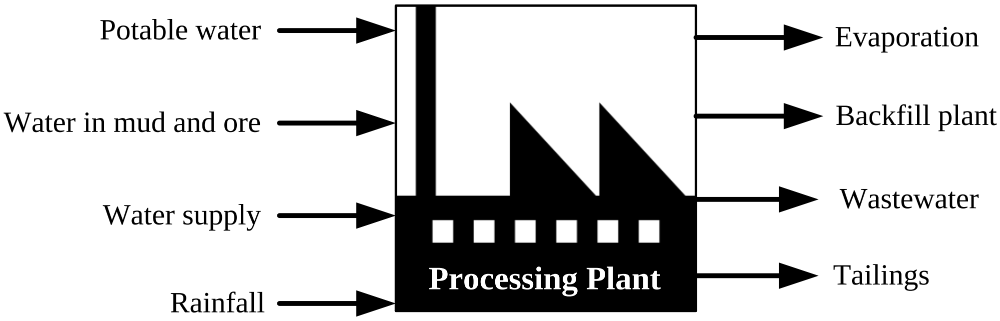


**Figure 31: Water balance for the processing plant in mining operation A.**

The processing plant sends a certain portion of tailings to a nearby backfilling plant. The processing plant receives its water supply from three resources: return water, water from a nearby lined process water dam, and water from the backfill plant. Additionally, potable water, water in mud and ore and rainfall are also seen as an inflow to the processing plant. The water received from the shaft can be either directly fed from the shaft or fed via a lined process water dam which acts as a holding dam for the water.

*Mining operation (summary)*

The process was repeated for all the processing units using the modular units developed in Section 2.2. The resulting flow diagram as well as additional detail on the processing units for mining operation A can be found in Appendix A.

Once all the inflows and outflows for the process units have been identified, the available data from the mining operation could be evaluated, and the flows could be quantified. This is done in detail for the processing plant. A summary of all the process units is available in Table 23.

### *Step 2.3 – Step 2.7: Consolidation of available data*

*Processing plant (detailed)*

**Potable water**

The potable water fed into the plant is measured and reported by the plant monthly.

**Water in mud and ore**

The processing plant receives mud and ore that is hoisted from Shaft 1. This inflow can be divided into two sections: water in mud and water in ore. The volume of mud that is received from the shaft is measured and recorded by the plant monthly. The moisture content of the ore that is hoisted is also measured by the plant, while the tonnes of ore that are hoisted are measured and recorded by the shaft. The mud hoisted from underground has a constant specific gravity of 1.0125 and a constant dry solids density of 2.67.

In July 2020, there was 0.96 $m^3$ of mine sludge and 65 164.55 tonnes of wet ore hoisted from underground. The moisture content of ore was measured as 3.19% for July 2020. Using the SG and density supplied by the plant, the volume of water present in the slurry could be calculated using Equation 12 and Equation 13:

$$x_{Sl} = \frac{2.67(1.0125 - 1)}{1.0125(2.67 - 1)} = 0.0197$$

$$Water\ in\ slurry = \frac{1 - 0.0197}{0.0197} = 47.68\%$$

$$Volume\ of\ water = 47.68\% \times 0.96 = 0.48\ \text{m}^3$$

Water in ore was calculated by using Equation 10 and Equation 11. However, Equation 10 requires dry tonnes as an input and therefore the wet tonnes must first be converted to dry tonnes using the moisture content as follows:

$$Dry\ tonnes = \frac{65\ 164.55}{1} \times (1 - 0.0319) = 63\ 085.80$$

The moisture volume present in the ore can then be calculated as shown:

$$Mass\ of\ water\ in\ ore = \frac{63\ 085.80}{1 - 0.0319} - 63\ 085.80 = 2\ 078.75$$

$$Volume\ of\ water\ in\ ore = \frac{2\ 078.75}{1000} = 2\ 078.75$$

It can be noted that since the wet tonnes of ore and moisture content was given, a simpler approach for calculating the water volume would be to simply multiply the wet tonnes with the moisture content.

The data obtained from the mining operation as well as the calculated volumes for these flows for a 12-month period is shown in Table 15.

**Table 15: Water in mud and ore volumes for the processing plant in mining operation A.**

| | Mine sludge volume ($m^3$) | Ore moisture % | Tonnes hoisted (wet tonnes) | Water in mud ($m^3$) | Water in ore ($m^3$) | Total water in mud and ore ($m^3$) |
|---|---|---|---|---|---|---|
| **Jul-20** | 0.960 | 3.2 | 65 165 | 0.48 | 2 079 | **2 079** |
| **Aug-20** | 8.336 | 3.7 | 72 345 | 4.14 | 2 641 | **2 645** |
| **Sep-20** | 88.050 | 3.3 | 82 029 | 43.73 | 2 740 | **2 784** |
| **Oct-20** | 56.011 | 3.0 | 79 883 | 27.82 | 2 412 | **2 440** |
| **Nov-20** | 42.817 | 2.7 | 82 180 | 21.26 | 2 252 | **2 273** |
| **Dec-20** | 70.890 | 3.6 | 64 304 | 35.21 | 2 341 | **2 376** |
| **Jan-21** | 70.890 | 2.9 | 57 053 | 35.21 | 1 643 | **1 678** |
| **Feb-21** | 36.259 | 4.3 | 47 652 | 18.01 | 2 040 | **2 058** |
| **Mar-21** | 61.010 | 3.8 | 65 389 | 30.30 | 1 850 | **1 880** |
| **Apr-21** | 10.320 | 2.7 | 78 327 | 5.13 | 2 097 | **2 102** |
| **May-21** | 50.546 | 2.6 | 62 734 | 25.10 | 1 642 | **1 667** |
| **Jun-21** | 25.380 | 2.7 | 68 486 | 12.60 | 1 844 | **1 857** |

**Water supply**

As discussed previously, the processing plant receives its water supply from three resources. The two major resources are return water from the TSF and water from the shaft. Water from the shaft can be received either directly from Shaft 1 or from a nearby lined process water dam which acts as a holding dam for shaft water. The third resource is water from the backfilling plant. The backfilling plant increases the density of the tailings before sending them underground. The water removed from the tailings is then sent back to the plant as a slurry since a small portion of solids is removed with the excess water.

The volume of the slurry received from the backfill plant is measured by the plant. An average slurry density of 1.16184 tonne/$m^3$ is assumed by the plant. A solids density of 2.67 is also reported by the plant. In July 2020 and August 2020, the slurry from the backfill plant totalled to 0 tonnes and 1 653.64 tonnes, respectively. There was therefore no water received from the backfill plant in July 2020. Equation 12 and Equation 13 was used to calculate the volume of water in the slurry as follows:

$$x_{Sl} = \frac{2.67(1.16184 - 1)}{1.16184(2.67 - 1)} = 0.2227$$

$$Water\ in\ slurry = \frac{1-0.2227}{0.2227} = 3.49\%$$

$$Water\ in\ slurry = 3.49\% \times 1\ 653.64 = 5\ 771.53\ tonnes$$

$$Volume\ of\ water = 5\ 771.53/1 = 5\ 771.53\ \ \text{m}^3$$

The slurry tonnes as well as the water in the slurry received from the backfill plant for 12 months are shown in Table 16.

**Table 16: Water in backfill received from backfill plant by the processing plant in mining operation A.**

| | Backfill to plant slurry (tonnes) | Water in slurry ($m^3$) |
|---|---|---|
| **Jul-20** | 0 | 0 |
| **Aug-20** | 1 654 | 5 772 |
| **Sep-20** | 9 990 | 34 866 |
| **Oct-20** | 13 725 | 47 903 |
| **Nov-20** | 12 652 | 44 158 |
| **Dec-20** | 3 188 | 11 125 |
| **Jan-21** | 0 | 0 |
| **Feb-21** | 0 | 0 |
| **Mar-21** | 0 | 0 |
| **Apr-21** | 2 179 | 7 604 |
| **May-21** | 3 381 | 11 801 |
| **Jun-21** | 2 502 | 8 732 |

There was no backfilling that was processed and sent underground in July 2020 and January to March 2021.

The total water supply received by the plant is the total of the return water, water from underground both directly and via the lined process water dam, and the water received from the backfill plant. The return water, water from Shaft 1 and water from the lined process water holding dam are all measured. The total water supply is shown Table 17.

**Table 17: Water supply for the processing plant in mining operation A.**

| | Return water ($m^3$) | Water from Shaft 1 ($m^3$) | Water from lined process water dam ($m^3$) | Water in slurry from backfill plant ($m^3$) | Total water supply ($m^3$) |
|---|---|---|---|---|---|
| **Jul-20** | 37 670 | 28 574 | 44 692 | 0 | **110 936** |
| **Aug-20** | 54 339 | 54 927 | 30 387 | 5 772 | **145 425** |
| **Sep-20** | 48 335 | 50 452 | 27 999 | 34 866 | **161 652** |
| **Oct-20** | 48 335 | 65 526 | 27 970 | 47 903 | **189 734** |
| **Nov-20** | 35 152 | 69 338 | 30 298 | 44 158 | **178 946** |
| **Dec-20** | 30 036 | 49 388 | 41 822 | 11 125 | **132 371** |
| **Jan-21** | 20 134 | 57 328 | 40 232 | 0 | **117 694** |
| **Feb-21** | 46 193 | 31 264 | 29 856 | 0 | **107 313** |
| **Mar-21** | 34 880 | 57 386 | 38 158 | 0 | **130 424** |
| **Apr-21** | 51 631 | 61 948 | 31 929 | 7 604 | **153 112** |
| **May-21** | 38 516 | 59 009 | 29 404 | 11 801 | **138 730** |
| **Jun-21** | 55 112 | 58 575 | 19 850 | 0 | **142 269** |

## Rainfall

The processing plant has a rainfall meter and the total rainfall received is reported monthly. Rainfall received on all open water dams and water tanks within boundary of the plant is considered. Google Earth was used to estimate the surface area of all the open water dams and water tanks as 2 915 $m^2$. There was no rainfall reported in July or August 2020, and 3 mm of rainfall was reported in September. Equation 14 was used to determine the total rainfall received for September as shown:

$$Rainfall = \left(\frac{3}{1000}\right) x \ (2\ 915) = 117 \ \text{m}^3$$

The rainfall measured as well as the obtained rainfall volumes for the 12-month period are shown in Table 18.

**Table 18: Rainfall volumes for the processing plant in mining operation A.**

| | Rainfall received (mm) | Rainfall volumes ($m^3$) |
|---|---|---|
| **Jul-20** | 0 | 0 |
| **Aug-20** | 0 | 0 |
| **Sep-20** | 3 | 9 |
| **Oct-20** | 40 | 117 |
| **Nov-20** | 51 | 149 |
| **Dec-20** | 205 | 598 |
| **Jan-21** | 114 | 332 |
| **Feb-21** | 94 | 274 |
| **Mar-21** | 94 | 274 |
| **Apr-21** | 18 | 52 |
| **May-21** | 0 | 0 |
| **Jun-21** | 0 | 0 |

### Evaporation

Evaporation occurs from the open water dams and tanks within the plant boundary. The surface area of these open dams is the same as that estimated for rainfall calculations in the preceding section. The evaporation rates listed in Table 3 can be used together with Equation 15 to determine the volumes of water lost to evaporation. The calculation for July is shown:

$$Evaporation = 2\,915 \times \left(\frac{206.25}{1000}\right) = 228 \text{ m}^3$$

The monthly evaporation calculate for the 12-month period is shown in Table 19.

**Table 19: Evaporation losses for the processing plant in mining operation A.**

| | Evaporation ($m^3$) |
|---|---|
| **Jul-20** | 228 |
| **Aug-20** | 312 |
| **Sep-20** | 428 |
| **Oct-20** | 535 |
| **Nov-20** | 588 |
| **Dec-20** | 620 |
| **Jan-21** | 601 |
| **Feb-21** | 475 |
| **Mar-21** | 424 |
| **Apr-21** | 321 |
| **May-21** | 252 |
| **Jun-21** | 201 |

### Water to backfill plant

A certain portion of the tailings generated by the plant is sent to a backfilling plant. The tonnes of this slurry as well as its density are measured continuously by the plant. A solids density of 2.67 is reported. There was no backfill for July 2020. Backfill of 3 720.69 tonnes with a density of 1.29 was reported in August 2020. Equation 12 and Equation 13 was used to calculate the volume of water in the slurry:

$$x_{Sl} = \frac{2.67(1.26 - 1)}{1.26(2.67 - 1)} = 0.33$$

$$Water\ in\ slurry = \frac{1 - 0.33}{0.33} = 2.03\%$$

$$Water\ in\ slurry = 2.03\% \times 3\,720.69 = 7\,557\ tonnes$$

$$Volume\ of\ water = \frac{7\,557}{1} = 7557\ \ \mathrm{m}^3$$

These figures and volumes for the 12-month period are shown in Table 20.

**Table 20: Water from processing plant to backfill plant in mining operation A.**

| | Tailings to backfill (tonnes) | Average slurry SG | Volume of water ($m^3$) |
|---|---|---|---|
| **Jul-20** | 0 | 1.29 | **0** |
| **Aug-20** | 3 721 | 1.26 | **7 557** |
| **Sep-20** | 22 477 | 1.30 | **38 444** |
| **Oct-20** | 30 882 | 1.24 | **68 915** |
| **Nov-20** | 28 467 | 1.28 | **52 929** |
| **Dec-20** | 7 172 | 1.28 | **13 335** |
| **Jan-21** | 0 | 1.26 | **0** |
| **Feb-21** | 0 | 1.21 | **0** |
| **Mar-21** | 0 | 1.25 | **0** |
| **Apr-21** | 4 902 | 1.26 | **10 150** |
| **May-21** | 7 608 | 1.26 | **15 452** |
| **Jun-21** | 5 629 | 1.26 | **11 413** |

There was no backfill in the months of Jul 2020, and January to March 2021.

### Wastewater

The potable water distribution within the plant is not measured. Therefore, the average water consumption as reported by Mckenzie, et al. [26] was used to estimate the wastewater. The average water consumption per person per day for the municipality in which the plant falls is 224 litres per person per day. There is an average of 84 people working on the plant every day throughout the whole month. The estimated wastewater generated from this is shown in Table 21.

**Table 21: Wastewater generated by the processing plant in mining operation A.**

| | Wastewater generated ($m^3$) |
|---|---|
| **Jul-20** | 5 824 |
| **Aug-20** | 5 824 |
| **Sep-20** | 5 636 |
| **Oct-20** | 5 824 |
| **Nov-20** | 5 636 |
| **Dec-20** | 5 824 |
| **Jan-21** | 5 824 |
| **Feb-21** | 5 261 |
| **Mar-21** | 5 824 |
| **Apr-21** | 5 636 |
| **May-21** | 5 824 |
| **Jun-21** | 5 636 |

**Tailings**

The tailings that are generated by the plant that are not sent to the backfilling plant are pumped to a TSF. The total tonnes and density of the tailings are continuously measured. A solids density of 2.67 is reported by the plant. In July 2020 the plant reported a total of 68 413 tonnes tailings deposited with an average density of 1.29. This information can be used in conjunction with Equation 12 and Equation 13 to calculate the volume of water exiting the boundary with the slurry:

$$x_{Sl} = \frac{2.67(1.29 - 1)}{1.29(2.67 - 1)} = 0.36$$

$$Water\ in\ slurry = \frac{1 - 0.36}{0.36} = 1.78\%$$

$$Water\ in\ slurry = 1.78\% \times 68\ 413 = 121\ 929\ tonnes$$

$$Volume\ of\ water = \frac{121\ 929}{1} = 121\ 929\ \ \mathrm{m}^3$$

The total slurry tonnes, average monthly density as well as calculated volume of water in the slurry for the period are shown in Table 22.

**Table 22: Water in tailings from processing plant to TSF in mining operation A.**

| | Tailings to TSF (tonnes) | Average slurry SG | Volume of water ($m^3$) |
|---|---|---|---|
| **Jul-20** | 68 413 | 1.29 | 121 929 |
| **Aug-20** | 71 967 | 1.26 | 146 173 |
| **Sep-20** | 68 338 | 1.30 | 116 882 |
| **Oct-20** | 63 330 | 1.24 | 141 325 |
| **Nov-20** | 65 841 | 1.28 | 122 417 |
| **Dec-20** | 61 135 | 1.28 | 113 668 |
| **Jan-21** | 58 104 | 1.26 | 118 016 |
| **Feb-21** | 46 821 | 1.21 | 123 258 |
| **Mar-21** | 63 271 | 1.25 | 135 022 |
| **Apr-21** | 75 507 | 1.26 | 156 345 |
| **May-21** | 56 540 | 1.26 | 114 838 |
| **Jun-21** | 66 625 | 1.26 | 135 076 |

*Complete mining operation (summary)*

The process of consolidating the available data was repeated for all the processing units in mining operation A. A summary of the data consolidation of the various flows is shown in Table 23, while detail regarding this process can be seen in Appendix A.

**Table 23: Data consolidation for all the flows relevant to mining operation A**

| Process unit | Flow number | Inflow or outflow | Flow | Metered | Calculation possible | Assumption available | Quantifiable | Comment |
|---|---|---|---|---|---|---|---|---|
| Shaft 1 | 1 | Inflow | Water in mud and ore | | ✓ | | ✓ | Equation 10 - 13 |
| | 2 | | Backfill from backfill plant | | ✓ | | ✓ | Equation 12 and 13 |
| | 3 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 4 | | Potable water | ✓ | | | ✓ | |
| | 5 | | Water from underground | ✓ | | | ✓ | |
| | 6 | Outflow | Water in mud and ore | | ✓ | | ✓ | Equation 10 - 13 |
| | 7 | | Backfill to underground | | ✓ | | ✓ | Equation 12 and 13 |
| | 8 | | Drinking water to UG | ✓ | | | ✓ | |
| | 9 | | Wastewater | | | ✓ | ✓ | All potable water not sent to underground is used for domestic purposes |
| | 10 | | Surplus water | ✓ | | | ✓ | |
| | 11 | | Runoff | | | ✓ | ✓ | All rainfall is lost through runoff |
| Shaft 2 | 12 | Inflow | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 13 | | Potable water | ✓ | | | ✓ | |
| | 14 | Outflow | Wastewater | | | ✓ | ✓ | All potable water is used for domestic purposes |
| | 15 | | Runoff | | | ✓ | ✓ | All rainfall is lost through runoff |
| Shaft 3 | 16 | Inflow | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 17 | | Potable water | ✓ | | | ✓ | |
| | 18 | | Water from underground | ✓ | | | ✓ | |
| | 19 | Outflow | Wastewater | | | ✓ | ✓ | All potable water is used for domestic purposes |
| | 20 | | Surplus water | ✓ | | | ✓ | |
| | 21 | | Runoff | | | ✓ | ✓ | All rainfall is lost through runoff |

| Process unit | Flow number | Inflow or outflow | Flow | Metered | Calculation possible | Assumption available | Quantifiable | Comment |
|---|---|---|---|---|---|---|---|---|
| Processing Plant | 22 | Inflow | Potable water | ✓ | | | ✓ | |
| | 23 | | Water in mud and ore | | ✓ | | ✓ | Equation 10 - 13 |
| | 24 | | Water supply | ✓ | | | ✓ | |
| | 25 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 26 | Outflow | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 27 | | Backfill plant | | ✓ | | ✓ | Equation 3 and 4 |
| | 28 | | Wastewater | | | ✓ | ✓ | Average water consumption per personnel member assumed |
| | 29 | | Water in tailings | | ✓ | | ✓ | Equation 12 and 13 |
| WRD 1-7 | 30 | Inflow | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 31 | Outflow | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 32 | | Runoff | | ✓ | | ✓ | Equation 21 |
| | 33 | | Seepage | | ✓ | | ✓ | Equation 20 |
| TSF 1 & 2 | 34 | Inflow | Dust suppression | | | ✓ | ✓ | Assumed average monthly dust suppression is applied |
| | 35 | | Water in tailings | | ✓ | | ✓ | Equation 12 and 13 |
| | 36 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 37 | Outflow | Return water | | ✓ | | ✓ | Balancing of TSF water balance |
| | 38 | | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 39 | | Seepage | | ✓ | | ✓ | Equation 20 |
| | 40 | | Interstitial water | | ✓ | | ✓ | Equation 7 - 10 |
| TSF 3 | 41 | Inflow | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 42 | Outflow | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 43 | | Seepage | | ✓ | | ✓ | Equation 20 |
| WWTF | 44 | Inflow | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 45 | | Wastewater | | | ✓ | ✓ | All potable water is used for domestic purposes |
| | 46 | Outflow | Clean Effluent | ✓ | | | ✓ | |
| | 47 | | Sludge removed | | ✓ | | ✓ | |
| | 48 | | Evaporation | | ✓ | | ✓ | Equation 15 |

| Process unit | Flow number | Inflow or outflow | Flow | Metered | Calculation possible | Assumption available | Quantifiable | Comment |
|---|---|---|---|---|---|---|---|---|
| **Backfill Plant** | 49 | Inflow | Water in tailings | | ✓ | | ✓ | Equation 12 and 13 |
| | 50 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 51 | | Potable water | ✓ | | | ✓ | |
| | 52 | Outflow | Backfill to shaft | | ✓ | | ✓ | Equation 12 and 13 |
| | 53 | | Water to plant | | ✓ | | ✓ | Equation 12 and 13 |
| | 54 | | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 55 | | Wastewater | | | ✓ | ✓ | Assumed all potable water is used for domestic purposes |
| **RWD 1** | 56 | Inflow | Water from pan 1 | | | | × | |
| | 57 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 58 | | Return water from TSF 1 | | ✓ | | ✓ | Balancing of TSF water balance |
| | 59 | | Runoff | | ✓ | | ✓ | Equation 21 |
| | 60 | Outflow | Seepage | | ✓ | | ✓ | Equation 20 |
| | 61 | | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 62 | | Return water to RWD 2 | | | | × | |
| | 63 | | Overflow to pan 1 | | | | × | |
| **RWD 2** | 64 | Inflow | Water from RWD 1 | | | | × | |
| | 65 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 66 | | Return water from TSF 2 | | ✓ | | ✓ | Balancing of TSF water balance |
| | 67 | | Runoff | | ✓ | | ✓ | Equation 21 |
| | 68 | Outflow | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 69 | | Return water to plant | ✓ | | | ✓ | |
| | 70 | | Overflow | | | | × | |

| Process unit | Flow number | Inflow or outflow | Flow | Metered | Calculation possible | Assumption available | Quantifiable | Comment |
|---|---|---|---|---|---|---|---|---|
| **Shaft 1 dam** | 71 | Inflow | Water from Shaft 1 | | ✓ | | ✓ | All water abstracted not going directly to the plant goes to Shaft 1 dam |
| | 72 | | Rainfall | | ✓ | | ✓ | Equation 14 |
| | 73 | | Runoff | | ✓ | | ✓ | Equation 21 |
| | 74 | Outflow | Evaporation | | ✓ | | ✓ | Equation 15 |
| | 75 | | Water to plant | ✓ | | | ✓ | |
| | 76 | | Overflow | | ✓ | | ✓ | Balancing of Shaft 1 dam water balance |

Certain flows were identified as unquantifiable when no data is available, or no available calculations or assumptions could be used to quantify these flows. One such unquantifiable flow is the water that is pumped from pan 1 to RWD 1, indicated as flow 56 (#56) in Table 23. This flow is not measured and cannot be approximated by balancing the water balance over RWD 1, since this was not the only unquantifiable flow within the balance of RWD 1. The return water pumped to RWD 2, as well as the overflow to pan 1, were also not quantifiable (#62 and #63). Thus, three variables require solving to complete the water balance for RWD 1.

RWD 2 had two flows which were not quantifiable from the data received from the mining operation: the water pumped from RWD 1 (#64) and the overflow (#70). The water pumped from RWD 1 to RWD 2 is therefore shared by two process units.

Monthly volumes for the overflow from RWD 2 as well as the water pumped from RWD 1 to RWD 2 can be estimated by balancing the water balance over RWD 2. For months where the initial water balance is positive (i.e. there is surplus water), it can be assumed that the surplus water overflowed. In months where the initial water balance is negative, it can be assumed that the required water was pumped from RWD 1. By making these assumptions, these two variables can be solved. However, these water balances will have a high uncertainty since multiple assumptions were required to solve the water balance.

Approximating the water pumped from RWD 1 to RWD 2 results in two remaining variables that need to be solved in the water balance over RWD 2. Applying the same assumptions for RWD 1 as for RWD 2, there will be an overflow to pan 1 in months where the initial water balance is positive, and in months where the water balance is negative, the required water is assumed to be pumped from pan 1.

Finally, all flows required for the individual water balances are recorded and quantified. The actual water balances over each process unit are discussed in the next step.

***Step 2.8: Consolidation of data into water balances***

Once all the inflows and outflows have been identified and quantified, these flows could be consolidated into the water balances. Table 24 shows the water balance for the processing plant for a one-year period beginning in July 2020 and ending in June 2021. The total inflows and outflows were then used to calculate the variance by using Equation 21. The variance is indicated in the last column of Table 24.

**Table 24: Water balance for the processing plant in mining operation A.**

| | Inflows ($m^3$) | | | | | Outflows ($m^3$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Potable water from municipality** | **Total water in mud and ore** | **Total water supply** | **Rainfall** | **Total inflows** | **Evaporation** | **Water to backfill plant** | **Wastewater generated** | **Water in tailings** | **Total outflows** | **Variance** |
| **Jul-20** | 7 755 | 2 079 | 110 936 | 0 | **120 770** | 228 | 0 | 5 824 | 121 929 | **127 982** | **-6%** |
| **Aug-20** | 8 790 | 2 645 | 145 425 | 0 | **156 859** | 312 | 7 557 | 5 824 | 146 173 | **159 867** | **-2%** |
| **Sep-20** | 14 736 | 2 784 | 161 652 | 9 | **179 181** | 428 | 38 444 | 5 636 | 116 882 | **161 390** | **10%** |
| **Oct-20** | 14 269 | 2 440 | 189 734 | 117 | **206 560** | 535 | 68 915 | 5 824 | 141 325 | **216 600** | **-5%** |
| **Nov-20** | 12 364 | 2 273 | 178 946 | 149 | **193 732** | 588 | 52 929 | 5 636 | 122 417 | **181 570** | **6%** |
| **Dec-20** | 10 476 | 2 376 | 132 371 | 598 | **145 821** | 620 | 13 335 | 5 824 | 113 668 | **133 447** | **8%** |
| **Jan-21** | 8 874 | 1 678 | 117 694 | 332 | **128 579** | 601 | 0 | 5 824 | 118 016 | **124 441** | **3%** |
| **Feb-21** | 14 963 | 2 058 | 107 313 | 274 | **124 608** | 475 | 0 | 5 261 | 123 258 | **128 993** | **-4%** |
| **Mar-21** | 7 966 | 1 880 | 130 424 | 274 | **140 544** | 424 | 0 | 5 824 | 135 022 | **141 271** | **-1%** |
| **Apr-21** | 13 060 | 2 102 | 153 112 | 52 | **168 326** | 321 | 10 150 | 5 636 | 156 345 | **172 453** | **-2%** |
| **May-21** | 10 181 | 1 667 | 138 730 | 0 | **150 578** | 252 | 15 452 | 5 824 | 114 838 | **136 366** | **9%** |
| **Jun-21** | 10 516 | 1 857 | 142 269 | 0 | **154 642** | 201 | 11 413 | 5 636 | 135 076 | **152 327** | **1%** |
| **Total** | **133 950** | **25 839** | **1 708 607** | **1 804** | **1 870 201** | **4 986** | **218 195** | **68 576** | **1 544 950** | **1 836 708** | **2%** |

The comparison between the inflows and outflows is graphically shown in Figure 32.

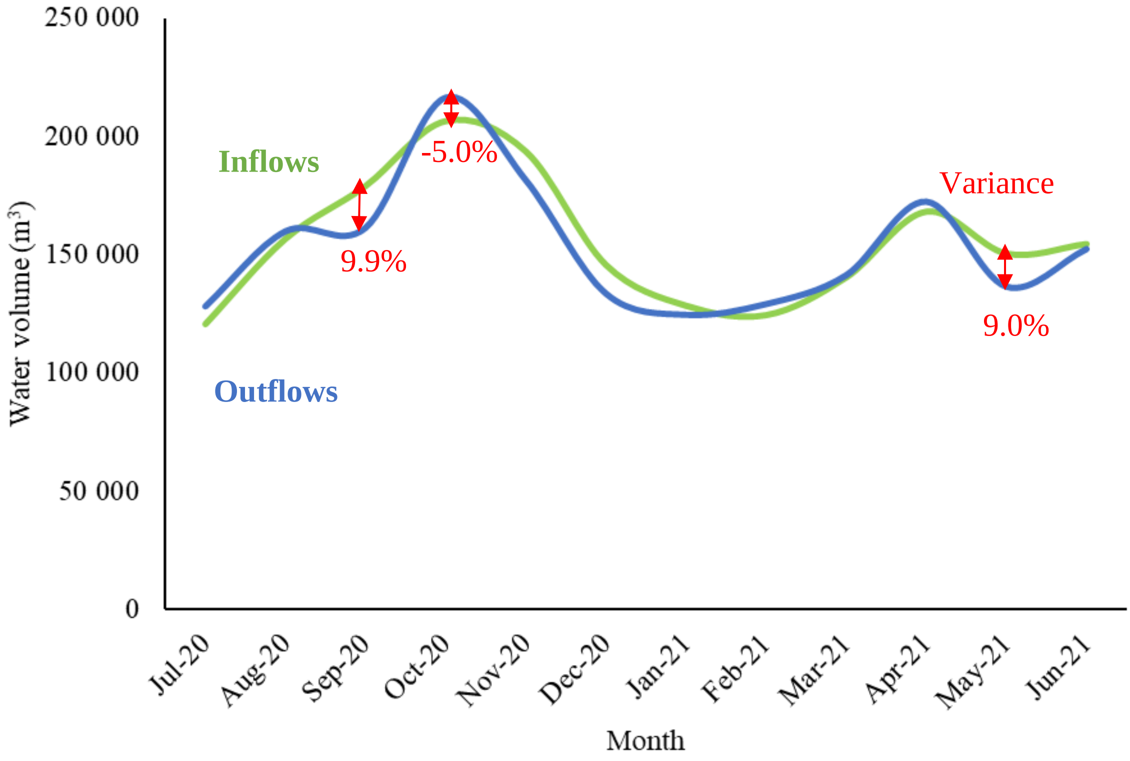


**Figure 32: Comparison of inflows and outflows for the processing plant in mining operation A.**

From Figure 32 it can be seen that the inflows are not exactly equal to the outflows for the processing plant. This can be due to numerous contributing factors such as metering errors and inaccuracies caused by assumptions made. The highest variance of 9.9% was recorded in the month of September 2020. The variance does, however, not exceed 10% for the process unit; therefore, the water balance is assumed to be accurate as discussed in Figure 21.

The water balances for all the other operations have been done in a similar manner and can be seen in Appendix A. The total variances for the water balances on all the process units are shown in Figure 33.

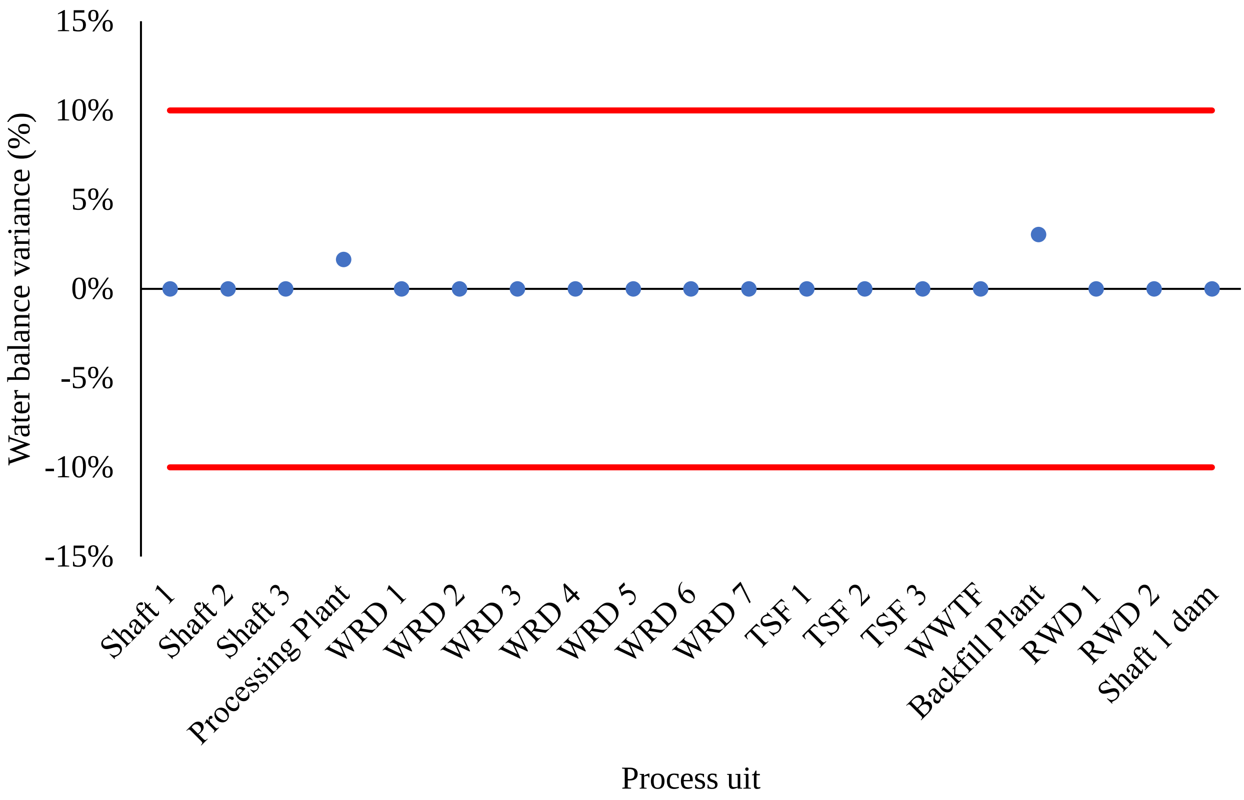


**Figure 33: Total variance for water balances of all process units in mining operation A.**

From Figure 33 it can be seen that 17 process units (out of 19) all have average variances close to 0%. Only the Processing Plant and the Backfill Plant have average variances of 2% and 3%, respectively. It is evident that the individual water balances over all the process units are within an acceptable accuracy range (less than 10%) and that the individual water balances are accurate.

The mining operation evaluated as mining operation A in the thesis consist of shafts that are no longer actively mining, dormant waste rock dumps, as well as very interlinked process water dams/pans. For shafts that are not actively mining (such as shaft 3), as well as dormant waste rock dumps, the water balance will be very basic. At inactive shafts, the only inflows are a small feed of potable water which is only used at the offices and rainfall. Since the potable water is only used at the offices, a reasonable assumption would be that all the potable water exits the shaft area as wastewater. As for rainfall, since there generally are no trenches or dams at inactive shafts, all the rainfall will exit the shaft boundary as either runoff or evaporation. This makes the water balance very simple and leads to a perfect water balance since the water is contained in a very controlled environment. The same principle applies to dormant waste rock dumps where the only inflow (rainfall) will either seep away, run off into the environment, or evaporate.

As for the interlinked process water dams/pans, the overflow to and from these dams are not economically feasible to measure. Therefore, due to a lack of other information available, the water balances were balanced by solving the unknowns for each of these process water dams/pans, therefore resulting in a perfect water balance.

***Step 2.9: Sensitivity analysis***

A sensitivity analysis was done on all the inflows and outflows to identify flows whose accuracies will have the highest impact on the water balance. By determining the sensitivity of the water balance on each stream, it can be determined whether any of the meters used to quantify the flow should be calibrated, and also if any additional metering is required as discussed in Section 2.3.1.

The flows were all increased and decreased by a fixed percentage of 10%. It was then observed how a change in the flow affects the variance, as discussed in Section 2.3.1. The results obtained are shown in Figure 34.

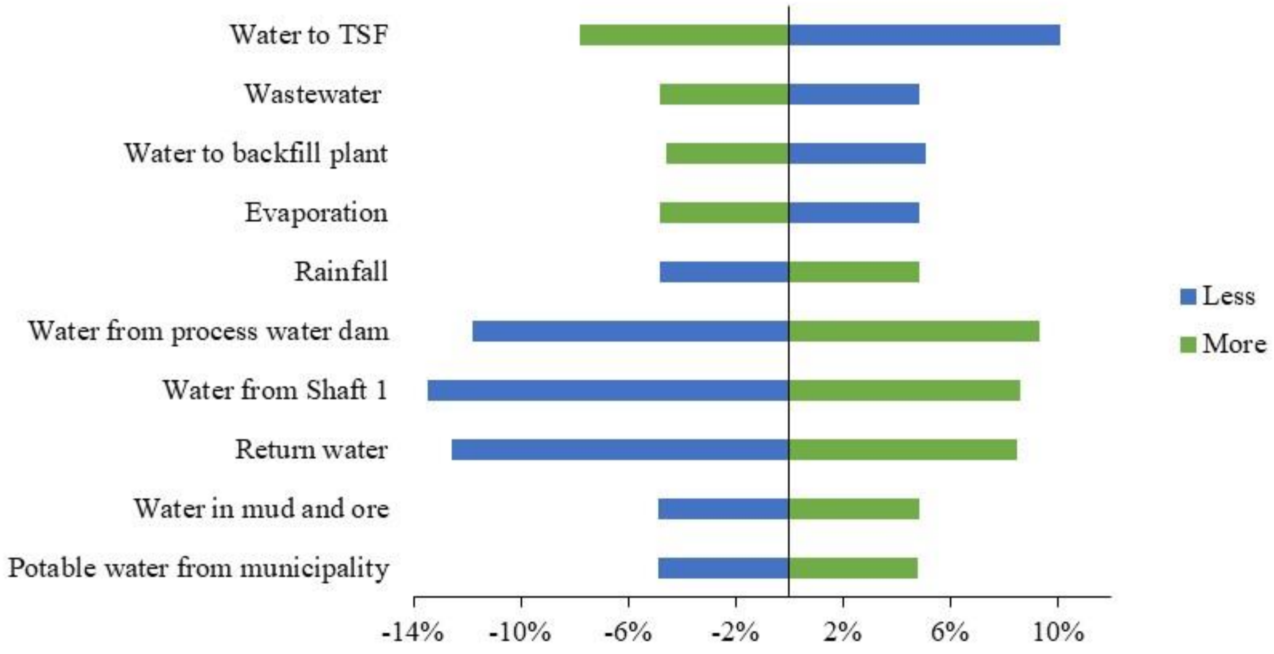


**Figure 34: Sensitivity analysis for the processing plant in mining operation A.**

From Figure 34, it can be seen that the water balance over the Processing Plant is highly sensitive to four streams. These streams all have an effect of more than 10% on the water balance. The stream affecting the balance the most is the water from Shaft 1, followed by the return water and thirdly the water from the lined process water dam. Water sent to the TSF has the fourth highest influence on the Processing Plant water balance.

Since the water balance shows a high sensitivity towards these flows, it is important to ensure these flows are accurate. The flow data for water from the return water dam, Shaft 1, and the lined process water dam is based directly on meter readings. It is therefore advised to have these meters calibrated annually.

The volume of water in the slurry sent to the TSF is calculated from the measured total volume of the slurry and the measured density of the slurry. An additional sensitivity analysis was done to determine the sensitivity of the calculated volume of water to both these variables. These variables were also increased and decreased by 10% respectively. The volume of water obtained after the change was then compared to the original volume of water calculated. The effects of the sensitivity analysis are shown in Figure 35.

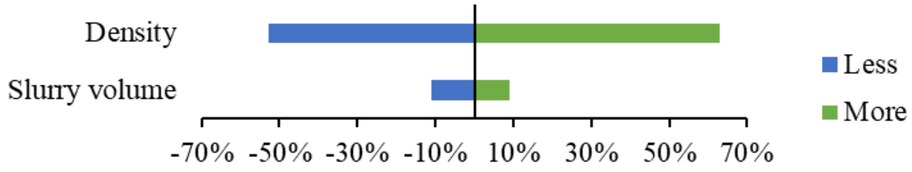


**Figure 35: Sensitivity of water in tailings to density and volume of slurry in mining operation A.**

From Figure 35 it is evident that the calculated volume of water in the slurry is highly sensitive to the density readings (a 10% change in density results in an almost 70% change in the volume of water in the slurry). Changing the total slurry volume without changing the density results in a change of roughly 10% in the calculated water in slurry volume. Both these variables therefore have a significant effect on the calculated water in slurry volume. It is therefore advised that both these meters (densitometer as well as slurry volume meter) are calibrated annually to ensure correct measurements are used for the evaluation. For this evaluation, the values presented by the densitometer and slurry volume meter is assumed to be correct.

A sensitivity analysis was done on all the other process units within the mining operation. The results for these sensitivity analyses are presented in Appendix A.

### 3.3.3 Step 3 and 4: Selection and identification of inflows and outflows for regional boundary

Once accurate water balances for all the process units have been developed, the next step in developing the regional water balance, as per Figure 26, is to establish the regional boundary. The dormant WRDs and TSFs have been removed from the regional water balance boundary, since they operate independently from the rest of the mining operation and therefore have no significant effect on the regional water balance. The boundary chosen for the regional water balance is indicated by the blue dotted line in Figure 36. The inflows and outflows for the regional water balance could then be identified.

### 3.3.4 Step 5: Consolidation of data into regional water balance

All the inflows and outflows for the regional water balance have already been quantified within the individual process unit water balances. The inflows and outflows could therefore be consolidated into the regional water balance shown in Table 25.

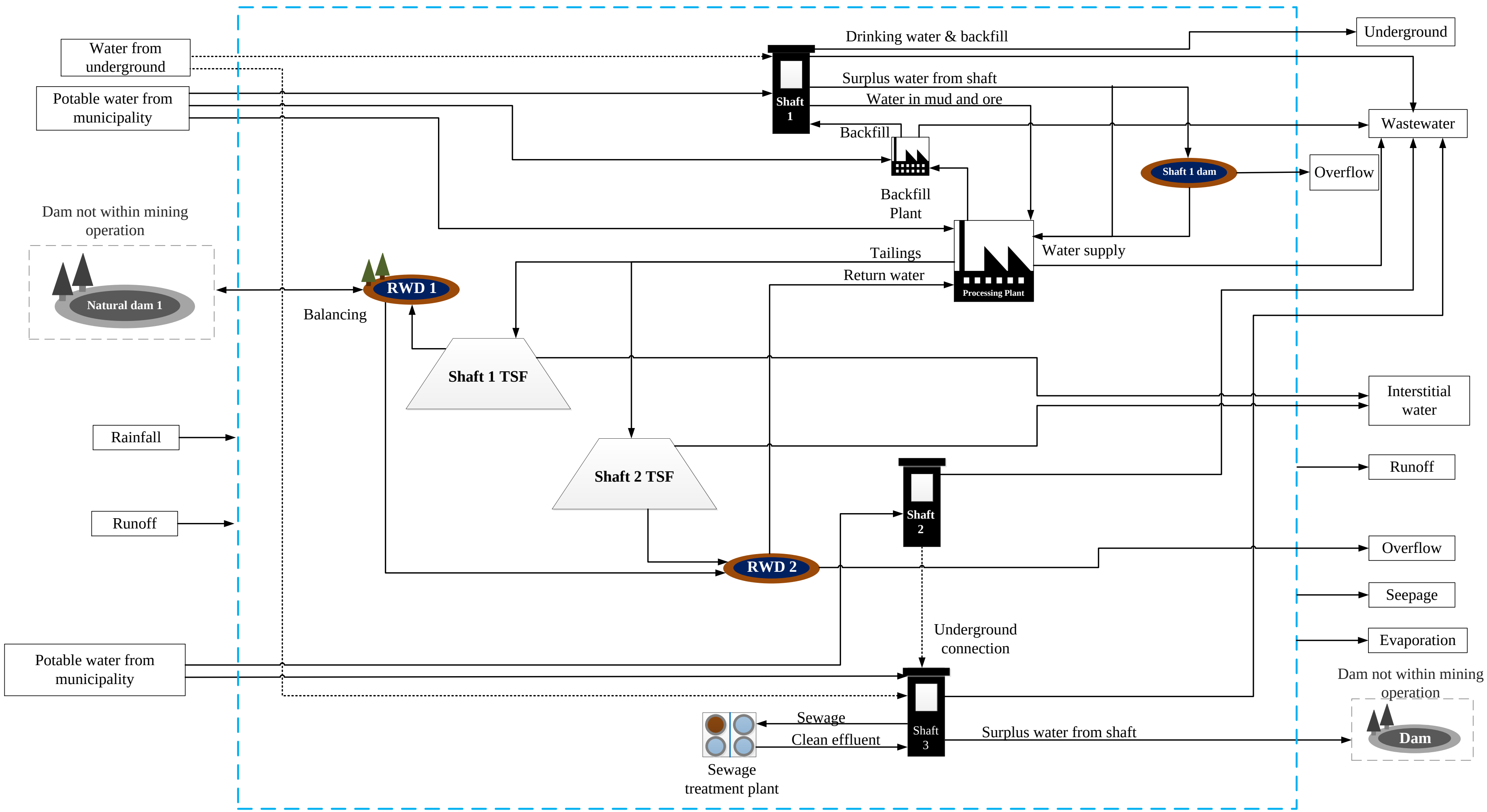


**Figure 36: Regional water balance boundary selection for mining operation A.**

**Table 25: Regional water balance for mining operation A.**

| | Flow descriptions | Jul-20 | Aug-20 | Sep-20 | Oct-20 | Nov-20 | Dec-20 | Jan-21 | Feb-21 | Mar-21 | Apr-21 | May-21 | Jun-21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inflows | Water from underground | 179 197 | 175 438 | 180 054 | 195 855 | 206 279 | 193 659 | 217 246 | 189 947 | 265 095 | 212 097 | 204 389 | 193 852 |
| | Potable water | 60 664 | 62 139 | 58 150 | 70 041 | 54 547 | 54 746 | 52 238 | 70 646 | 48 877 | 62 745 | 73 105 | 65 152 |
| | Water from Pan 1 | 0 | 7 301 | 40 320 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 432 | 0 |
| | Rainfall | 0 | 0 | 4 558 | 60 785 | 77 501 | 311 523 | 173 237 | 142 844 | 142 844 | 27 354 | 0 | 0 |
| | Runoff | 0 | 0 | 268 | 3 577 | 4 560 | 18 331 | 10 194 | 8 406 | 8 406 | 1 610 | 0 | 0 |
| | **Total inflows** | **239 861** | **244 878** | **283 350** | **330 257** | **342 888** | **578 259** | **452 915** | **411 843** | **465 222** | **303 805** | **279 926** | **259 004** |
| Outflows | Shaft 1 dam overflow | 15 657 | 1 749 | 11 104 | 8 912 | 17 187 | 12 711 | 18 524 | 46 718 | 22 503 | 11 923 | 26 673 | 28 185 |
| | Wastewater | 39 236 | 40 279 | 29 961 | 34 758 | 14 634 | 13 482 | 12 918 | 31 897 | 12 535 | 24 088 | 32 976 | 26 968 |
| | Interstitial water | 29 108 | 30 620 | 29 076 | 26 945 | 28 013 | 26 011 | 24 721 | 19 921 | 26 920 | 32 126 | 24 056 | 28 347 |
| | Runoff from shaft surfaces | 0 | 0 | 150 | 2 011 | 2 564 | 10 306 | 5 731 | 4 725 | 4 725 | 905 | 0 | 0 |
| | Seepage | 12 932 | 15 352 | 11 247 | 21 107 | 20 364 | 50 035 | 32 505 | 30 415 | 32 055 | 20 167 | 12 039 | 14 910 |
| | Evaporation | 40 222 | 54 977 | 75 265 | 94 204 | 103 497 | 109 087 | 105 805 | 83 604 | 74 696 | 56 510 | 44 340 | 35 427 |
| | Surplus water from Shaft 3 to nearby pan | 90 000 | 88 000 | 90 000 | 93 000 | 89 000 | 90 000 | 101 000 | 82 000 | 147 000 | 106 000 | 89 000 | 87 000 |
| | Overflow to pan 1 | 3 627 | 0 | 0 | 31 241 | 16 909 | 134 443 | 71 484 | 71 713 | 77 645 | 25 661 | 0 | 2 849 |
| | Backfill to UG | 0 | 1 060 | 6 513 | 9 240 | 8 168 | 2 078 | 0 | 0 | 0 | 1 474 | 2 490 | 1 727 |
| | Drinking water to UG | 19 497 | 18 894 | 19 089 | 26 838 | 33 185 | 36 612 | 36 270 | 29 047 | 34 200 | 31 233 | 35 772 | 33 304 |
| | RWD 2 overflow | 0 | 0 | 0 | 2 528 | 0 | 84 490 | 42 623 | 19 372 | 36 675 | 0 | 0 | 0 |
| | **Total outflows** | **250 278** | **250 931** | **272 405** | **350 785** | **333 522** | **569 256** | **451 582** | **419 412** | **468 955** | **310 087** | **267 346** | **258 717** |
| **Variance** | | **-4%** | **-2%** | **4%** | **-6%** | **3%** | **2%** | **0%** | **-2%** | **-1%** | **-2%** | **4%** | **0%** |

### 3.3.5 Step 6: Determine regional water balance variance

The total inflows and outflows from Table 25 were compared to evaluate the variance of the water balance. This comparison is shown in Figure 37.

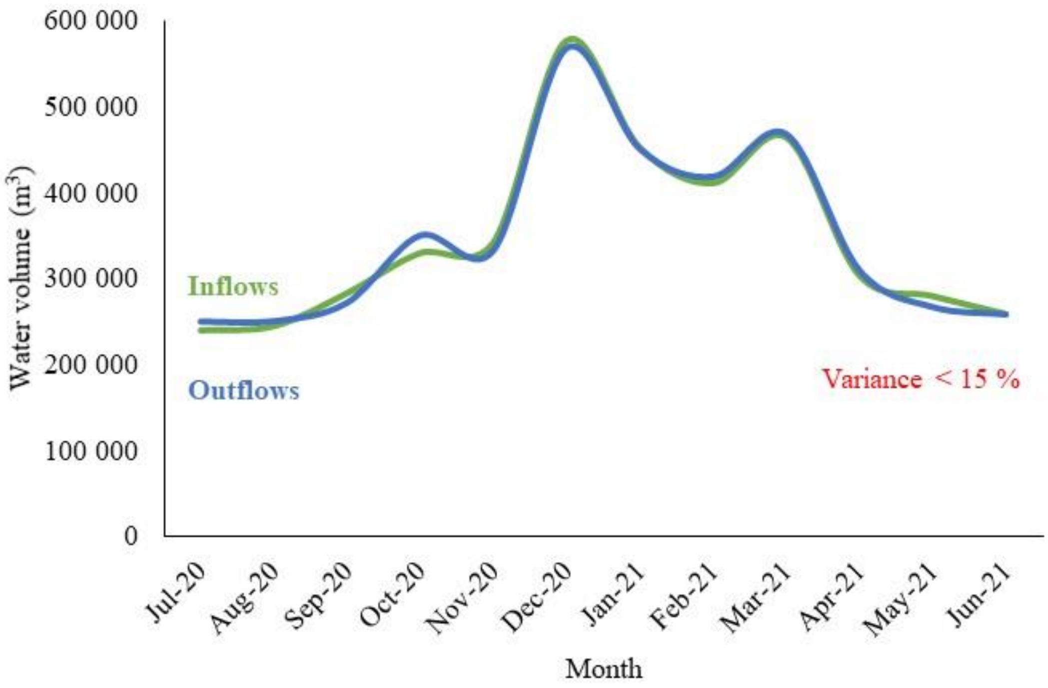


**Figure 37: Inflows in comparison to outflows for the regional water balance in mining operation A.**

From Table 25 and Figure 37 it is clear that the variance for the regional water balance remains below 15% for the 12 consecutive months in this case study. Since a regional water balance can be seen as accurate when the variance remains below 15% as discussed in 0, the regional water balance for mining operation A is therefore accurate.

***Sensitivity analysis***

Finally, a sensitivity analysis was done to determine which flow streams are the most important in the balance. This will indicate whether additional metering is required or whether any existing meters should be calibrated to ensure the regional water balance remains accurate. The results from the sensitivity analysis are shown in Figure 38.

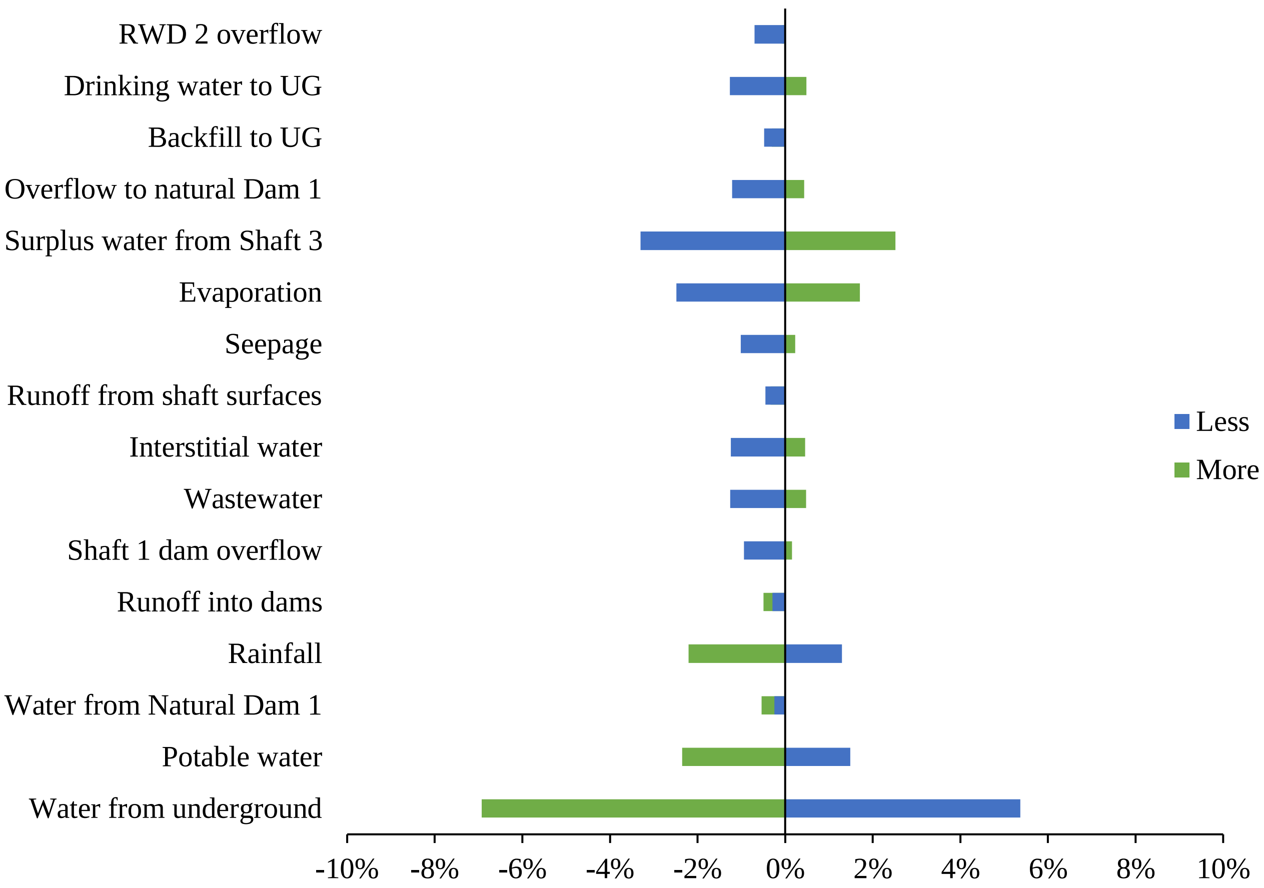


**Figure 38: Sensitivity analysis for the regional water balance in mining operation A.**

From the analysis shown in Figure 38 it was deduced that there is no additional metering required. No change in a single inflow or outflow has a significant effect on the variance of the water balance, therefore no additional calibration of meters is required. The analysis can be found in Appendix A.

### 3.3.6 Verification of water balance compliance

The criteria discussed in Section 2.5 were used to evaluate the compliance of the water balances developed for mining operation A. The evaluation is shown in Table 26.

**Table 26: Evaluation of the water balance compliance for mining operation A**

| Criteria | Yes/No |
|---|---|
| Are all process units accounted for? | Yes |
| Are all relevant streams accounted for? | Yes |
| Is the variance over all process units lower than 10%? | Yes |
| Is the variance over the mining operation lower than 15%? | Yes |
| Has a sensitivity analysis been done to identify flowmeters that require calibration? | Yes |
| Are all assumptions validated? | Yes |

All criteria in Table 26 have been met. As discussed in Section 2.5, the calibration of the required meters is not a requirement to ensure compliance of the initial water balances developed. However, these meters should be calibrated to ensure the water balances remain accurate in the future.

From the evaluation of the water balances in Table 26, the water balances developed for mining operation A are fully compliant with all the regulations set out by the DWS. Using the methodology described in Figure 21 and Figure 26 therefore resulted in the development of accurate and detailed water balances for mining operation A.

## 3.4 Expanded implementation of framework

The mining operation which was discussed in detail in the previous sections forms part of a larger water network by interacting with nearby mining operations. To obtain a compliant water balance for the region, the interactions between the mining operations within the water network should be investigated. Although individual mining operations generally apply for individual water use licenses, the volumes reported by the mining operations should correspond.

Two of the nearby mining operations were investigated as an expansion of the water balance developed in Section 3.3, and will be referred to as mining operations B and C, respectively. The process units included in these facilities are shown in Table 27.

**Table 27: Process units included in mining operations B and C.**

| Case Study | Process unit | Number of process units in operation | Additional comments |
|---|---|---|---|
| Mining operation B | Reclamation Plant | 1 | The reclamation plant receives tailings from a nearby TSF |
| | Tailings storage facility | 4 | There are two active TSFs within the mining operation which receives tailings from the reclamation plant. One of the TSFs is being reclaimed by the reclamation plant, while the other TSF is dormant |
| | Unlined water body | 5 | There are five return water dams within the mining operation. One of the RWDs receives return water from one of the active TSFs, while the other dams receive mainly natural catchment or runoff from the dormant TSF. All of these RWDs are unlined |
| Mining operation C | Reclamation Plant | 1 | The reclamation plant receives tailings from two nearby TSFs |
| | Tailings storage facility | 7 | There is one active TSF within the mining operation which receives tailings from the reclamation plant. Two of the TSFs are being reclaimed by the processing plant, while four of the TSFs are dormant |
| | Unlined water bodies | 5 | There are five return water dams within the mining operation. One of the RWDs received return water from one of the active TSFs, while the other dams receive mainly natural catchment or runoff from the dormant TSFs |

### 3.4.1 Regional water balance development

Following the methodology described in Figure 28 and Figure 29, the water balances for these mining operations were developed for the period of July 2020 to June 2021.

Figure 39 displays the variance between the inflows and outflows obtained for the regional water balance of mining operation B.

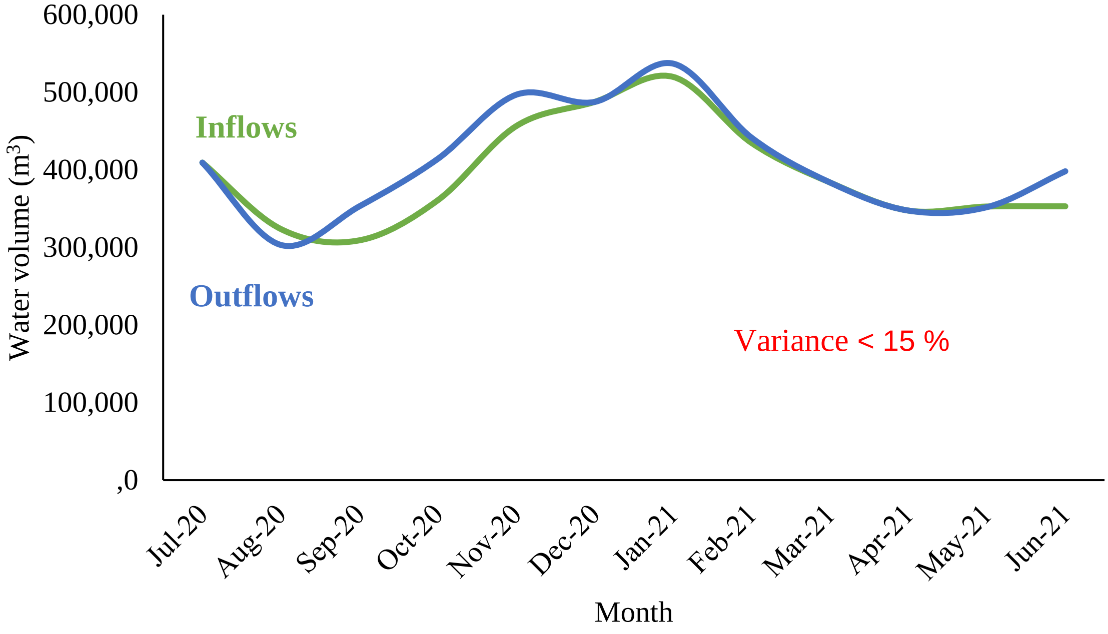


**Figure 39: Inflows in comparison to outflows for the regional water balance in mining operation B.**

From Figure 39 it is evident that the variance of the water balance does not exceed 15% for any month in the period under investigation. The regional water balance for mining operation B is therefore accurate.

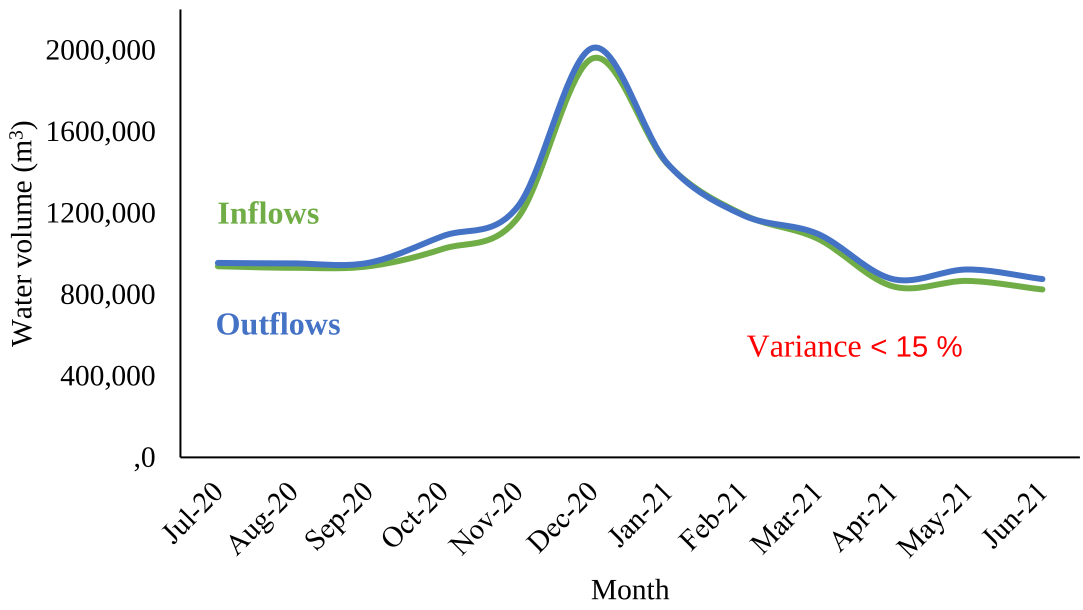


**Figure 40: Inflows in comparison to outflows for the regional water balance in mining operation C.**

Figure 40 indicates that the variance for the regional water balance of mining operation C remains below 15% throughout the period under investigation. Therefore, the regional water balance for mining operation C is accurate.

***Sensitivity analysis***

A sensitivity analysis was done on the regional water balances for both mining operation B and C. The various flows were increased and decreased by 10% as discussed in Section 2.3.1 and the effect of this change on the variance was evaluated. The results for mining operations B and C are shown in Figure 41 and Figure 42, respectively.

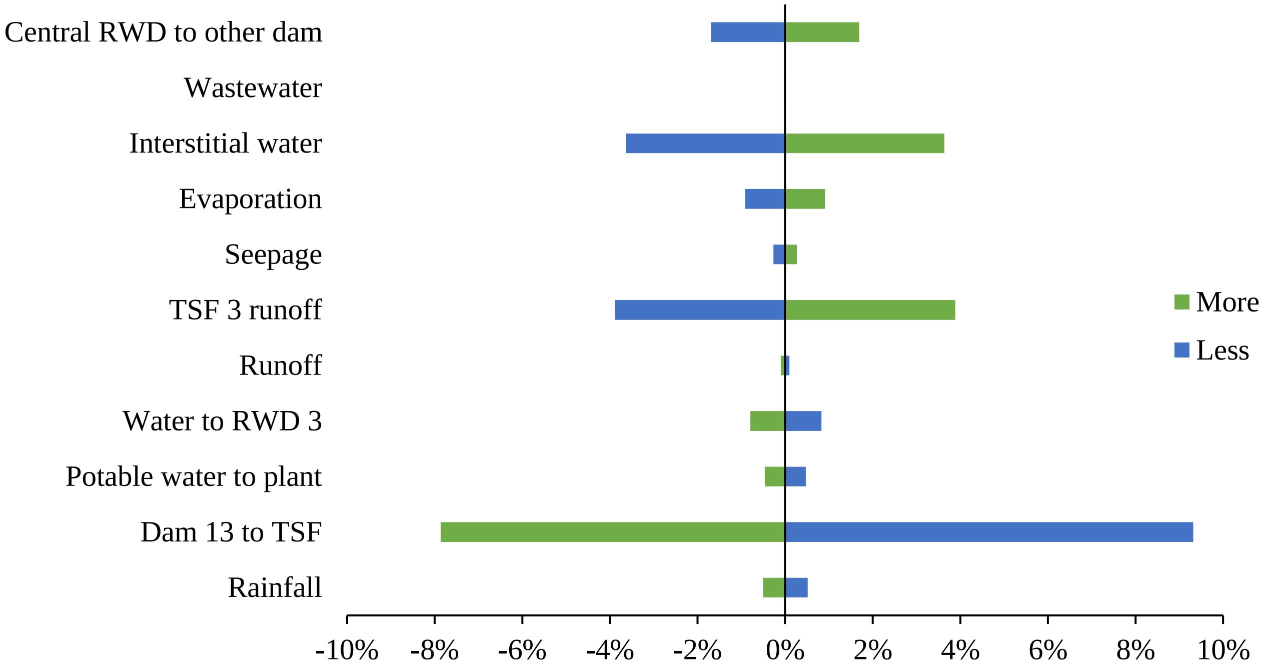


**Figure 41: Sensitivity analysis for the regional water balance in mining operation B.**

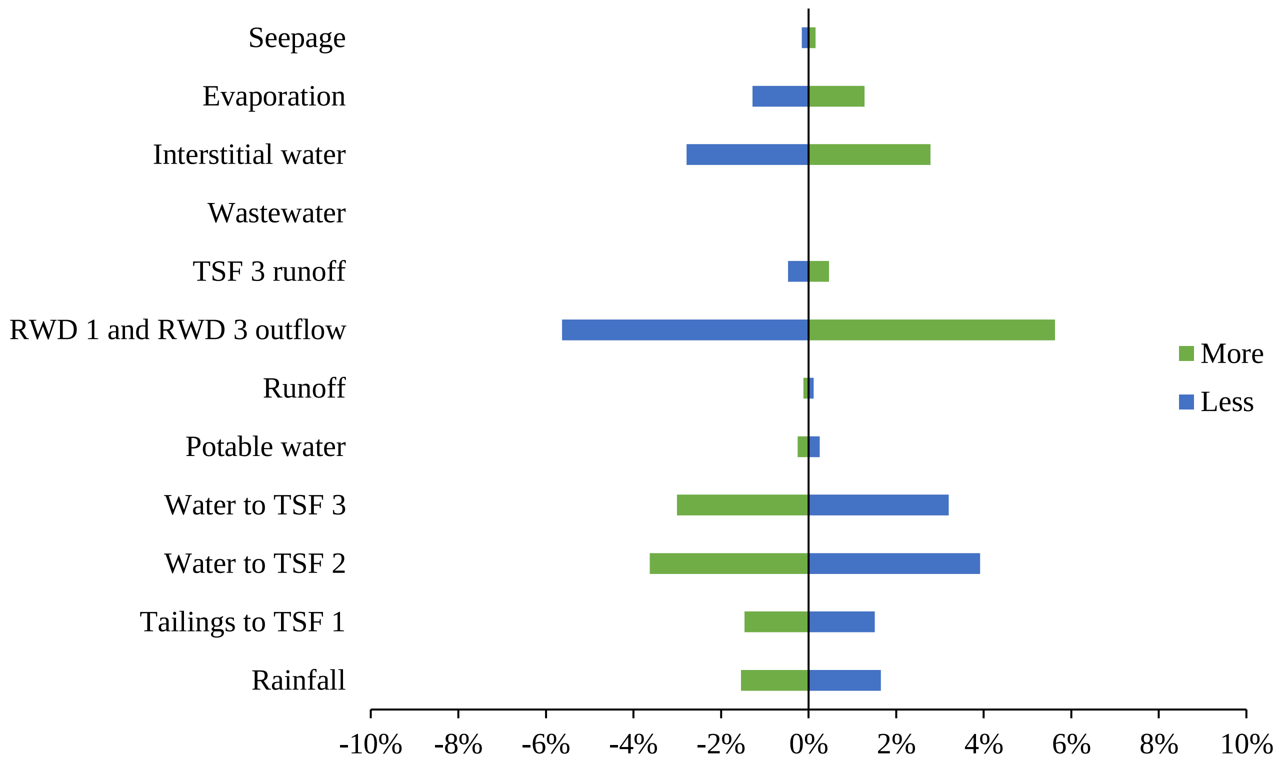


**Figure 42: Sensitivity analysis for the regional water balance in mining operation C.**

Figure 41 and Figure 42 indicate that the regional water balances for both mining operation B and mining operation C are not significantly sensitive to any of their respective inflows or outflows. Therefore, no additional metering or calibration of meters is required.

### 3.4.2 Verification of water balance compliance

The criteria discussed in Section 2.5 were used to evaluate the compliance of the water balances developed for mining operations B and C. The evaluation is shown in Table 28.

**Table 28: Evaluation of the water balance compliance for mining operations B and C.**

| Criteria | Mining operation B | Mining operation C |
|---|---|---|
| Are all process units accounted for? | Yes | Yes |
| Are all relevant streams accounted for? | Yes | Yes |
| Is the variance over all process units lower than 10%? | Yes | Yes |
| Is the variance over the mining operation lower than 15%? | Yes | Yes |
| Has a sensitivity analysis been done to identify flowmeters that require calibration? | Yes | Yes |
| Are all assumptions validated? | Yes | Yes |

The regional water balances developed meets all the criteria shown in Table 28. Therefore, using the methodology described in Figure 21 and Figure 26 resulted in the development of accurate and detailed water balances that are fully compliant to all the regulations set out by the DWS.

### 3.4.3 Overall water balance

As mentioned previously, all three mining operations investigated form part of a larger integrated water network in SA. These mining operations are all interlinked together with other mining operations in the area and can be merged to form an overall water balance for the region. The final flow diagram for this overall water balance is shown in Figure 43.

Mining operations A, B, and C are indicated by the dotted lines and labels in Figure 43, attesting to the intricate interconnectivity between mining operations. Mining operation A is connected through the overflow of one of the unlined water bodies to a process water dam within a different mining operation. Overflow from a fridge plant and storm water dam from a different operation also flows via trenches into the unlined water body in mining operation A.

Water used for reclamation at mining operation B and C is sourced from a process water dam within a different mining operation. The return water from the deposited tailings from mining operation C is pumped to a process water dam within mining operation C. The total return water for both mining operation B and mining operation C is then routed to an additional process water dam within a neighbouring mining operation. It is therefore evident that the different mining operations are very reliant on data from nearby mining operations to complete their own water balances.

The development of the overall water balance can be developed by using the methodology shown in Figure 28. This is, however, not in the scope of this thesis and will not be discussed.

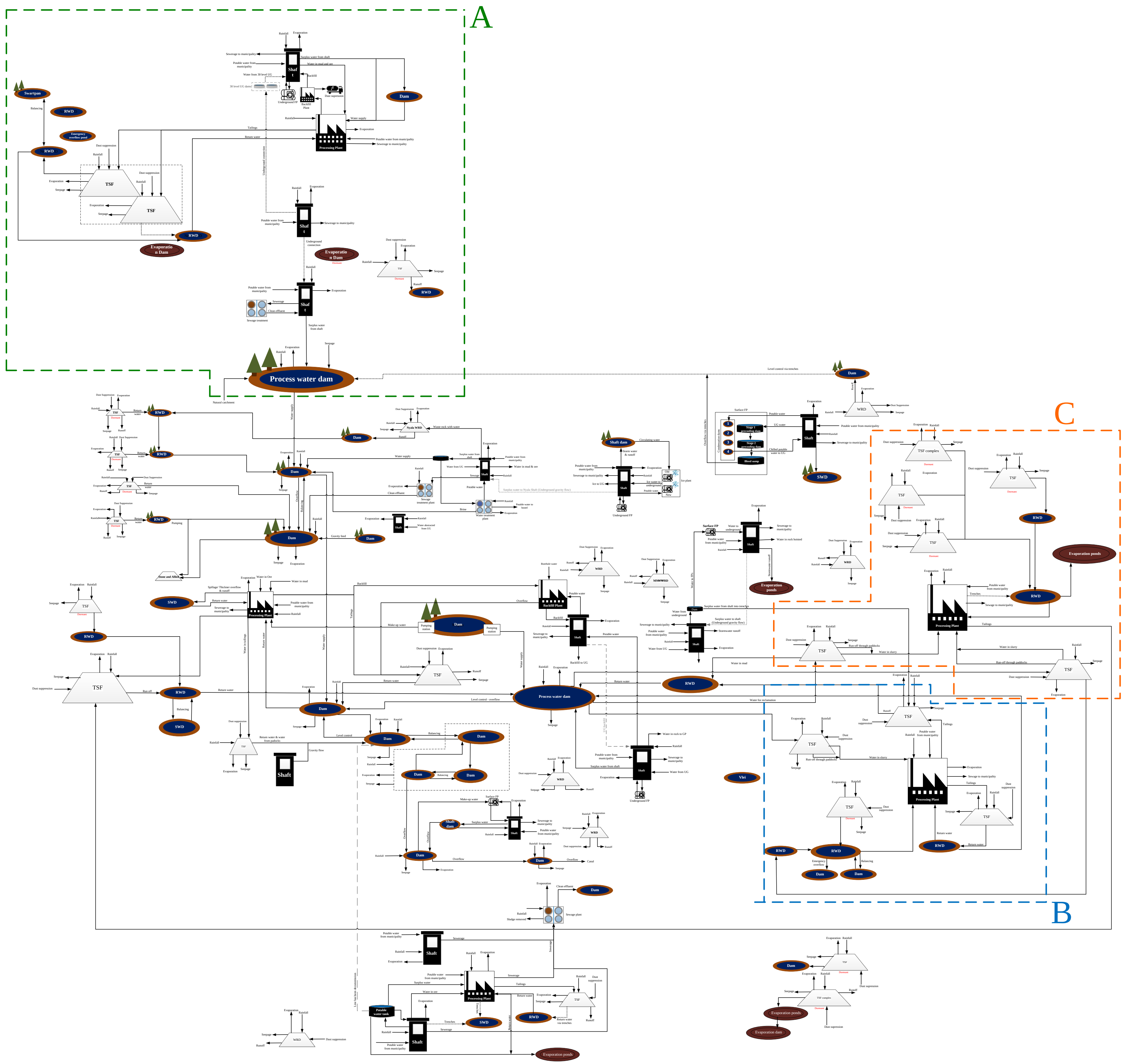


**Figure 43: Regional water balance.**

## 3.5 Validation of methodology

As discussed in Chapter 1, gold mines are facing increasing pressure to obtain their water use licenses. Detailed and accurate water balances (variance <10% per process unit and <15% for regional water balance) are a fundamental requirement for both applying for and maintaining a water use license.

In Chapter 2, a methodology was developed which enables gold mining operations in SA to develop accurate and detailed water balances. The methodology focuses on developing water balances which comply with the WUL regulations set out by the DWS.

The criteria developed in Table 13 list the requirements for a water balance to be compliant.

1. The water balance should include all the relevant process units and streams.
2. The variance for a water balance over a process unit should not exceed 10% and the variance for a regional water balance should not exceed 15%.
3. Sensitivity analyses should be done on the water balances to identify whether additional meters should be installed or whether existing meters should be calibrated.
4. Lastly all assumptions made to quantify flows should be validated.

These criteria were used to evaluate the water balances developed for three mining operations. The evaluation is shown in Table 26 and Table 28. By using the methodology discussed in Sections 2.2 to 2.5, water balances which meet all the required criteria were developed for these different mining operations.

## 3.6 Conclusion

The methodology developed in Chapter 2 was applied to various mining operations. The water balances obtained through this methodology were validated based on various criteria to confirm their compliance with DWS regulations.

The water balances obtained through the developed methodology proved to be fully compliant with the developed criteria and proved to be more accurate and detailed than existing water balances. Therefore, the effectiveness of the methodology developed in Chapter 2 and used to develop compliant water balances was verified.

# CONCLUSION AND RECOMMENDATIONS

## 4.1 Preamble

This concluding chapter presents a brief summary of the thesis and discusses the workings and main findings of the research. The objectives from Chapter 1 are reintroduced and a short discussion substantiates how these objectives were met throughout the thesis. Recommendations for further work are presented and finally the document is concluded in Section 4.4.

## 4.2 Summary of work

Gold mines in South Africa (SA) are under increasing pressure to apply for and maintain their water use licenses (WUL). Detailed and accurate water balances are a fundamental requirement in both the application process and maintenance of a WUL.

The aim of this thesis was to develop a methodology which can be applied to any gold mining operation in SA. The methodology is used to obtain accurate and detailed water balances to ensure WUL compliance.

In **Chapter 1**, a literature study was conducted regarding water uses in SA. The importance of water management, especially in the gold mining sector, was discussed. This led to the investigation of legislation and regulations relevant to water management in gold mines, after which the responsibility of gold mining companies to obtain and maintain water use licenses was highlighted. Accurate and detailed water balances were identified as an essential part of the WUL application and maintaining process. A clear literature gap in guidance on how to develop and quantify these water balances was identified. There was therefore an evident need to develop a methodology which can be followed to obtain compliant water balances.

**Chapter 2** discusses the development of the required methodology. All possible process units which can be found in a gold mining operation, as identified in Chapter 1, were investigated in to identify all the possible water inflows and outflows. Quantification of the inflows and outflows were investigated and quantification methods for every flow was discussed. This resulted in the development of modular water balance units for all the process units. A methodology in which a regional water balance for a mining operation can be consolidated from these modular process units was developed and discussed. Lastly, a method to validate whether the obtained water balance is compliant with all the relevant regulations and legislations was introduced.

**Chapter 3** provides verification and validation of the methodology through detailed application and evaluation in a mining operation. The methodology was further validated by evaluating two mining operations in close proximity to the first mining operation. A summary of the outcomes of these evaluations proved the validity of the methodology.

### 4.2.1 Meeting the required objectives

The main objective of this thesis is to develop a methodology that can be followed to obtain accurate and detailed water balances for gold mining operations in SA. A few additional objectives were needed to ensure that the main objective is met. These objectives have been identified in Section 1.7 and are listed below:

- Evaluating existing methodologies for the development of water balances from literature and identifying how these methodologies can be applied to this thesis.
- Identifying and understanding the requirements from standards and regulations.
- Developing a water balance methodology to deliver detailed and accurate water balances for gold mines.
- Validating the methodology with industrial case studies.

These objectives were achieved as explained in the sections to follow.

***Evaluating existing methodologies***

Existing methodologies from literature were investigated in Section 1.6. Sections within the methodologies which can be adapted and applied within this thesis were identified. Shortcomings within the methodologies were also discussed.

***Identifying and understanding the requirements from standards and regulations***

The regulations and legislation applicable to water uses in SA were considered in Section 1.5. The legal responsibilities and requirements to which gold mines are obliged were identified in Section 1.5.2.

***Developing a water balance methodology***

A comprehensive methodology which can be followed to obtain accurate and detailed water balances for gold mining operations was developed in Section 2.2 to Section 2.4.

***Validating the methodology with industrial case studies***

The methodology was applied to a mining operation in Chapter 3. The methodology was validated by verifying the compliance of the obtained water balances for the mining operation by using developed criteria.

## 4.3 Recommendations for further work

The gold mining industry in SA is one of many mining operations which all fall under the same legislative pressure to apply for and maintain their water uses licenses. The development of accurate and detailed water balances therefore holds significant importance in all the operations controlled by these laws and regulations. The need therefore exists to develop a similar methodology for other mining and industrial industries.

The DWS recommends doing water balances in conjunction with salt balances. The simultaneous development of these balances will offer additional possibilities in quantifying unmeasurable flows. It is also expected that a simultaneous investigation of both balances will result in balances with a higher accuracy. Since improving accuracy is critically important when considering water balances, including salt balances in the investigations will positively affect the quality of the water balances developed. Therefore, developing a similar methodology for salt balances within all mining operations will be advantageous for future use.

## 4.4 Closure

South African gold mines are under pressure to apply for and maintain their water use licenses. A critical element in both the application and maintenance of a WUL is a detailed and accurate water balance. The DWS describes a compliant water balance as a water balance which is detailed (includes all flows with more than 10% materiality) and accurate (variance over process units <10% and <15% for the regional water balance). A methodology that can be used to develop water balances that are compliant with the regulations set out by the DWS was therefore required.

This thesis introduces a methodology which can be followed to develop water balances that are compliant with these regulations. Generic modular water balance units were developed for all the processing units typically found within a gold mining operation. These processing units are shafts, process plants, reclamation plants, tailings storage facilities, waste rock dumps, water treatment plants, backfill plants, and water bodies. For every process units, all the possible inflows and outflows were identified. Quantification methods of these flows were investigated and discussed. The steps required to consolidate water balances for the individual process units from these modular units were listed.

A methodology to connect these modular units to form regional water balances for the mining operation was developed. Lastly criteria were developed which can be used to validate the accuracy of the obtained water balances.

The developed methodology was applied to a mining operation and expanded to two nearby mining operations. The compliance of the water balances produced for these mining operations was verified by using the criteria developed. The evaluation proved that the methodology was successful in producing compliant water balances.

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# A. APPENDIX A: Supplementary information for mining operation A

This appendix includes supplementary information on mining operation A.

## Appendix A.1:

### 1. Shaft 1

The first shaft to be investigated is the active mining shaft, Shaft 1. Considering the generic modular unit shown in Figure 10, all inflows and outflows relating to Shaft 1 were identified. The inflows and outflows for Shaft 1 is shown in Figure A-1.

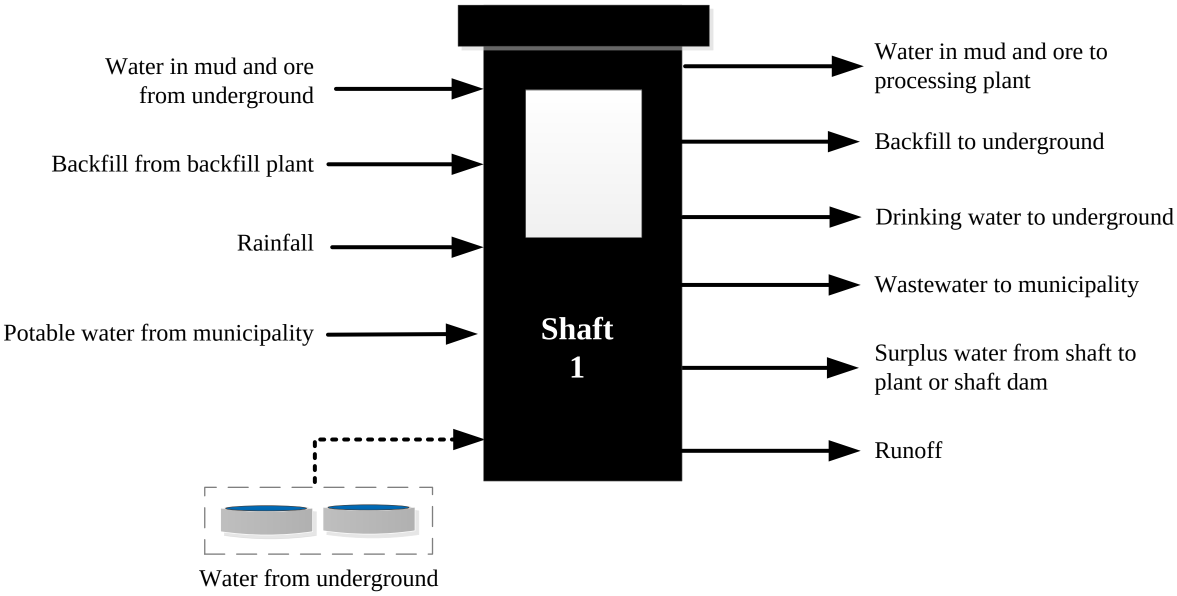


**Figure A-1: Shaft 1 water balance.**

The steps taken to quantify the inflows and outflows shown in Figure A-1 are shown in the sections to follow.

***Water in mud and ore from underground***

The volume of mud that is hoisted from underground is measured and recorded by the plant monthly. The moisture content of the ore that is hoisted is also measured together with the tonnes of ore that is hoisted. The mud hoisted from underground has a constant specific gravity of 1.0125 and a constant dry solids density of 2.67.

From the information known, the volume of water present in the mud hoisted from underground can be calculated by using Equation 12 and Equation 13. Water in ore can be calculated by using Equation

10 and Equation 11. The final flow data obtained and calculated for water in mud and ore for July 2020 to June 2021 is shown in Table A-1.

**Table A-1: Water in mud and ore data for Shaft 1 in gold mining operation A.**

| | Mine sludge volume ($m^3$) | Ore moisture % | Tonnes hoisted | Water in mud ($m^3$) | Water in ore ($m^3$) | Total water in mud and ore ($m^3$) |
|---|---|---|---|---|---|---|
| **Jul-20** | 0.960 | 0.032 | 65 165 | 0.48 | 2 079 | **2 079** |
| **Aug-20** | 8.336 | 0.037 | 72 345 | 4.14 | 2 641 | **2 645** |
| **Sep-20** | 88.050 | 0.033 | 82 029 | 43.73 | 2 740 | **2 784** |
| **Oct-20** | 56.011 | 0.030 | 79 883 | 27.82 | 2 412 | **2 440** |
| **Nov-20** | 42.817 | 0.027 | 82 180 | 21.26 | 2 252 | **2 273** |
| **Dec-20** | 70.890 | 0.036 | 64 304 | 35.21 | 2 341 | **2 376** |
| **Jan-21** | 70.890 | 0.029 | 57 053 | 35.21 | 1 643 | **1 678** |
| **Feb-21** | 36.259 | 0.043 | 47 652 | 18.01 | 2 040 | **2 058** |
| **Mar-21** | 61.010 | 0.028 | 65 389 | 30.30 | 1 850 | **1 880** |
| **Apr-21** | 10.320 | 0.027 | 78 327 | 5.13 | 2 097 | **2 102** |
| **May-21** | 50.546 | 0.026 | 62 734 | 25.10 | 1 642 | **1 667** |
| **Jun-21** | 25.380 | 0.027 | 68 486 | 12.60 | 1 844 | **1 857** |

Following the methodology in Figure 21, the next step was to validate the available data. A sensitivity analysis will be done after all the data has been consolidated into the water balance to determine where meters should be calibrated. Seeing as these volumes are not very big, it was assumed that these meters will not require calibration and the data is therefore validated.

***Backfill from backfill plant***

The tonnes of backfill as well as the density of the backfill slurry is measured and reported by the plant monthly. A constant solids density of 2.67 is reported by the plant. From the available data, Equation 12 and Equation 13 can be used to calculate the volume of water in the backfill slurry. The data received and calculated is shown in Table A-2.

**Table A-2: Water in backfill to Shaft 1 in gold mining operation A.**

| | **Backfill to shaft SG** | **Tonnes backfill to shaft** | **Water in backfill to shaft ($m^3$)** |
|---|---|---|---|
| **Jul-20** | 1.701 | 0 | **0** |
| **Aug-20** | 1.705 | 2 067 | **1 060** |
| **Sep-20** | 1.698 | 12 487 | **6 513** |
| **Oct-20** | 1.685 | 17 156 | **9 240** |
| **Nov-20** | 1.702 | 15 815 | **8 168** |
| **Dec-20** | 1.698 | 3 985 | **2 078** |
| **Jan-21** | 1.698 | 0 | **0** |
| **Feb-21** | 1.698 | 0 | **0** |
| **Mar-21** | 1.698 | 0 | **0** |
| **Apr-21** | 1.683 | 2 723 | **1 474** |
| **May-21** | 1.649 | 4 227 | **2 490** |
| **Jun-21** | 1.675 | 3 127 | **1 727** |

The next step in the methodology followed (Figure 21) was to validate the available data. The calculations to quantify the volume of water in backfill is based on measured values. The sensitivity analysis to evaluate whether these meters should be calibrated is discussed in a later section.

***Rainfall***

Rainfall is measured by the plant. Shaft 1 and the processing plant are in very close proximity to each other therefore the same rainfall is expected at Shaft 1. Google earth was used to estimate the surface area of the Shaft 1 area as 32 482 $m^2$. With the available data the rainfall could be calculated by using Equation 14. The rainfall reported by the plant as well as the calculated rainfall for the Shaft 1 area is shown in Table A-3

**Table A-3: Rainfall data for Shaft 1 in gold mining operation A.**

| | Rainfall (mm) | Rainfall received ($m^3$) |
|---|---|---|
| **Jul-20** | 0 | 0 |
| **Aug-20** | 0 | 0 |
| **Sep-20** | 3 | 97 |
| **Oct-20** | 40 | 1 299 |
| **Nov-20** | 51 | 1 657 |
| **Dec-20** | 205 | 6 659 |
| **Jan-21** | 114 | 3 703 |
| **Feb-21** | 94 | 3 053 |
| **Mar-21** | 94 | 3 053 |
| **Apr-21** | 18 | 585 |
| **May-21** | 0 | 0 |
| **Jun-21** | 0 | 0 |

The final rainfall figures are based on measured rainfall data. A sensitivity analysis was done after all the inflows and outflows have been quantified and is discussed in a later section. The sensitivity analysis was done to determine which meter should be calibrated.

***Potable water from municipality***

Shaft 1 receives monthly invoices from the local municipality stating the monthly potable water consumption. The data from the invoices was consolidated and is shown in Table A-4.

**Table A-4: Potable water data for Shaft 1 in gold mining operation A.**

| | **Potable water from municipality ($m^3$)** |
|---|---|
| **Jul-20** | 39 600 |
| **Aug-20** | 49 500 |
| **Sep-20** | 39 600 |
| **Oct-20** | 49 500 |
| **Nov-20** | 39 600 |
| **Dec-20** | 42 060 |
| **Jan-21** | 40 826 |
| **Feb-21** | 51 089 |
| **Mar-21** | 36 432 |
| **Apr-21** | 43 028 |
| **May-21** | 53 959 |
| **Jun-21** | 46 809 |

A sensitivity analysis as proposed in Figure 21 is discussed in a later section. From the sensitivity analysis it was determined which meters should be calibrated.

***Water from underground***

The water abstracted from underground is measured. The data obtained is shown in Table A-5.

**Table A-5: Water from underground data for Shaft 1 in gold mining operation A.**

| | **Water abstracted from underground ($m^3$)** |
|---|---|
| **Jul-20** | 89 197 |
| **Aug-20** | 87 438 |
| **Sep-20** | 90 054 |
| **Oct-20** | 102 855 |
| **Nov-20** | 117 279 |
| **Dec-20** | 103 659 |
| **Jan-21** | 116 246 |
| **Feb-21** | 107 947 |
| **Mar-21** | 118 095 |
| **Apr-21** | 106 097 |
| **May-21** | 115 389 |
| **Jun-21** | 106 852 |

A sensitivity analysis was done and is discussed in a later section to determine whether the meter should be calibrated.

***Water in mud and ore to processing plant***

The water in mud and ore that is hoisted from underground is sent directly to the plant. With the assumption that no water is lost in the transportation process, the volume of water will be the same as that shown in Table A-1.

***Backfill to underground***

The backfill received by the backfilling plant is sent underground directly. With the assumption that no water is lost through the transportation process, the volume of water in the backfill sent underground is the same as that tabulated in Table A-2.

### *Drinking water to underground*

The potable water sent underground for drinking purposes is measured. The data obtained is shown in Table A-6

**Table A-6: Drinking water to underground for Shaft 1 in gold mining operation A.**

| | **Drinking water to UG ($m^3$)** |
|---:|---:|
| **Jul-20** | 19 497 |
| **Aug-20** | 18 894 |
| **Sep-20** | 19 089 |
| **Oct-20** | 26 838 |
| **Nov-20** | 33 185 |
| **Dec-20** | 36 612 |
| **Jan-21** | 36 270 |
| **Feb-21** | 29 047 |
| **Mar-21** | 34 200 |
| **Apr-21** | 31 233 |
| **May-21** | 35 772 |
| **Jun-21** | 33 304 |

A sensitivity analysis was done and is discussed in a later section to determine whether the meter should be calibrated.

### *Wastewater to municipality*

Shaft 1 has no potable water feed for any industrial purposes such as compressors. The potable water received from the municipality is therefore either sent underground for drinking or used for domestic purposes. Since the potable water sent to underground is known, this can be subtracted from the total incoming potable water to obtain the potable water for domestic use. With the assumption that all potable water for domestic uses exits the system as wastewater, the wastewater can be approximated. The resulting wastewater volumes are shown in Table A-7.

**Table A-7: Wastewater to municipality data for Shaft 1 in gold mining operation A**

| | **Wastewater to municipality ($m^3$)** |
|---|---|
| **Jul-20** | 20 103 |
| **Aug-20** | 30 606 |
| **Sep-20** | 20 511 |
| **Oct-20** | 22 662 |
| **Nov-20** | 6 415 |
| **Dec-20** | 5 448 |
| **Jan-21** | 4 556 |
| **Feb-21** | 22 042 |
| **Mar-21** | 2 232 |
| **Apr-21** | 11 795 |
| **May-21** | 18 187 |
| **Jun-21** | 13 505 |

A sensitivity analysis was done and is discussed in a later section to determine whether there should be a meter installed to measure this flow.

***Surplus water from shaft to plant or shaft dam***

The water abstracted from underground at the shaft is sent either directly to the plant, or it is sent to the shaft dam. The shaft dam aids as a holding dam for water from where the processing plant can pump water when needed. The total water sent to both these process units is the same as that reported in Table A-5, assuming there are no leaks on the pipelines.

***Runoff***

The runoff from a shaft area is assumed to be the total rainfall received on the shaft area. The volume of runoff is therefore the same as the rainfall volumes reported in Table A-3.

### ***Shaft 1 water balance***

Now that all the inflows and outflows for Shaft 1 has been quantified, the water balance can be set up. The final flow data obtained for every flow in the water balance for Shaft 1 is shown in Table A-8. All the flows are shown in $m^3$.

**Table A-8: Water balance for Shaft 1 in gold mining operation A.**

| | Inflows | | | | | | Outflows | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total water in mud and ore | Water in backfill to shaft | Rainfall | Potable water from municipality | Water from under-ground | **Total** | Water in mud and ore to processing plant | Backfill to underground | Drinking water to underground | Wastewater to municipality | Surplus water to plant or shaft dam | Runoff | **Total** |
| **20-Jul** | 2 079 | 0 | 0 | 39 600 | 89 197 | **130 876** | 2 079 | 0 | 19 497 | 20 103 | 89 197 | 0 | **130 876** |
| **20-Aug** | 2 645 | 1 060 | 0 | 49 500 | 87 438 | **140 643** | 2 645 | 1 060 | 18 894 | 30 606 | 87 438 | 0 | **140 643** |
| **20-Sep** | 2 784 | 6 513 | 97 | 39 600 | 90 054 | **139 048** | 2 784 | 6 513 | 19 089 | 20 511 | 90 054 | 97 | **139 048** |
| **20-Oct** | 2 440 | 9 240 | 1 299 | 49 500 | 102 855 | **165 334** | 2 440 | 9 240 | 26 838 | 22 662 | 102 855 | 1 299 | **165 334** |
| **20-Nov** | 2 273 | 8 168 | 1 657 | 39 600 | 117 279 | **168 977** | 2 273 | 8 168 | 33 185 | 6 415 | 117 279 | 1 657 | **168 977** |
| **20-Dec** | 2 376 | 2 078 | 6 659 | 42 060 | 103 659 | **156 832** | 2 376 | 2 078 | 36 612 | 5 448 | 103 659 | 6 659 | **156 832** |
| **21-Jan** | 1 678 | 0 | 3 703 | 40 826 | 116 246 | **162 453** | 1 678 | 0 | 36 270 | 4 556 | 116 246 | 3 703 | **162 453** |
| **21-Feb** | 2 058 | 0 | 3 053 | 51 089 | 107 947 | **164 147** | 2 058 | 0 | 29 047 | 22 042 | 107 947 | 3 053 | **164 147** |
| **21-Mar** | 1 880 | 0 | 3 053 | 36 432 | 118 095 | **159 460** | 1 880 | 0 | 34 200 | 2 232 | 118 095 | 3 053 | **159 460** |
| **21-Apr** | 2 102 | 1 474 | 585 | 43 028 | 106 097 | **153 286** | 2 102 | 1 474 | 31 233 | 11 795 | 106 097 | 585 | **153 286** |
| **21-May** | 1 667 | 2 490 | 0 | 53 959 | 115 389 | **173 505** | 1 667 | 2 490 | 35 772 | 18 187 | 115 389 | 0 | **173 505** |
| **21-Jun** | 1 857 | 1 727 | 0 | 46 809 | 106 852 | **157 245** | 1 857 | 1 727 | 33 304 | 13 505 | 106 852 | 0 | **157 245** |

The variance for the water balance for Shaft 1 shown in Table A-8 can be calculated using Equation 21. The total inflows and total outflows are compared in Figure A-2.

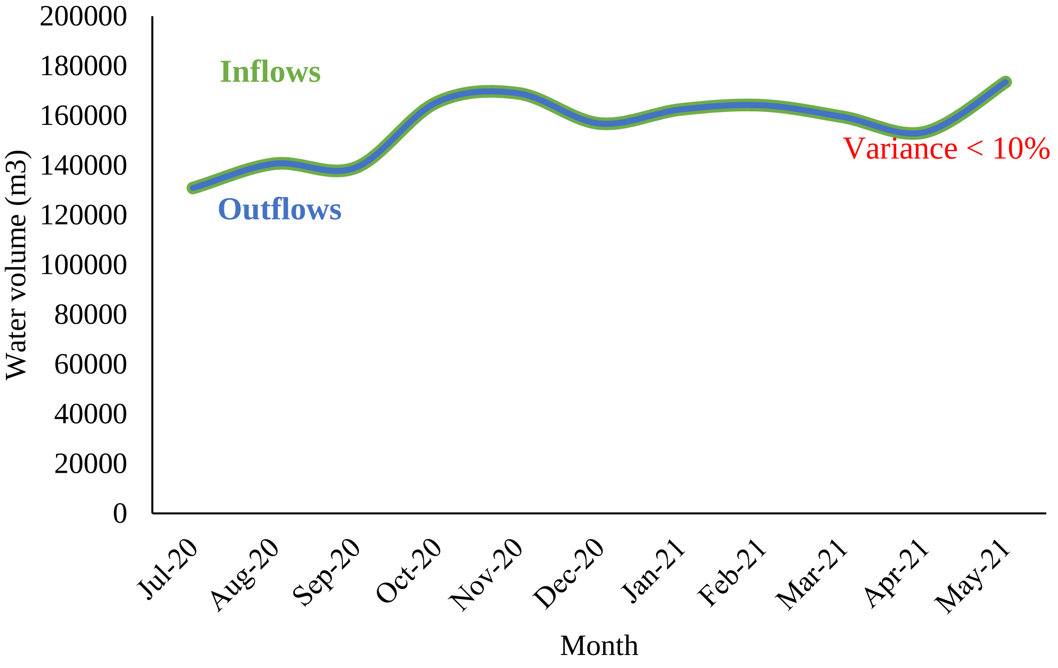


**Figure A-2: Total inflows vs total outflows for Shaft 1 in gold mining operation A.**

From Figure A-2 it can be seen that the variance for the water balance for Shaft 1 is less than 10% for 12 consecutive months. The water balance is therefore seen as accurate.

***Sensitivity analysis***

A sensitivity analysis was done to determine if meters should be calibrated. The method discussed in Section 2.3 was followed and 10% was chosen as the varying percentage. Figure A-3 shows the results obtained for the sensitivity analysis.

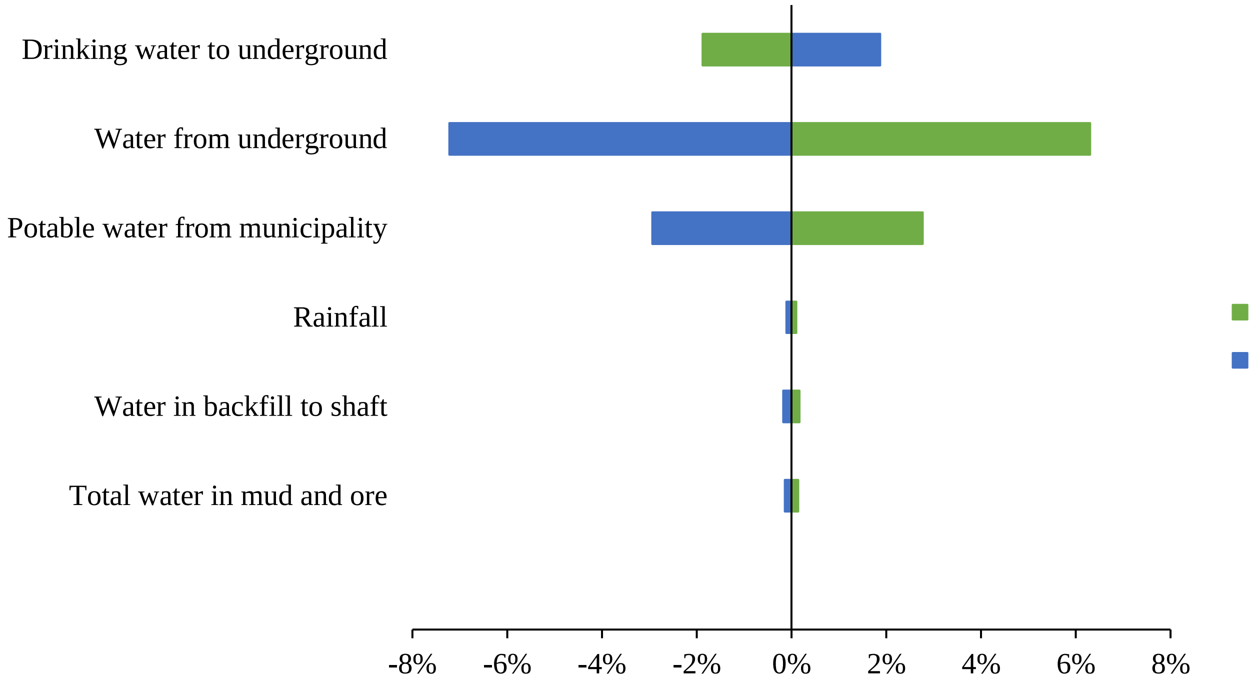


**Figure A-3: Sensitivity analysis for Shaft 1 in gold mining operation A.**

From Figure A-3 it is evident that the water balance shows the highest sensitivity to the water pumped from underground volumes. However, changing this variable by 10% results in the water balance variance changing with less than 8%. Since a 10% change in this variable did not result in an imbalance of the water balance, it is not necessary to have the meter calibrated.

Therefore, no additional meters or calibration of meters are required for Shaft 1.

## 1. Shaft 2

Shaft 2 is a ventilation shaft, meaning that there are no activities at the shaft except for ventilation fans. There is therefore no water abstracted from the shaft and no water sent down the shaft. The modular unit developed in Section 2 was used to identify all the possible inflows and outflows. Figure A-4 shows the water balance for Shaft 2.

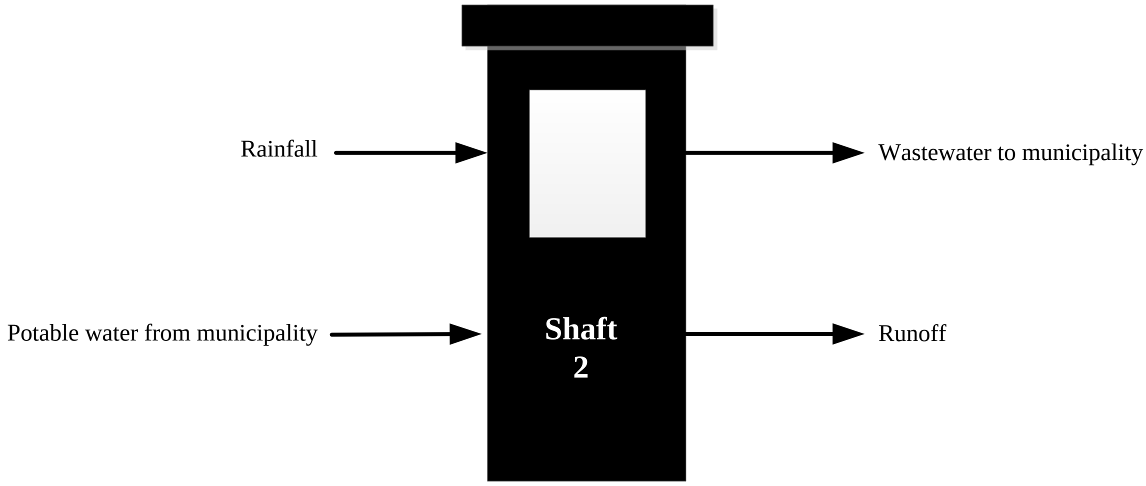


**Figure A-4: Water balance for Shaft 2 in gold mining operation A.**

The only inflows relevant to Shaft 2 is rainfall and potable water from the municipality. The resulting outflows are wastewater to the municipality and runoff from the rainfall. The quantification of these flows is discussed in the sections that follow.

***Rainfall***

Shaft 2 does not have a rainfall meter. Shaft 2 is in close proximity to the processing plant which has a rainfall meter. It is therefore assumed that the rainfall received at the processing plant is also received at Shaft 2. The rainfall received by the processing plant is shown in Table A-3. The surface area of Shaft 2 was estimated as 9 138 $m^2$ by using Google Earth. Equation 14 was then used to calculate the rainfall. The resulting rainfall received by Shaft 2 is shown in Table A-8.

**Table A-9: Rainfall data for Shaft 2 in gold mining operation A.**

| | **Rainfall received ($m^3$)** |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 27 |
| **Oct-20** | 366 |
| **Nov-20** | 466 |
| **Dec-20** | 1 873 |
| **Jan-21** | 1 042 |
| **Feb-21** | 859 |
| **Mar-21** | 859 |
| **Apr-21** | 164 |
| **May-21** | 0 |
| **Jun-21** | 0 |

The rainfall data is based on meter rainfall readings and is therefore verified.

***Potable water from municipality***

The potable water received by Shaft 2 is meter by the mine. These meter readings are reported monthly. The meter readings are shown in Table A-10.

**Table A-10: Potable water data for Shaft 2 in gold mining operation A.**

| | **Potable water from municipality ($m^3$)** |
|---|---|
| **Jul-20** | 204 |
| **Aug-20** | 244 |
| **Sep-20** | 159 |
| **Oct-20** | 357 |
| **Nov-20** | 288 |
| **Dec-20** | 85 |
| **Jan-21** | 353 |
| **Feb-21** | 289 |
| **Mar-21** | 174 |
| **Apr-21** | 232 |
| **May-21** | 290 |
| **Jun-21** | 232 |

This data is based on a meter reading and is considered to be verified. A sensitivity analysis was done in a later section to determine whether this meter should be calibrated.

***Wastewater to municipality***

The potable water used at Shaft 2 is used only for domestic purposes. Therefore, the total potable water received is expected to exit the system as wastewater. The wastewater volumes are therefore the same as the potable water figures reported.

***Runoff***

There is no area o Shaft 2 where rainfall accumulates. Therefore, all rainfall is expected to be lost as runoff. The runoff volumes are therefore equal to the rainfall figures reported.

### *Shaft 2 water balance*

Once all the inflows and outflows for Shaft 2 have been quantified, the water balance could be set up. The water balance is shown in Table A-11.

**Table A-11: Water balance for Shaft 2 in gold mining operation A.**

| | Inflows | | | Outflows | | |
|---|---|---|---|---|---|---|
| | **Rainfall** | **Potable water from municipality** | **Total inflows** | **Wastewater to municipality** | **Runoff** | **Total outflows** |
| **Jul-20** | 0 | 204 | **204** | 204 | 0 | **204** |
| **Aug-20** | 0 | 244 | **244** | 244 | 0 | **244** |
| **Sep-20** | 27 | 159 | **186** | 159 | 27 | **186** |
| **Oct-20** | 366 | 357 | **723** | 357 | 366 | **723** |
| **Nov-20** | 466 | 288 | **754** | 288 | 466 | **754** |
| **Dec-20** | 1 873 | 85 | **1 958** | 85 | 1 873 | **1 958** |
| **Jan-21** | 1 042 | 353 | **1 395** | 353 | 1 042 | **1 395** |
| **Feb-21** | 859 | 289 | **1 148** | 289 | 859 | **1 148** |
| **Mar-21** | 859 | 174 | **1 033** | 174 | 859 | **1 033** |
| **Apr-21** | 164 | 232 | **396** | 232 | 164 | **396** |
| **May-21** | 0 | 290 | **290** | 290 | 0 | **290** |
| **Jun-21** | 0 | 232 | **232** | 232 | 0 | **232** |

The variance for the water balance for Shaft 2 shown in Table A-11 can be calculated using Equation 21. The total inflows and total outflows are compared in Figure A-5.

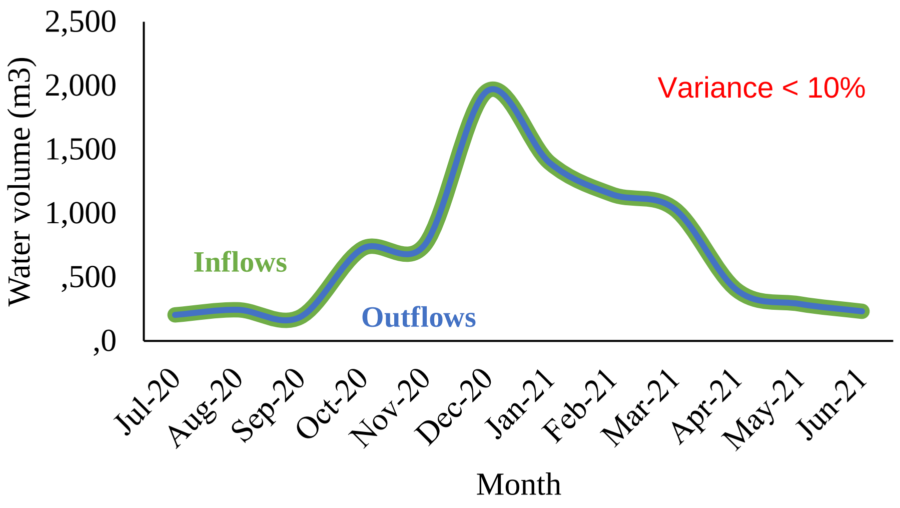


**Figure A-5: Water balance variance for Shaft 2 in gold mining operation A.**

From Figure A-5 it can be seen that the variance for the water balance is less than 10% for 12 consecutive months. The water balance is therefore seen as accurate.

***Sensitivity analysis***

A sensitivity analysis was done to determine whether meters should be calibrated. Both variables had a 0% effect on the water balance when they were varied by 10%. This was to be expected since both the outflows are based directly on the volumes of the inflows. None of the meters need to be calibrated.

## 2. Shaft 3

The third shaft in the mining operation is a dewatering shaft. Water is pumped from underground to prevent the underground area from flooding. The water abstracted from underground at the shaft is sent to a nearby pan. The modular unit for a shaft was used to determine all the inflows and outflows for this shaft. The resulting water balance can be seen in Figure A-6.

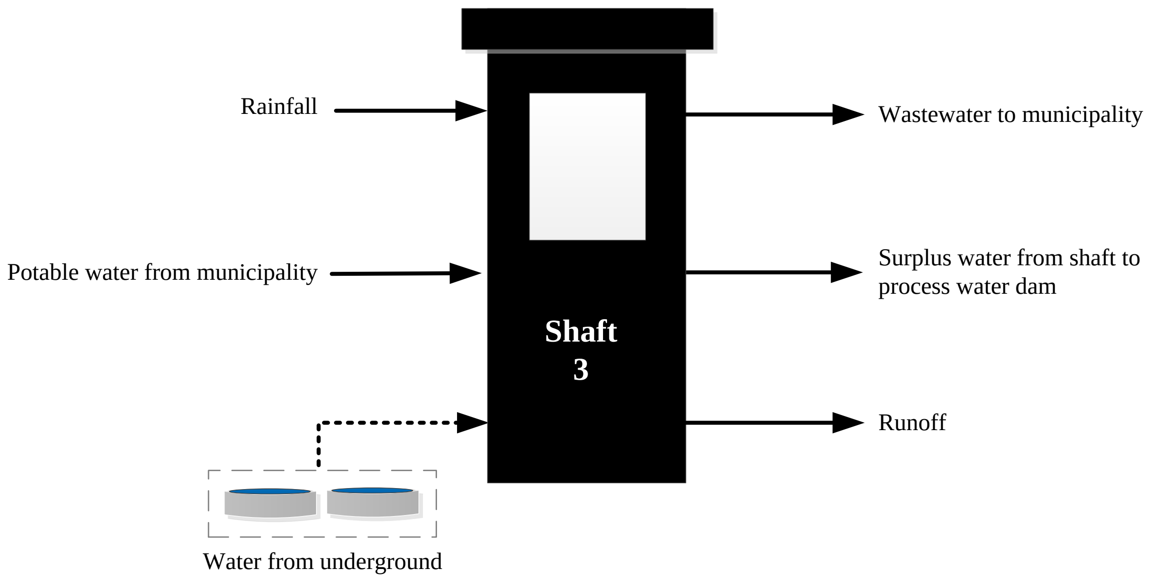


**Figure A-6: Water balance for Shaft 3 in gold mining operation A.**

In additional to the water pumped from underground, Shaft 3 also received potable water from the municipality and rainfall. The resulting outflows are the abstracted water that is pumped to the nearby pan, wastewater to the municipality, and runoff from the rainfall.

***Rainfall***

Shaft 3 does not have a rainfall meter. Shaft 3 is not in very close proximity to the processing plant, but it is assumed that they receive the same rainfall. The surface area for Shaft 3 was estimated as 8 653 by using Google Earth. The rainfall could be calculated by using Equation 14 and the rainfall data reported in Table A-3. The resulting rainfall is shown in

Table A-12.

**Table A-12: Rainfall data for Shaft 3 in gold mining operation A.**

| | Rainfall received ($m^3$) |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 26 |
| **Oct-20** | 346 |
| **Nov-20** | 441 |
| **Dec-20** | 1 774 |
| **Jan-21** | 986 |
| **Feb-21** | 813 |
| **Mar-21** | 813 |
| **Apr-21** | 156 |
| **May-21** | 0 |
| **Jun-21** | 0 |

This data was considered as verified since it was based on rainfall meter readings.

***Potable water from municipality***

The potable water received from the municipality is measured by the mining operation and reported monthly. The measured potable water consumption is shown in Table A-13.

**Table A-13: Potable water consumption data for Shaft 3 in gold mining operation A.**

| | Potable water from municipality ($m^3$) |
|---:|---:|
| **Jul-20** | 11 670 |
| **Aug-20** | 2 170 |
| **Sep-20** | 2 220 |
| **Oct-20** | 4 480 |
| **Nov-20** | 860 |
| **Dec-20** | 690 |
| **Jan-21** | 750 |
| **Feb-21** | 2 870 |
| **Mar-21** | 2 870 |
| **Apr-21** | 4 990 |
| **May-21** | 7 240 |
| **Jun-21** | 6 160 |

This data was considered as verified since it is based on a meter reading. A sensitivity analysis was done to determine whether the meter should be calibrated. The analysis is discussed in a later section.

***Water from underground***

The water abstracted from underground is metered and the total volume is reported monthly. The volumes obtained from the mining operation is shown in Table A-14.

**Table A-14: Water pumped from underground data for Shaft 3 in gold mining operation A.**

| | **Water from underground ($m^3$)** |
|---:|---:|
| **Jul-20** | 90 000 |
| **Aug-20** | 88 000 |
| **Sep-20** | 90 000 |
| **Oct-20** | 93 000 |
| **Nov-20** | 89 000 |
| **Dec-20** | 90 000 |
| **Jan-21** | 101 000 |
| **Feb-21** | 82 000 |
| **Mar-21** | 147 000 |
| **Apr-21** | 106 000 |
| **May-21** | 89 000 |
| **Jun-21** | 87 000 |

Since the volumes for water pumped from underground at the shaft is based on meter readings, they are considered to be validated. A sensitivity analysis is discussed in a later section where it was investigated whether it is necessary to calibrate the meter.

***Wastewater to municipality***

Since Shaft 3 is only a dewatering shaft, there are no industrial processes such as cooling towers and compressors running. There is also no active mining at the shaft, therefore no potable water is sent underground as drinking water. It was therefore assumed that all the potable water received by the shaft exits the system as wastewater. The wastewater is therefore the same volume as the potable water reported.

***Surplus water from shaft to process water dam***

The water abstracted from the shaft is sent directly to a nearby process water dam. Therefore, with the assumption that there are no leaks on the pipeline, the water sent to this processing dam is the same as the water abstracted reported.

### *Runoff*

It was assumed that all rainfall received by the shaft area is lost through runoff. The runoff volumes are therefore the same as that reported for rainfall.

### *Shaft 3 water balance*

Once all the inflows and outflows for Shaft 3 have been quantified, the water balance could be set up. The water balance is shown in Table A-15.

**Table A-15: Water balance for Shaft 3 in gold mining operation A.**

| | **Inflows** | | | | **Outflows** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Rainfall** | **Potable water from municipality** | **Water from under-ground** | **Total inflows** | **Wastewater to municipality** | **Runoff** | **Surplus water to process water dam** | **Total outflows** |
| **Jul-20** | 0 | 11 670 | 90 000 | **101 670** | 11 670 | 0 | 90 000 | **101 670** |
| **Aug-20** | 0 | 2 170 | 88 000 | **90 170** | 2 170 | 0 | 88 000 | **90 170** |
| **Sep-20** | 26 | 2 220 | 90 000 | **92 246** | 2 220 | 26 | 90 000 | **92 246** |
| **Oct-20** | 346 | 4 480 | 93 000 | **97 826** | 4 480 | 346 | 93 000 | **97 826** |
| **Nov-20** | 441 | 860 | 89 000 | **90 301** | 860 | 441 | 89 000 | **90 301** |
| **Dec-20** | 1 774 | 690 | 90 000 | **92 464** | 690 | 1 774 | 90 000 | **92 464** |
| **Jan-21** | 986 | 750 | 101 000 | **102 736** | 750 | 986 | 101 000 | **102 736** |
| **Feb-21** | 813 | 2 870 | 82 000 | **85 683** | 2 870 | 813 | 82 000 | **85 683** |
| **Mar-21** | 813 | 2 870 | 147 000 | **150 683** | 2 870 | 813 | 147 000 | **150 683** |
| **Apr-21** | 156 | 4 990 | 106 000 | **111 146** | 4 990 | 156 | 106 000 | **111 146** |
| **May-21** | 0 | 7 240 | 89 000 | **96 240** | 7 240 | 0 | 89 000 | **96 240** |
| **Jun-21** | 0 | 6 160 | 87 000 | **93 160** | 6 160 | 0 | 87 000 | **93 160** |

The total inflows and outflows could then be compared to calculate the variance with Equation 21. The comparison between the inflows and outflows is shown in Figure A-7.

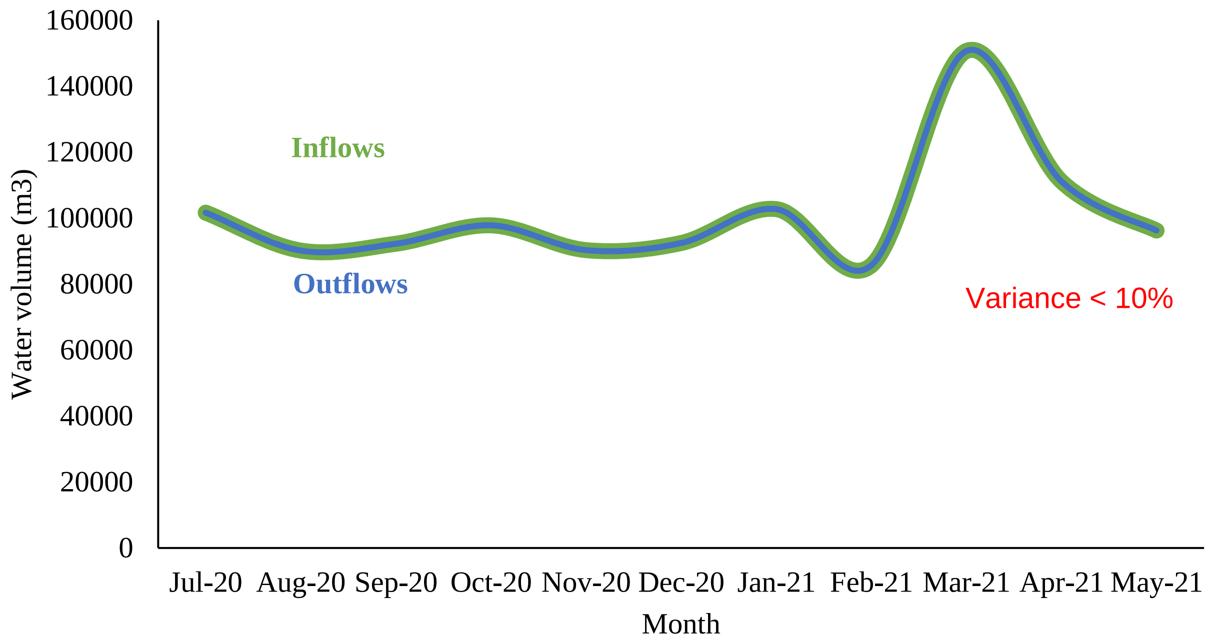


**Figure A-7: Variance for Shaft 3 in gold mining operation A.**

From Figure A-7 it can be seen that the variance for Shaft 3 over a 12-month period is less than 10%. The water balance is therefore assumed to be accurate.

***Sensitivity analysis***

A sensitivity analysis was done to determine whether any of the meters used to quantify the inflows and outflows for Shaft 3 must be calibrated. The methodology discussed in Section 2.3 was used. The variables were all changed with 10% to assess the sensitivity of the water balance variance towards them. Since all the outflows are directly related to the inflows, the water balance showed no sensitivity to any of the variables. The meters therefore do not need to be calibrated.

## 3. Waste rock dump

There are 7 waste rock dumps that form part of this mining operation. One of these waste rock dumps are being remined by the processing plant. This does however have no effect on the water balance since the waste rock transportation does not involve any water.

The modular unit developed for a waste rock dump in Section 2.2 was used to identify all the possible inflows and outflows for the waste rock dumps. The basic water balance for all the waste rock dumps remains constant and can be seen in Figure A-8.

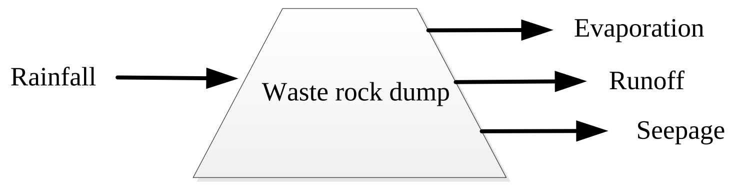


**Figure A-8: Waste rock dump water balance for gold mining operation A.**

There is no dust suppression applied to any of the waste rock dumps in the area. There is also no active deposition of waste rock onto any of these waste rock dumps; therefore, no water will enter the boundary through waste rock deposition. The only water inflow to these waste rock dumps is therefore rainfall. The rainfall received either runs off into the environment, seeps into the ground, or evaporates.

***Rainfall***

The only rainfall meter in the area is at the processing plant. The waste rock dumps in this mining operation are all relatively closely located to the processing plant. It is therefore assumed that the rainfall received by the plant reported in

Table A-3 is received by all of the waste rock dumps. The surface area for all the waste rock dumps was estimated using Google Earth. The surface areas obtained is shown in Table A-16.

**Table A-16: Surface areas for the waste rock dumps in gold mining operation A.**

| | **Surface area ($m^2$)** |
|---|---|
| **WRD 1** | 54 398 |
| **WRD 2** | 110 794 |
| **WRD 3** | 143 299 |
| **WRD 4** | 130 680 |
| **WRD 5** | 90 870 |
| **WRD 6** | 22 525 |
| **WRD 7** | 458 783 |

Once the surface areas and rainfall received have been determined, Equation 14 was used to calculate the volumes of rainfall received by the waste rock dumps. The rainfall volumes are shown in Table A-17.

**Table A-17: Rainfall received by waste rock dumps in gold mining operation A.**

| | WRD 1 | WRD 2 | WRD 3 | WRD 4 | WRD 5 | WRD 6 | WRD 7 |
|---|---|---|---|---|---|---|---|
| **Jul-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Aug-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Sep-20** | 163 | 332 | 430 | 392 | 273 | 68 | 1 376 |
| **Oct-20** | 2 176 | 4 432 | 5 732 | 5 227 | 3 635 | 901 | 18 351 |
| **Nov-20** | 2 774 | 5 650 | 7 308 | 6 665 | 4 634 | 1 149 | 23 398 |
| **Dec-20** | 11 152 | 22 713 | 29 376 | 26 789 | 18 628 | 4 618 | 94 051 |
| **Jan-21** | 6 201 | 12 631 | 16 336 | 14 898 | 10 359 | 2 568 | 52 301 |
| **Feb-21** | 5 113 | 10 415 | 13 470 | 12 284 | 8 542 | 2 117 | 43 126 |
| **Mar-21** | 5 113 | 10 415 | 13 470 | 12 284 | 8 542 | 2 117 | 43 126 |
| **Apr-21** | 979 | 1 994 | 2 579 | 2 352 | 1 636 | 405 | 8 258 |
| **May-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Jun-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

***Runoff***

Runoff was calculated using Equation 21. The drainage area was chosen as the surface area of the waste rock dumps, while a runoff coefficient of 70% was chosen. The runoff volumes obtained is shown in Table A-18.

**Table A-18: Runoff volumes for the waste rock dumps in gold mining operation A.**

| | WRD 1 | WRD 2 | WRD 3 | WRD 4 | WRD 5 | WRD 6 | WRD 7 |
|---|---|---|---|---|---|---|---|
| **Jul-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Aug-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Sep-20** | 114 | 233 | 301 | 274 | 191 | 47 | 963 |
| **Oct-20** | 1 523 | 3 102 | 4 012 | 3 659 | 2 544 | 631 | 12 846 |
| **Nov-20** | 1 942 | 3 955 | 5 116 | 4 665 | 3 244 | 804 | 16 379 |
| **Dec-20** | 7 806 | 15 899 | 20 563 | 18 753 | 13 040 | 3 232 | 65 835 |
| **Jan-21** | 4 341 | 8 841 | 11 435 | 10 428 | 7 251 | 1 797 | 36 611 |
| **Feb-21** | 3 579 | 7 290 | 9 429 | 8 599 | 5 979 | 1 482 | 30 188 |
| **Mar-21** | 3 579 | 7 290 | 9 429 | 8 599 | 5 979 | 1 482 | 30 188 |
| **Apr-21** | 685 | 1 396 | 1 806 | 1 647 | 1 145 | 284 | 5 781 |
| **May-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Jun-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

***Seepage***

The seepage from the waste rock dumps was calculating by using Equation 20 and the inflows discussed above. The volumes of water lost through seepage is shown in Table A-19.

**Table A-19: Water lost through seepage for the waste rock dumps in gold mining operation A.**

| | WRD 1 | WRD 2 | WRD 3 | WRD 4 | WRD 5 | WRD 6 | WRD 7 |
|---|---|---|---|---|---|---|---|
| **Jul-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Aug-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Sep-20** | 15 | 30 | 39 | 35 | 25 | 6 | 124 |
| **Oct-20** | 196 | 399 | 516 | 470 | 327 | 81 | 1 652 |
| **Nov-20** | 250 | 509 | 658 | 600 | 417 | 103 | 2 106 |
| **Dec-20** | 1 004 | 2 044 | 2 644 | 2 411 | 1 677 | 416 | 8 465 |
| **Jan-21** | 558 | 1 137 | 1 470 | 1 341 | 932 | 231 | 4 707 |
| **Feb-21** | 460 | 937 | 1 212 | 1 106 | 769 | 191 | 3 881 |
| **Mar-21** | 460 | 937 | 1 212 | 1 106 | 769 | 191 | 3 881 |
| **Apr-21** | 88 | 179 | 232 | 212 | 147 | 36 | 743 |
| **May-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Jun-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

***Evaporation***

Evaporation was calculated by balancing all the other inflows and outflows over the waste rock dumps. The obtained evaporation volumes are shown in Table A-20.

**Table A-20: Evaporation from the waste rock dumps in gold mining operation A.**

| | WRD 1 | WRD 2 | WRD 3 | WRD 4 | WRD 5 | WRD 6 | WRD 7 |
|---|---|---|---|---|---|---|---|
| **Jul-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Aug-20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Sep-20** | 34 | 70 | 90 | 82 | 57 | 14 | 289 |
| **Oct-20** | 457 | 931 | 1 204 | 1 098 | 763 | 189 | 3 854 |
| **Nov-20** | 583 | 1 187 | 1 535 | 1 400 | 973 | 241 | 4 914 |
| **Dec-20** | 2 342 | 4 770 | 6 169 | 5 626 | 3 912 | 970 | 19 751 |
| **Jan-21** | 1 302 | 2 652 | 3 431 | 3 128 | 2 175 | 539 | 10 983 |
| **Feb-21** | 1 074 | 2 187 | 2 829 | 2 580 | 1 794 | 445 | 9 056 |
| **Mar-21** | 1 074 | 2 187 | 2 829 | 2 580 | 1 794 | 445 | 9 056 |
| **Apr-21** | 206 | 419 | 542 | 494 | 343 | 85 | 1 734 |
| **May-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Jun-21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

***Water balance***

Consolidating the inflows and outflows of WRD 1 resulted in the water balance shown in Table A-21.

**Table A-21: Water balance for waste rock dump 1 in gold mining operation A.**

| | Inflows | | Outflows | | | |
|---|---|---|---|---|---|---|
| | **Rainfall** | **Total inflows** | **Runoff** | **Seepage** | **Evaporation** | **Total outflows** |
| **Jul-20** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Aug-20** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Sep-20** | 163 | 163 | 114 | 15 | 34 | 163 |
| **Oct-20** | 2 176 | 2 176 | 1 523 | 196 | 457 | 2 176 |
| **Nov-20** | 2 774 | 2 774 | 1 942 | 250 | 583 | 2 774 |
| **Dec-20** | 11 152 | 11 152 | 7 806 | 1 004 | 2 342 | 11 152 |
| **Jan-21** | 6 201 | 6 201 | 4 341 | 558 | 1 302 | 6 201 |
| **Feb-21** | 5 113 | 5 113 | 3 579 | 460 | 1 074 | 5 113 |
| **Mar-21** | 5 113 | 5 113 | 3 579 | 460 | 1 074 | 5 113 |
| **Apr-21** | 979 | 979 | 685 | 88 | 206 | 979 |
| **May-21** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Jun-21** | 0 | 0 | 0 | 0 | 0 | 0 |

Because evaporation was calculated by balancing the water balance, it is expected that the variance is 0, as shown in Figure A-9.

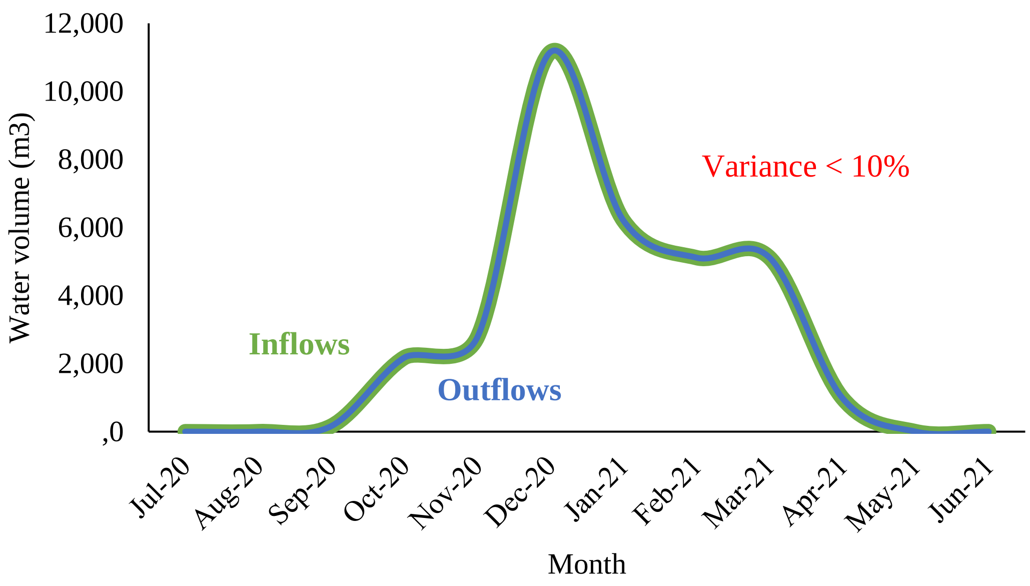


**Figure A-9: Inflows compared to outflows for WRD 1 in gold mining operation A.**

Since the variance of the water balance is less than 10% for 12 consecutive months as shown in Figure A-9 the water balance is assumed to be accurate. The water balances resulting from the inflows and outflows discussed in this section as well as the comparison of these inflows and outflows will be very similar and will therefore not be discussed.

***Sensitivity analysis***

Since the evaporation is calculated by balancing all the other inflows and outflows of the water balance, the water balance will show no sensitivity towards a change in any of the variables. It is therefore assumed that no additional meters need to be installed to monitor any of these inflows or outflows.

## 4. Active Tailings Storage Facilities

There is one active tailings storage facility within the mining operation. The TSF consists of two sections which operate independent from one another and are therefore seen as separate process units. The modular unit developed for a TSF was used to identify all the inflows and outflows for the two TSFs. The resulting water balance is shown in Figure A-10.

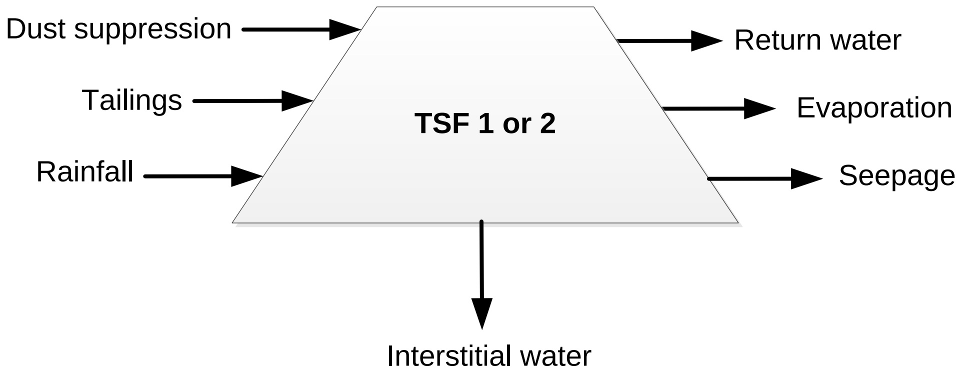


**Figure A-10: Water balance for TSF 1 and 2 in gold mining operation A.**

Both TSF 1 and TSF 2 have the same general water balance. The main water inflow into the TSF's is the water in tailings. The main outflows are interstitial water and return water.

***Dust suppression***

Dust suppression is applied to both of the TSF. An average volume of 548 $m^3$ per month is applied as dust suppression. The dust suppression volumes are shown in Table A-22.

**Table A-22: Volume of water applied as dust suppression for TSF 1 and TSF 2 in gold mining operation A in units of m$^3$.**

| | TSF 1 | TSF 2 |
|---|---|---|
| **Jul-20** | 548 | 548 |
| **Aug-20** | 548 | 548 |
| **Sep-20** | 548 | 548 |
| **Oct-20** | 548 | 548 |
| **Nov-20** | 548 | 548 |
| **Dec-20** | 548 | 548 |
| **Jan-21** | 548 | 548 |
| **Feb-21** | 548 | 548 |
| **Mar-21** | 548 | 548 |
| **Apr-21** | 548 | 548 |
| **May-21** | 548 | 548 |
| **Jun-21** | 548 | 548 |

***Water in tailings***

Water in tailings deposited on the TSFs is the same as that reported by the plant with the assumption that there are no leaks on the pipelines. The tailings deposited are split equally between the two TSFs. The water in tailings deposited on the respective TSFs is shown in Table A-23.

**Table A-23: Water in tailings deposited on TSF 1 and TSF 2 in m$^3$.**

| | TSF 1 | TSF 2 |
|---|---|---|
| **Jul-20** | 60 965 | 60 965 |
| **Aug-20** | 73 087 | 73 087 |
| **Sep-20** | 58 441 | 58 441 |
| **Oct-20** | 70 663 | 70 663 |
| **Nov-20** | 61 208 | 61 208 |
| **Dec-20** | 56 834 | 56 834 |
| **Jan-21** | 59 008 | 59 008 |
| **Feb-21** | 61 629 | 61 629 |
| **Mar-21** | 67 511 | 67 511 |
| **Apr-21** | 78 173 | 78 173 |
| **May-21** | 57 419 | 57 419 |
| **Jun-21** | 67 538 | 67 538 |

***Rainfall***

The rainfall received by the TSF is assumed to be the same as that received by the plant seeing as they are in the same vicinity. The surface area for TSF 1 and TSF 2 was estimated as 802 809 m$^3$ and 624 804 m$^3$ respectively using Google Earth. The volume of rainfall received on the TSFs were calculated using Equation 14 and is shown in Table A-24.

**Table A-24: Rainfall received on TSF 1 and TSF 2 in gold mining operation A.**

| | TSF 1 | TSF 2 |
|---|---|---|
| **Jul-20** | 0 | 0 |
| **Aug-20** | 0 | 0 |
| **Sep-20** | 2 408 | 1 874 |
| **Oct-20** | 32 112 | 24 992 |
| **Nov-20** | 40 943 | 31 865 |
| **Dec-20** | 164 576 | 128 085 |
| **Jan-21** | 91 520 | 71 228 |
| **Feb-21** | 75 464 | 58 732 |
| **Mar-21** | 75 464 | 58 732 |
| **Apr-21** | 14 451 | 11 246 |
| **May-21** | 0 | 0 |
| **Jun-21** | 0 | 0 |

***Evaporation***

The mining operation is considered to be in a dry area seeing as no water is released into the environment to maintain the water balance. Using Equation Equation 12, the average tailings solids density for the 12 months was calculated as 0.33.

Solgi [29] developed a standard comparison for pool area based on tailings solids content. The comparison is done for two climate conditions: dry climates and wet climates. Welch [50] describes a wet climate as an area where extra accumulated water must be released into the environment to maintain the annual water balance for the TSF. A wet climate area is therefore an area where no extra water accumulates that needs to be released to maintain the water balance for the TSF. The relationships are shown in Table 7. From here, a pool area of 33% of the total TSF area was derived for this tailings solids content. Therefore, the pool area on TSF 1 and TSF 2 are 264 927 $m^3$ and 206 185 $m^3$ respectively. With the pool area and evaporation rates known, Equation 15 was used to calculate the volumes of water lost through evaporation. These volumes are shown in Table A-25.

**Table A-25: Water lost through evaporation for TSF 1 and TSF in gold mining operation A.**

| | TSF 1 | TSF 2 |
|---|---|---|
| **Jul-20** | 20 762 | 16 159 |
| **Aug-20** | 28 384 | 22 091 |
| **Sep-20** | 38 865 | 30 247 |
| **Oct-20** | 48 649 | 37 862 |
| **Nov-20** | 53 449 | 41 598 |
| **Dec-20** | 56 337 | 43 845 |
| **Jan-21** | 54 641 | 42 526 |
| **Feb-21** | 43 172 | 33 600 |
| **Mar-21** | 38 571 | 30 019 |
| **Apr-21** | 29 176 | 22 707 |
| **May-21** | 22 890 | 17 814 |
| **Jun-21** | 18 285 | 14 231 |

***Seepage***

Seepage is considered to by 9% of the total inflows into the TSF. The calculated volume of water lost through seepage is shown in Table A-26.

**Table A-26: Water lost through seepage for TSF 1 and TSF 2 in gold mining operation A.**

| | TSF 1 | TSF 2 |
|---:|---:|---:|
| **Jul-20** | 5 536 | 5 536 |
| **Aug-20** | 6 627 | 6 627 |
| **Sep-20** | 5 526 | 5 478 |
| **Oct-20** | 9 299 | 8 658 |
| **Nov-20** | 9 243 | 8 426 |
| **Dec-20** | 19 976 | 16 692 |
| **Jan-21** | 13 597 | 11 771 |
| **Feb-21** | 12 388 | 10 882 |
| **Mar-21** | 12 917 | 11 411 |
| **Apr-21** | 8 385 | 8 097 |
| **May-21** | 5 217 | 5 217 |
| **Jun-21** | 6 128 | 6 128 |

***Interstitial water***

Interstitial water is dependent on the dry density of the slurry. The processing plant reports an average dry density of 1.25 tonnes/$m^3$ and an average solids density of 2.67 tonnes/$m^3$ for the tailings. Since the tailings from the plant is split equally between TSF 1 and TSF 2, the interstitial water at both TSF's will be the same. Equation 16 to Equation 19 was used to calculate the interstitial water shown in Table A-27.

**Table A-27: Interstitial water for TSF 1 and TSF 2 in gold mining operation A.**

| | TSF 1 | TSF 2 |
|---|---|---|
| **Jul-20** | 14 554 | 14 554 |
| **Aug-20** | 15 310 | 15 310 |
| **Sep-20** | 14 538 | 14 538 |
| **Oct-20** | 13 472 | 13 472 |
| **Nov-20** | 14 007 | 14 007 |
| **Dec-20** | 13 005 | 13 005 |
| **Jan-21** | 12 361 | 12 361 |
| **Feb-21** | 9 960 | 9 960 |
| **Mar-21** | 13 460 | 13 460 |
| **Apr-21** | 16 063 | 16 063 |
| **May-21** | 12 028 | 12 028 |
| **Jun-21** | 14 173 | 14 173 |

***Return water***

The return water from TSF 1 is sent to an unlined return water dam where the return water from TSF 2 is sent to a lined return water dam. The return water is calculated by balancing all the inflows and outflows. The volumes of the return water calculated is shown in Table A-28.

**Table A-28: Return water from TSF 1 and TSF 2 in gold mining operation A.**

| | TSF 1 | TSF 2 |
|---|---|---|
| **Jul-20** | 20 660 | 25 264 |
| **Aug-20** | 23 313 | 29 607 |
| **Sep-20** | 2 469 | 10 601 |
| **Oct-20** | 31 903 | 36 210 |
| **Nov-20** | 26 001 | 29 591 |
| **Dec-20** | 132 639 | 111 924 |
| **Jan-21** | 70 477 | 64 127 |
| **Feb-21** | 72 120 | 66 466 |
| **Mar-21** | 78 575 | 71 901 |
| **Apr-21** | 39 547 | 43 100 |
| **May-21** | 17 833 | 22 908 |
| **Jun-21** | 29 500 | 33 554 |

***Water balance***

The water balance for TSF 1 is shown in Table A-29.

**Table A-29: Water balance for TSF 1 in gold mining operation A.**

| | Inflows | | | | Outflows | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Dust suppression** | **Water in tailings** | **Rainfall** | **Total inflows** | **Evaporation** | **Seepage** | **Interstitial water** | **Return water** | **Total outflows** |
| **Jul-20** | 548 | 60 965 | 0 | **61 513** | 20 762 | 5 536 | 14 554 | 20 660 | **61 513** |
| **Aug-20** | 548 | 73 087 | 0 | **73 635** | 28 384 | 6 627 | 15 310 | 23 313 | **73 635** |
| **Sep-20** | 548 | 58 441 | 2 408 | **61 398** | 38 865 | 5 526 | 14 538 | 2 469 | **61 398** |
| **Oct-20** | 548 | 70 663 | 32 112 | **103 323** | 48 649 | 9 299 | 13 472 | 31 903 | **103 323** |
| **Nov-20** | 548 | 61 208 | 40 943 | **102 700** | 53 449 | 9 243 | 14 007 | 26 001 | **102 700** |
| **Dec-20** | 548 | 56 834 | 164 576 | **221 958** | 56 337 | 19 976 | 13 005 | 132 639 | **221 958** |
| **Jan-21** | 548 | 59 008 | 91 520 | **151 076** | 54 641 | 13 597 | 12 361 | 70 477 | **151 076** |
| **Feb-21** | 548 | 61 629 | 75 464 | **137 641** | 43 172 | 12 388 | 9 960 | 72 120 | **137 641** |
| **Mar-21** | 548 | 67 511 | 75 464 | **143 523** | 38 571 | 12 917 | 13 460 | 78 575 | **143 523** |
| **Apr-21** | 548 | 78 173 | 14 451 | **93 171** | 29 176 | 8 385 | 16 063 | 39 547 | **93 171** |
| **May-21** | 548 | 57 419 | 0 | **57 967** | 22 890 | 5 217 | 12 028 | 17 833 | **57 967** |
| **Jun-21** | 548 | 67 538 | 0 | **68 086** | 18 285 | 6 128 | 14 173 | 29 500 | **68 086** |

Since the return water has been calculate by balancing all the inflows and outflows for the TSF, it is expected that the variance for the water balance will be 0. The inflows and outflows are compared in Figure A-11.

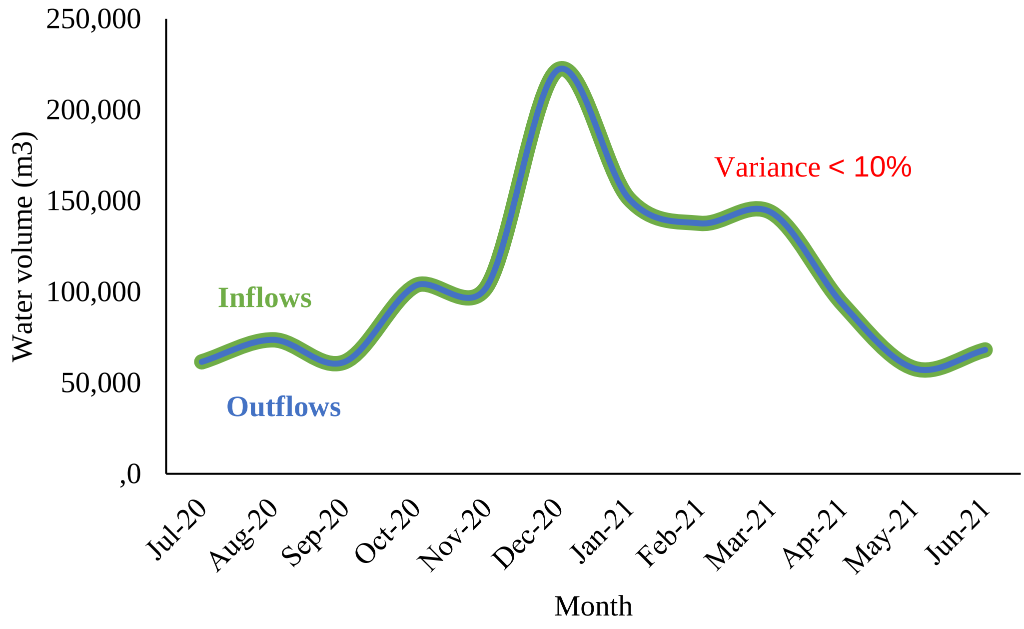


**Figure A-11: Inflows in comparison with outflows for TSF 1 in gold mining operation A.**

From Figure A-11 it is evident that the variance of the water balance over TSF 1 is 0, as expected. The water balance for TSF 1 is therefore assumed to be in balance.

The water balance for TSF 2 is shown in Table A-30.

**Table A-30: Water balance for TSF 2 in gold mining operation A.**

| | Inflows | | | | Outflows | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Dust suppression | Water in tailings | Rainfall | Total inflows | Evaporation | Seepage | Interstitial water | Return water | Total outflows |
| **Jul-20** | 548 | 60 965 | 0 | **61 513** | 16 159 | 5 536 | 14 554 | 25 264 | **61 513** |
| **Aug-20** | 548 | 73 087 | 0 | **73 635** | 22 091 | 6 627 | 15 310 | 29 607 | **73 635** |
| **Sep-20** | 548 | 58 441 | 1 874 | **60 864** | 30 247 | 5 478 | 14 538 | 10 601 | **60 864** |
| **Oct-20** | 548 | 70 663 | 24 992 | **96 203** | 37 862 | 8 658 | 13 472 | 36 210 | **96 203** |
| **Nov-20** | 548 | 61 208 | 31 865 | **93 621** | 41 598 | 8 426 | 14 007 | 29 591 | **93 621** |
| **Dec-20** | 548 | 56 834 | 128 085 | **185 467** | 43 845 | 16 692 | 13 005 | 111 924 | **185 467** |
| **Jan-21** | 548 | 59 008 | 71 228 | **130 784** | 42 526 | 11 771 | 12 361 | 64 127 | **130 784** |
| **Feb-21** | 548 | 61 629 | 58 732 | **120 908** | 33 600 | 10 882 | 9 960 | 66 466 | **120 908** |
| **Mar-21** | 548 | 67 511 | 58 732 | **126 791** | 30 019 | 11 411 | 13 460 | 71 901 | **126 791** |
| **Apr-21** | 548 | 78 173 | 11 246 | **89 967** | 22 707 | 8 097 | 16 063 | 43 100 | **89 967** |
| **May-21** | 548 | 57 419 | 0 | **57 967** | 17 814 | 5 217 | 12 028 | 22 908 | **57 967** |
| **Jun-21** | 548 | 67 538 | 0 | **68 086** | 14 231 | 6 128 | 14 173 | 33 554 | **68 086** |

Again, it is expected that the variance for the water balance over TSF 2 is 0 since the return water was calculated by balancing the water balance. The inflows and outflows are compared in Figure A-12.

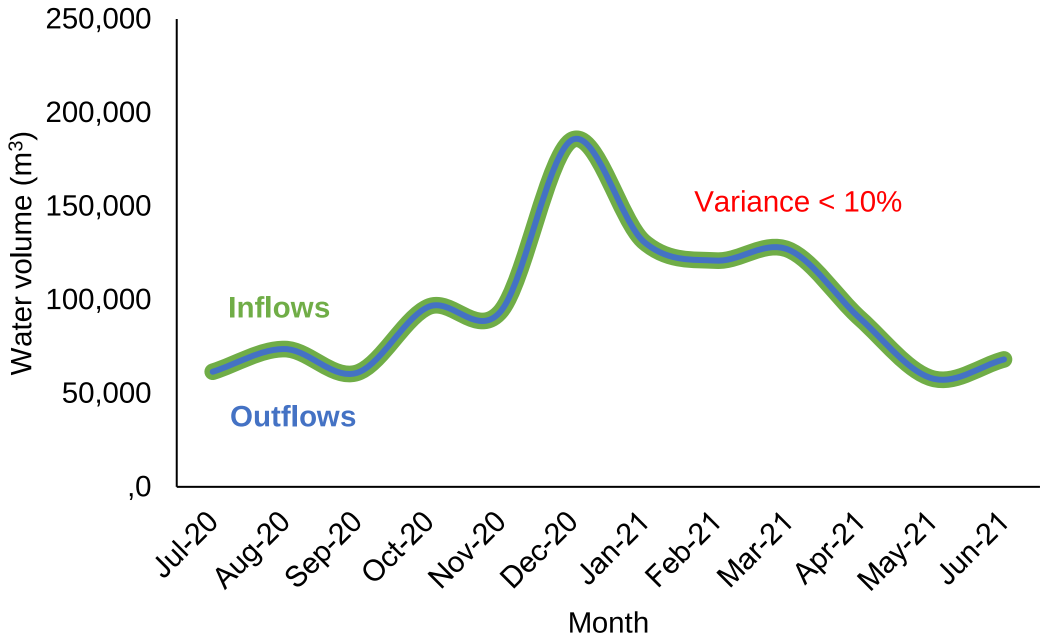


**Figure A-12: Inflows in comparison with outflows for TSF 2 in gold mining operation A.**

From Figure A-12 it can be seen that the variance for the water balance over TSF 2 is 0. It is therefore assumed that the water balance is accurate.

***Sensitivity analysis***

Since the return water is calculated by balancing the inflows and other outflows in the water balances for these tow TSFs, any change in other variables will be cancelled out by the return water.

## 5. Dormant Tailings Storage Facility

The water balance over the dormant TSF (TSF 3) was developed from the modular unit discussed in Section 2.2 and is shown in Figure A-13.

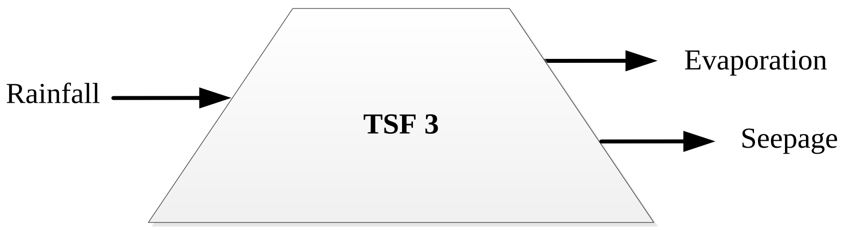


**Figure A-13: Water balance over TSF 3 in gold mining operation A.**

The only inflow relevant to TSF 3 is rainfall. The water entering the boundary as rainfall either seeps away or is lost through evaporation.

***Rainfall***

The surface area of TSF 3 was estimated to be 1 116 533 m$^2$ by using Google Earth. The rainfall received by the TSF is assumed to be the same rainfall recorded by the plant that is shown in Table A-3.Equation 14 was used to calculate the volumes of rainfall received. These volumes are tabulated in

Table A-31.

**Table A-31: Rainfall received on TSF 3 in gold mining operation A.**

| | **Rainfall ($m^3$)** |
|---:|---:|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 3 350 |
| **Oct-20** | 44 661 |
| **Nov-20** | 56 943 |
| **Dec-20** | 228 889 |
| **Jan-21** | 127 285 |
| **Feb-21** | 104 954 |
| **Mar-21** | 104 954 |
| **Apr-21** | 20 098 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Seepage***

Water lost through seepage can be calculated by using Equation 20. The volumes obtained are shown in Table A-32.

**Table A-32: Seepage for TSF 3 in gold mining operation A.**

| | **Seepage ($m^3$)** |
|---:|---:|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 301 |
| **Oct-20** | 4 020 |
| **Nov-20** | 5 125 |
| **Dec-20** | 20 600 |
| **Jan-21** | 11 456 |
| **Feb-21** | 9 446 |
| **Mar-21** | 9 446 |
| **Apr-21** | 1 809 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Evaporation***

Evaporation on a TSF is generally calculated from the pool area. Seeing as this TSF is dormant, there will not be a pool on top of the TSF. From analysis of Figure A-13, evaporation is then all water that enters the boundary as rainfall that is not lost through seepage. Evaporation can therefore be calculated by balancing the water balance. The volumes obtained are shown in Table A-33.

**Table A-33: Evaporation from TSF 3 in gold mining operation A.**

| | **Evaporation ($m^3$)** |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 3 048 |
| **Oct-20** | 40 642 |
| **Nov-20** | 51 818 |
| **Dec-20** | 208 289 |
| **Jan-21** | 115 829 |
| **Feb-21** | 95 508 |
| **Mar-21** | 95 508 |
| **Apr-21** | 18 289 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Water balance***

The inflows and outflows were consolidated to obtain the water balance over TSF 3. The water balance is shown in Table A-34.

**Table A-34: Water balance over TSF 3 in gold mining operation A.**

| | Inflows | | Outflows | | |
|---|---|---|---|---|---|
| | **Rainfall** | **Total inflows** | **Seepage** | **Evaporation** | **Total outflows** |
| **Jul-20** | 0 | **0** | 0 | 0 | **0** |
| **Aug-20** | 0 | **0** | 0 | 0 | **0** |
| **Sep-20** | 3 350 | **3 350** | 301 | 3 048 | **3 350** |
| **Oct-20** | 44 661 | **44 661** | 4 020 | 40 642 | **44 661** |
| **Nov-20** | 56 943 | **56 943** | 5 125 | 51 818 | **56 943** |
| **Dec-20** | 228 889 | **228 889** | 20 600 | 208 289 | **228 889** |
| **Jan-21** | 127 285 | **127 285** | 11 456 | 115 829 | **127 285** |
| **Feb-21** | 104 954 | **104 954** | 9 446 | 95 508 | **104 954** |
| **Mar-21** | 104 954 | **104 954** | 9 446 | 95 508 | **104 954** |
| **Apr-21** | 20 098 | **20 098** | 1 809 | 18 289 | **20 098** |
| **May-21** | 0 | **0** | 0 | 0 | **0** |
| **Jun-21** | 0 | **0** | 0 | 0 | **0** |

The inflows and outflows can be compared to calculate the variance as shown in Equation 24. The inflows and outflows are compared in Figure A-14.

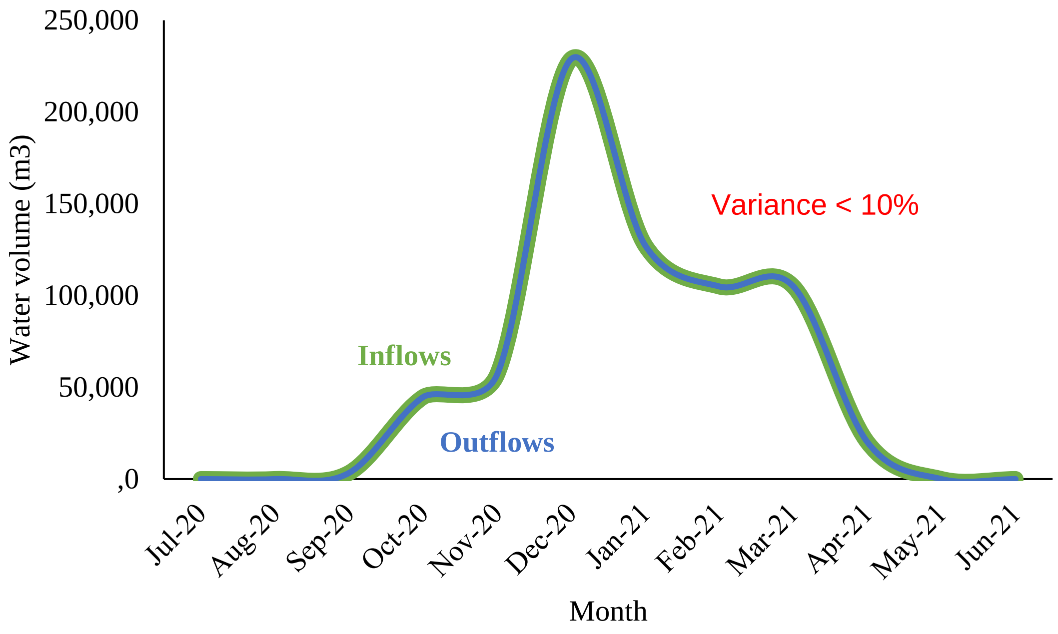


**Figure A-14: Inflows in comparison to outflows for TSF 3 in gold mining operation A.**

Figure A-14 indicates that the variance for the water balance over TSF 3 is less than 10% for 12 consecutive months. This was to be expected since evaporation was calculated by balancing the water balance. The water balance is therefore assumed to be accurate.

***Sensitivity analysis***

Since evaporation was calculated by balancing the water balance, any change in other variables would be cancelled by the balancing of the water balance. The water balance therefore shows no sensitivity towards any of the variables. No additional metering is required for the TSF 3 water balance.

## 6. Wastewater Treatment Facility

The wastewater treatment facility receives sewage from Shaft 3. The sewage is treated, and the purified sewage effluent is sent to the process water dam within the boundary of Shaft 3. The modular unit developed for a water treatment plant in Section 2.2 was used to derive the water balance for this wastewater treatment facility shown in Figure A-15.

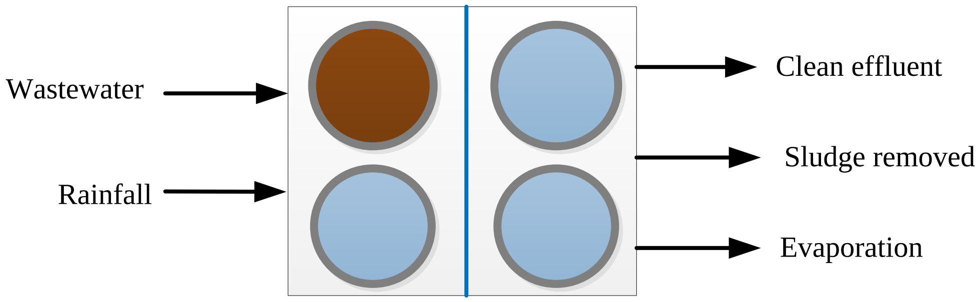


**Figure A-15: Water balance over wastewater treatment plant in gold mining operation A.**

In addition to the wastewater received by the wastewater treatment plant, rainfall is received on all the open process dams or tanks. Water exits the boundary either as clean effluent or as sludge removed. Evaporation also occurs on open dams or tanks within the process.

***Wastewater***

The wastewater generated by Shaft 3 is sent to the wastewater treatment facility. The wastewater volumes are shown in Table A-35.

**Table A-35: Wastewater received by wastewater treatment plant in gold mining operation A.**

| | **Wastewater received ($m^3$)** |
|---:|---:|
| **Jul-20** | 11 670 |
| **Aug-20** | 2 170 |
| **Sep-20** | 2 220 |
| **Oct-20** | 4 480 |
| **Nov-20** | 860 |
| **Dec-20** | 690 |
| **Jan-21** | 750 |
| **Feb-21** | 2 870 |
| **Mar-21** | 2 870 |
| **Apr-21** | 4 990 |
| **May-21** | 7 240 |
| **Jun-21** | 6 160 |

***Rainfall***

Rainfall received by the wastewater treatment plant is assumed to be the same as that received by the processing plant tabulated in Table A-3.

The area of the open water dams and tanks within the treatment plant was estimated as 250 $m^2$ by using Google Earth. The rainfall was then calculated by using Equation 14. The volumes are shown in

Table A-36.

**Table A-36: Rainfall received by the wastewater treatment plant in caste study 1.**

| | **Rainfall ($m^3$)** |
|---:|---:|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 1 |
| **Oct-20** | 10 |
| **Nov-20** | 13 |
| **Dec-20** | 51 |
| **Jan-21** | 29 |
| **Feb-21** | 24 |
| **Mar-21** | 24 |
| **Apr-21** | 5 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Clean Effluent***

The clean effluent from the wastewater treatment plant that is sent to the process water dam in Shaft 3 is measured. The monthly volumes are shown in Table A-37.

**Table A-37: Clean effluent from the wastewater treatment plant in gold mining operation A.**

| | Clean Effluent ($m^3$) |
|---|---|
| **Jul-20** | 102 |
| **Aug-20** | 104 |
| **Sep-20** | 334 |
| **Oct-20** | 326 |
| **Nov-20** | 342 |
| **Dec-20** | 309 |
| **Jan-21** | 676 |
| **Feb-21** | 380 |
| **Mar-21** | 619 |
| **Apr-21** | 623 |
| **May-21** | 967 |
| **Jun-21** | 586 |

***Sludge removed***

Sludge removed can be calculated by balancing the water balance over the wastewater treatment facility.

***Evaporation***

Evaporation will occur from the open dams and tanks within the wastewater treatment plant. The evaporation rates from Table 3 as well as the estimated open dam area of 250 m2 was used in Equation 15 to calculate the volumes of water lost through evaporation. These volumes are shown in Table A-38.

**Table A-38: Evaporation from the wastewater treatment plant in gold mining operation A.**

| | **Evaporation ($m^3$)** |
|---|---|
| **Jul-20** | 20 |
| **Aug-20** | 27 |
| **Sep-20** | 37 |
| **Oct-20** | 46 |
| **Nov-20** | 50 |
| **Dec-20** | 53 |
| **Jan-21** | 52 |
| **Feb-21** | 41 |
| **Mar-21** | 36 |
| **Apr-21** | 28 |
| **May-21** | 22 |
| **Jun-21** | 17 |

***Water balance***

The inflows and outflows for the wastewater treatment plant were consolidated into the water balance. The water balance is shown in Table A-39.

**Table A-39: Water balance over the wastewater treatment plant in gold mining operation A.**

| | Inflows | | | Outflows | | | |
|---|---|---|---|---|---|---|---|
| | Wastewater | Rainfall | Total inflows | Clean effluent | Evaporation | Sludge removed | Total outflows |
| **Jul-20** | 11 670 | 0 | **102** | 102 | 11 548 | 11 670 | **122** |
| **Aug-20** | 2 170 | 0 | **104** | 104 | 2 039 | 2 170 | **131** |
| **Sep-20** | 2 220 | 1 | **335** | 334 | 1 850 | 2 221 | **371** |
| **Oct-20** | 4 480 | 10 | **336** | 326 | 4 118 | 4 490 | **372** |
| **Nov-20** | 860 | 13 | **355** | 342 | 480 | 873 | **392** |
| **Dec-20** | 690 | 51 | **360** | 309 | 379 | 741 | **362** |
| **Jan-21** | 750 | 29 | **705** | 676 | 51 | 779 | **728** |
| **Feb-21** | 2 870 | 24 | **404** | 380 | 2 473 | 2 894 | **421** |
| **Mar-21** | 2 870 | 24 | **643** | 619 | 2 238 | 2 894 | **655** |
| **Apr-21** | 4 990 | 5 | **628** | 623 | 4 344 | 4 995 | **651** |
| **May-21** | 7 240 | 0 | **967** | 967 | 6 251 | 7 240 | **989** |
| **Jun-21** | 6 160 | 0 | **586** | 586 | 5 557 | 6 160 | **603** |

The inflows and outflows can be compared by using Equation 24 to calculate the variance. The inflows and outflows are compared in Figure A-16.

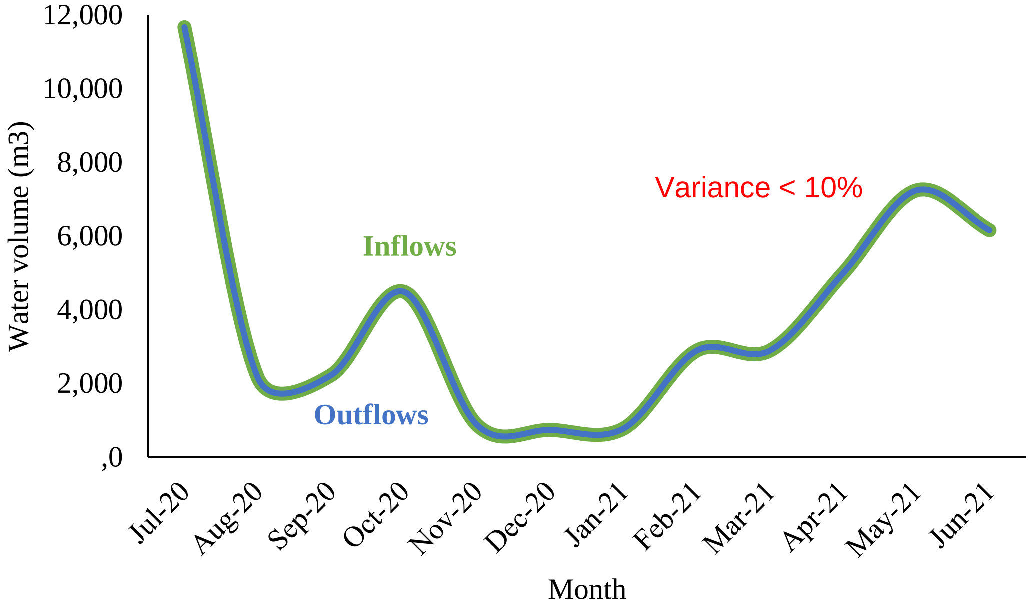


**Figure A-16: Inflows in comparison to outflows for the wastewater treatment plant in gold mining operation A.**

From Figure A-16 it is evident that the variance for the water balance remains 0 for 12 consecutive months. The water balance is therefore accurate.

## 7. Backfill plant

A certain portion of the tailings produced by the processing plant is sent to the backfill plant. The modular unit developed in Section 2.2 was used to identify the relevant inflows and outflows for the backfill plant. The water balance derived is shown in Figure A-17.

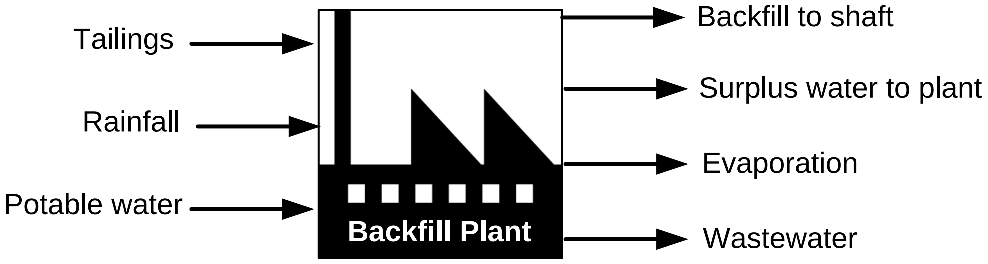


**Figure A-17: Water balance over the backfill plant in gold mining operation A.**

The main inflows into the backfill plant is the water in tailings from the processing plant. A small portion of potable water is used within the backfilling plant and rainfall received on open tanks are also considered an inflow. Water mainly exits the system through the backfill that is sent to Shaft 1 and the water that is sent back to the plant. A small portion of water is lost through evaporation on open tanks.

***Water in tailings***

The water in tailings received by the plant is the same as that pumped from the processing plant with the assumption that there are no leaks on the pipeline. The volumes of water is therefore the volumes reported in A certain portion of the tailings generated by the plant is sent to a backfilling plant. The volume of this slurry as well as its density are measured continuously by the plant. A solids density of 2.67 is reported. Monthly totals and average slurry densities were used in Equation 3 and Equation 4 to calculate the volume of water in the slurry. These figures and volumes are shown in Table 20

***Rainfall***

The rainfall received by the backfill plant is the same as that received by the processing plant shown in

Table A-3 since they are located in very close proximity to one another. The area of the open tanks in the backfilling plant was estimated as 132 $m^2$ by using Google Earth. The rainfall values obtained from calculation by using Equation 14 is shown in Table A-40.

**Table A-40: Rainfall volumes for the backfill plant in gold mining operation A.**

| | **Rainfall ($m^3$)** |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 0 |
| **Oct-20** | 5 |
| **Nov-20** | 7 |
| **Dec-20** | 27 |
| **Jan-21** | 15 |
| **Feb-21** | 12 |
| **Mar-21** | 12 |
| **Apr-21** | 2 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Potable water***

The potable water received by the backfill plant is measured. The monthly potable water volumes are shown in Table A-41.

**Table A-41: Potable water received by backfill plant in gold mining operation A.**

| | Potable water ($m^3$) |
|---|---|
| **Jul-20** | 1 435 |
| **Aug-20** | 2 373 |
| **Sep-20** | 2 362 |
| **Oct-20** | 2 261 |
| **Nov-20** | 2 487 |
| **Dec-20** | 2 303 |
| **Jan-21** | 1 377 |
| **Feb-21** | 2 210 |
| **Mar-21** | 3 380 |
| **Apr-21** | 3 020 |
| **May-21** | 3 247 |
| **Jun-21** | 3 656 |

***Backfill to shaft***

The backfill sent to the Shaft 1 is the same as that reported in Table 16, assuming there are no leaks on the pipeline.

***Surplus water to processing plant***

The surplus water sent to the processing plant is shown in Table 17.This assumes that there is no water lost during transportation between the backfill plant and the processing plant.

***Evaporation***

Evaporation was calculated using an open tank area of 132 $m^2$ and Equation 15. The volumes of water lost through evaporation are shown in Table A-42.

**Table A-42: Water lost through evaporation at the backfill plant in gold mining operation A.**

| | **Evaporation ($m^3$)** |
|---|---|
| **Jul-20** | 10 |
| **Aug-20** | 14 |
| **Sep-20** | 19 |
| **Oct-20** | 24 |
| **Nov-20** | 27 |
| **Dec-20** | 28 |
| **Jan-21** | 27 |
| **Feb-21** | 22 |
| **Mar-21** | 19 |
| **Apr-21** | 15 |
| **May-21** | 11 |
| **Jun-21** | 9 |

***Wastewater***

All potable water received by the backfill plant is assumed to be used for domestic purposes since none of the processes in a backfill plant require potable water. The wastewater generated by the plant is therefore the same volume as the potable water received shown in Table A-41.

***Water balance***

Once all the inflows and outflows for the backfill plant have been quantified, the volumes could be consolidated into a water balance as shown in Table A-43.

**Table A-43: Water balance for the backfill plant in gold mining operation A.**

| | Inflows | | | | Outflows | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Water in tailings | Rainfall | Potable water | Total inflows | Backfill to Shaft 1 | Water to processing plant | Evaporation | Wastewater | Total outflows |
| **Jul-20** | 0 | 0 | 1 435 | **1 435** | 0 | 0 | 10 | 1 435 | **1 445** |
| **Aug-20** | 7 557 | 0 | 2 373 | **9 930** | 1 060 | 5 772 | 14 | 2 373 | **9 219** |
| **Sep-20** | 38 444 | 0 | 2 362 | **40 806** | 6 513 | 34 866 | 19 | 2 362 | **43 761** |
| **Oct-20** | 68 915 | 5 | 2 261 | **71 181** | 9 240 | 47 903 | 24 | 2 261 | **59 429** |
| **Nov-20** | 52 929 | 7 | 2 487 | **55 422** | 8 168 | 44 158 | 27 | 2 487 | **54 840** |
| **Dec-20** | 13 335 | 27 | 2 303 | **15 665** | 2 078 | 11 125 | 28 | 2 303 | **15 535** |
| **Jan-21** | 0 | 15 | 1 377 | **1 392** | 0 | 0 | 27 | 1 377 | **1 404** |
| **Feb-21** | 0 | 12 | 2 210 | **2 222** | 0 | 0 | 22 | 2 210 | **2 232** |
| **Mar-21** | 0 | 12 | 3 380 | **3 392** | 0 | 0 | 19 | 3 380 | **3 399** |
| **Apr-21** | 10 150 | 2 | 3 020 | **13 172** | 1 474 | 7 604 | 15 | 3 020 | **12 112** |
| **May-21** | 15 452 | 0 | 3 247 | **18 699** | 2 490 | 11 801 | 11 | 3 247 | **17 549** |
| **Jun-21** | 11 413 | 0 | 3 656 | **15 069** | 1 727 | 8 732 | 9 | 3 656 | **14 125** |

Equation 24 can be used to calculate the variance of the water balance. Figure A-18 shows the inflows compared to the outflows for the water balance of the backfill plant.

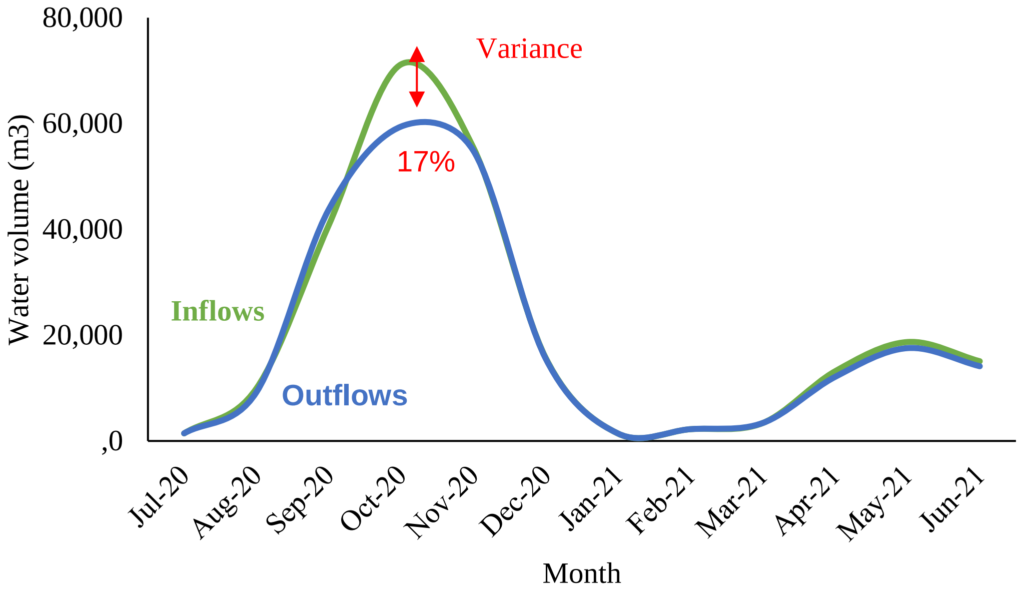


**Figure A-18: Inflows in comparison to outflows for the backfill plant in gold mining operation A.**

Figure A-18 indicates that the variance for the backfill plant exceeded the 10% limit in the month of October. For all the other months the variance is below 10%. A sensitivity analysis was done to determine which of the meters might have to be calibrated.

***Sensitivity analysis***

A sensitivity analysis was done to determine whether any additional metering is required and whether any of the existing meter should be calibrated. All the variables of the water balance were increased and decreased by 10%. The effect of this change in the variance of the water balance was observed. Figure A-19 shows the 12-month average results for the sensitivity analysis.

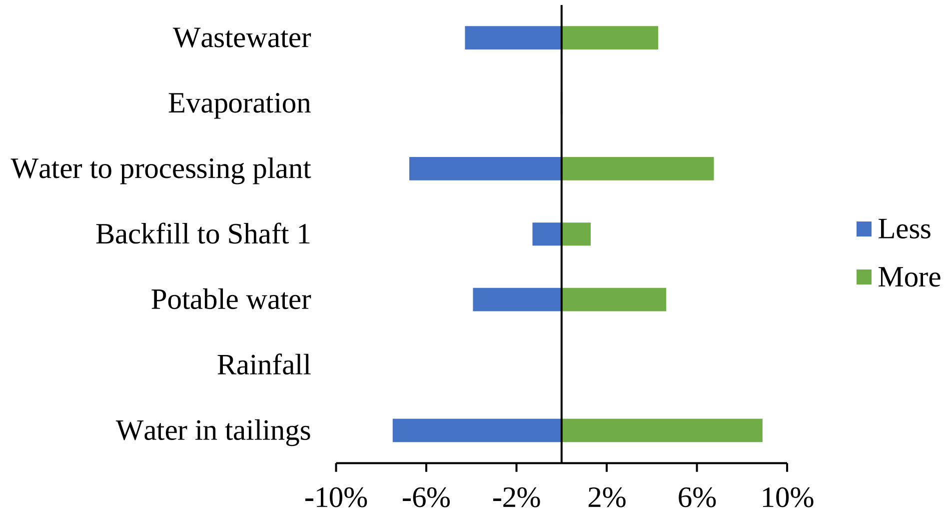


**Figure A-19: Sensitivity analysis for the backfill plant in gold mining operation A.**

From Figure A-19 it is evident that the variance of the water balance shows the highest sensitivity to wastewater, water to the processing plant, and water in tailings. Although a change in these variables have the highest impact on the variance, none of these variables have an effect of more than 10% on the variance of the water balance. Therefore, no additional meters required and none of the existing meters need to be calibrated.

The steps outlined in Figure 21 and Figure 22 have all been reiterated and no obvious reason for the outlier variance of 17% as shown in Figure A-18 has been found. The variance for the month of October is therefore expected to be due to a metering error or an unexpected occurrence such as a burst pipeline. Since all the other months have a variance of well below 10%, the water balance is seen as accurate.

## 8. Water bodies

*RWD 2*

The modular unit developed in Section 2.2 was used to identify all the inflows and outflow for RWD 2. The level of the dam is not monitored and is therefore assumed to be unchanged. The resulting water balance is shown in Figure A-20.

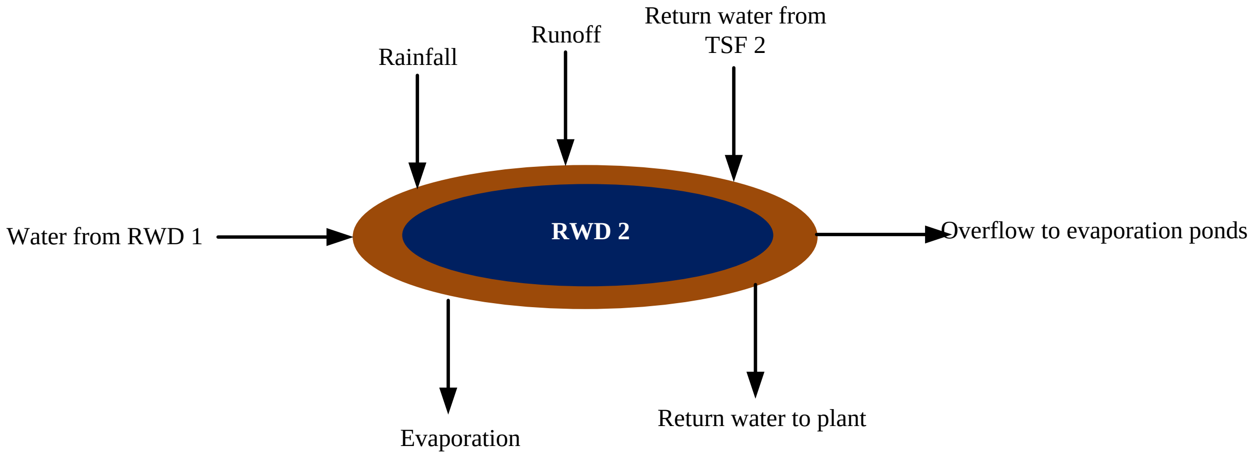


**Figure A-20: Water balance for RWD 2 in gold mining operation A.**

RWD 2 receives water from RWD 1 as well as return water from TSF 2. The return water is then pumped to the plant as needed. RWD also received water from rainfall as well as rainfall runoff from its catchment area. A certain volume of water is lost through evaporation from the dam surface. RWD overflows into adjacent evaporation ponds. RWD 2 is lined, therefore no water is lost through seepage.

***Rainfall***

The rainfall received by RWD 2 is the same as that receive by the processing plant that is reported in

Table A-3. A surface area for RWD 2 of 32 000 $m^2$ is reported by the plant. With all the known information, Equation 14 could be used to calculate the direct rainfall received by RWD 2. These volumes are shown in Table A-44.

**Table A-44: Rainfall received by RWD 2 in gold mining operation A.**

| | Rainfall ($m^3$) |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 96 |
| **Oct-20** | 1 280 |
| **Nov-20** | 1 632 |
| **Dec-20** | 6 560 |
| **Jan-21** | 3 648 |
| **Feb-21** | 3 008 |
| **Mar-21** | 3 008 |
| **Apr-21** | 576 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Runoff***

Runoff is directly related to the rainfall received in the area. A catchment area of 27 770 for RWD 2 is reported by the plant. Equation 21 was used to estimate the runoff volumes received by RWD. These volumes are shown in Table A-45.

**Table A-45: Runoff received by RWD 2 in gold mining operation A.**

| | Runoff ($m^3$) |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 42 |
| **Oct-20** | 555 |
| **Nov-20** | 708 |
| **Dec-20** | 2 846 |
| **Jan-21** | 1 583 |
| **Feb-21** | 1 305 |
| **Mar-21** | 1 305 |
| **Apr-21** | 250 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Return water from TSF 2***

The return water from TSF 2 is the same as that reported by the TSF with the assumption that no water is lost in the transportation process. These volumes are shown in Table A-29.

***Evaporation***

Evaporation occurs from the surface of the RWD. Equation 15 and the evaporation rates shown in Table 3 was used to calculate the evaporation shown in Table A-46.

**Table A-46: Evaporation from RWD 2 in gold mining operation A.**

| | Evaporation ($m^3$) |
|---|---|
| **Jul-20** | 2 508 |
| **Aug-20** | 3 428 |
| **Sep-20** | 4 694 |
| **Oct-20** | 5 876 |
| **Nov-20** | 6 456 |
| **Dec-20** | 6 805 |
| **Jan-21** | 6 600 |
| **Feb-21** | 5 215 |
| **Mar-21** | 4 659 |
| **Apr-21** | 3 524 |
| **May-21** | 2 765 |
| **Jun-21** | 2 209 |

***Return water to plant***

The water pumped back to the processing plant is measured by the processing plant. Assuming there are no leaks on the pipeline, the water pumped from RWD 2 is the same as that reported by the plant shown in Table 17.

***Water from RWD 1***

The water pumped from RWD 1 is not measured. The water from RWD can be estimated by balancing the water balance over RWD 2 for the months that RWD 2 experiences a negative water balance (i.e., when RWD 2 requires a water inflow to maintain the water balance). This assumes that water will only be pumped from RWD 1 to RWD 2 when RWD 2 requires additional water.

***Overflow to evaporation ponds***

The overflow to the evaporation ponds is also not measured. The overflow can be estimated by balancing the water balance over RWD 2 in the months when RWD 2 is water positive.

***Water balance***

All the inflows and outflows were consolidated into the water balance for RWD 2 is shown in Table A-47.

**Table A-47: Water balance for RWD 2 in gold mining operation A.**

| | Inflows | | | | | Outflows | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Rainfall** | **Runoff** | **Return water from TSF 2** | **Return water from RWD 1** | **Total inflows** | **Evaporation** | **Return water to plant** | **Overflow to evaporation ponds** | **Total outflows** |
| **Jul-20** | 0 | 0 | 25 264 | 0 | **25 264** | 2 508 | 2 508 | 20 248 | **25 264** |
| **Aug-20** | 0 | 0 | 29 607 | 8 688 | **38 295** | 3 428 | 34 866 | 0 | **38 295** |
| **Sep-20** | 96 | 42 | 10 601 | 41 860 | **52 598** | 4 694 | 47 903 | 0 | **52 598** |
| **Oct-20** | 1 280 | 555 | 36 210 | 11 989 | **50 035** | 5 876 | 44 158 | 0 | **50 035** |
| **Nov-20** | 1 632 | 708 | 29 591 | 0 | **31 931** | 6 456 | 11 125 | 14 350 | **31 931** |
| **Dec-20** | 6 560 | 2 846 | 111 924 | 0 | **121 330** | 6 805 | 0 | 114 526 | **121 330** |
| **Jan-21** | 3 648 | 1 583 | 64 127 | 0 | **69 357** | 6 600 | 0 | 62 757 | **69 357** |
| **Feb-21** | 3 008 | 1 305 | 66 466 | 0 | **70 779** | 5 215 | 0 | 65 565 | **70 779** |
| **Mar-21** | 3 008 | 1 305 | 71 901 | 0 | **76 214** | 4 659 | 7 604 | 63 952 | **76 214** |
| **Apr-21** | 576 | 250 | 43 100 | 0 | **43 926** | 3 524 | 11 801 | 28 601 | **43 926** |
| **May-21** | 0 | 0 | 22 908 | 0 | **22 908** | 2 765 | 8 732 | 11 411 | **22 908** |
| **Jun-21** | 0 | 0 | 33 554 | 0 | **33 554** | 2 209 | 0 | 31 345 | **33 554** |

The variance over the water balance was calculated using Equation 24. The inflows and outflows are compared in Figure A-21.

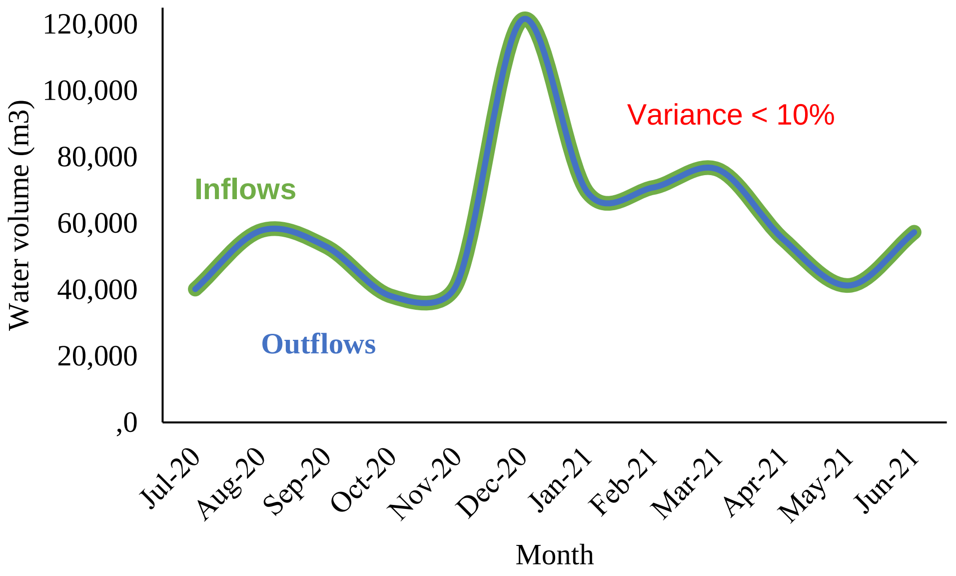


**Figure A-21: Inflows in comparison to outflows for RWD 2 in gold mining operation A.**

From Figure A-21 it is clear that the variance is 0 for all 12 months. This was expected since two variables were calculated by balancing the water balance.

***Sensitivity analysis***

A sensitivity analysis was done to determine which inflows and outflows have the highest impact on the variance of the water balance variance. The results obtained are shown in Figure A-22.

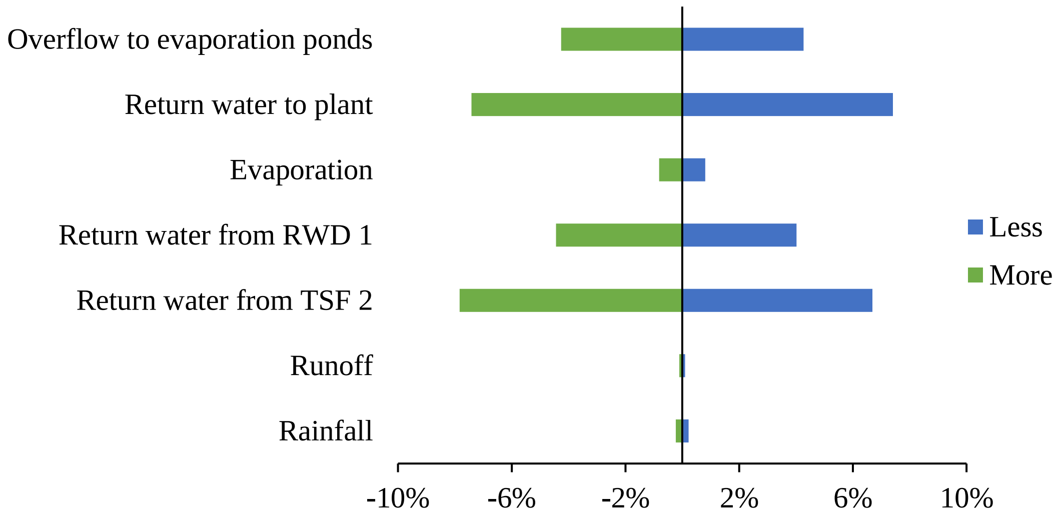


**Figure A-22: Sensitivity analysis for RWD 2 in gold mining operation A.**

The variance shows the highest sensitivity towards the return water sent back to the plant, and the return water from TSF 2. None of these variables have an effect of more than 10% on the water balance so none of the existing meters need to be calibrated.

The water balance over RWD 2 has two variables which are solved depending on whether the water balance before solving is positive or negative. Since the inflows and outflows are evaluated monthly, it is expected that this assumption will not deliver very accurate final volumes. It is therefore advised to have a flowmeter installed to measure the return water that is pumped from RWD 1 to RWD 2. This will leave only one variable (the overflow) to be solved which will result in a more accurate water balance.

*RWD 1*

RWD 1 is unlined. The modular unit developed in Section 2.2 was used to identify all the inflows and outflow for RWD 1. The level of the dam is not monitored and is therefore assumed to be unchanged. The resulting water balance is shown in Figure A-23.

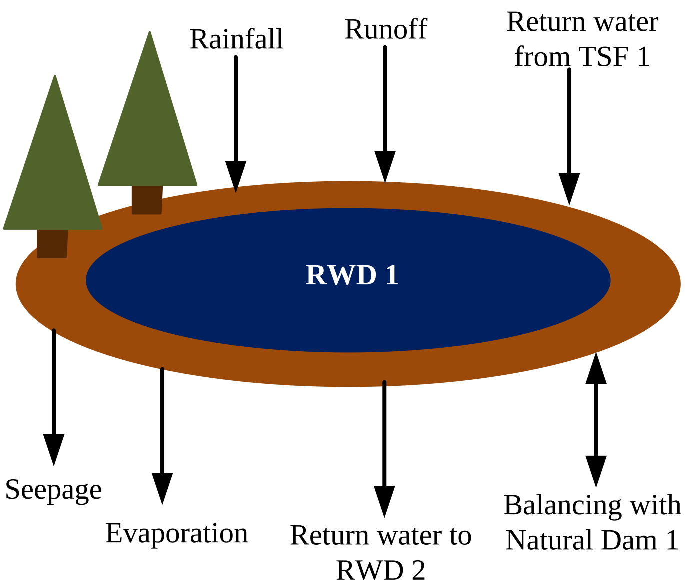


**Figure A-23: Water balance over RWD 1 in gold mining operation A.**

The return water from TSF 1 is sent to RWD 1. From here water is pumped to RWD 2 from where it is pumped back to the plant. RWD overflows into Pan 1, from where the water can be pumped back to RWD 1 if needed.

***Rainfall***

The surface area of RWD was received by the mining operation as 3 319 $m^2$. The rainfall received by RWD is assumed to be that received by the plant reported in

Table A-3. Equation 14 was used to calculate the rainfall volumes shown in Table A-48.

**Table A-48: Rainfall received by RWD 1 in gold mining operation A.**

| | **Rainfall ($m^3$)** |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 10 |
| **Oct-20** | 133 |
| **Nov-20** | 169 |
| **Dec-20** | 680 |
| **Jan-21** | 378 |
| **Feb-21** | 312 |
| **Mar-21** | 312 |
| **Apr-21** | 60 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Runoff***

A catchment area for RWD 1 of 148 251 $m^2$ was provided by the mining operation. Using Equation 21 the runoff into RWD 1 could be estimated as shown in Table A-49.

**Table A-49: Runoff into RWD 1 in gold mining operation A.**

| | Runoff ($m^3$) |
|---|---|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 222 |
| **Oct-20** | 2 965 |
| **Nov-20** | 3 780 |
| **Dec-20** | 15 196 |
| **Jan-21** | 8 450 |
| **Feb-21** | 6 968 |
| **Mar-21** | 6 968 |
| **Apr-21** | 1 334 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Return water from TSF 1***

The return water received by RWD 1 is the same as that reported for TSF 1 in Table A-28, assuming no losses occur between the TSF and the RWD.

***Water pumped to RWD 2***

The water pumped to RWD 2 is not measured but was calculated in the water balance for RWD 2. The volumes reported in Table A-47 was therefore used.

***Seepage***

Seepage was calculated using Equation 20. The calculated volumes of water lost through seepage is shown in Table A-50.

**Table A-50: Seepage from RWD 1 in gold mining operation A.**

| | **Seepage ($m^3$)** |
|---|---|
| **Jul-20** | 1 859 |
| **Aug-20** | 2 098 |
| **Sep-20** | 243 |
| **Oct-20** | 3 150 |
| **Nov-20** | 2 696 |
| **Dec-20** | 13 366 |
| **Jan-21** | 7 138 |
| **Feb-21** | 7 146 |
| **Mar-21** | 7 727 |
| **Apr-21** | 3 685 |
| **May-21** | 1 605 |
| **Jun-21** | 2 655 |

***Evaporation***

The evaporation from RWD was calculated by using Equation 15 and the evaporation rates shown in Table 3. The obtained volumes are shown in Table A-51.

**Table A-51: Evaporation from RWD 1 in gold mining operation A.**

| | **Evaporation ($m^3$)** |
|---|---|
| **Jul-20** | 260 |
| **Aug-20** | 356 |
| **Sep-20** | 487 |
| **Oct-20** | 609 |
| **Nov-20** | 670 |
| **Dec-20** | 706 |
| **Jan-21** | 685 |
| **Feb-21** | 541 |
| **Mar-21** | 483 |
| **Apr-21** | 366 |
| **May-21** | 287 |
| **Jun-21** | 229 |

***Balancing with pan 1***

The water overflowing to pan 1 and the water pumped back from pan 1 is not measured. These variables were calculated by balancing the water balance. In months where the water balance was positive, the surplus water was assumed to overflow to pan 1. In months where the water balance was negative, the additional water required was assumed to be pumped from the pan.

**Table A-52: Water balance over RWD 1 in gold mining operation A in m³.**

| | Inflows | | | | | Outflows | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Rainfall** | **Runoff** | **Return water from TSF 1** | **Water pumped from pan 1** | **Total inflows** | **Seepage** | **Evaporation** | **Return water to RWD 2** | **Overflow to pan 1** | **Total outflows** |
| **Jul-20** | 0 | 0 | 20 660 | 0 | **20 660** | 1 859 | 260 | 14 914 | 3 627 | **20 660** |
| **Aug-20** | 0 | 0 | 23 313 | 7 301 | **30 614** | 2 098 | 356 | 28 161 | 0 | **30 614** |
| **Sep-20** | 10 | 222 | 2 469 | 40 320 | **43 021** | 243 | 487 | 42 291 | 0 | **43 021** |
| **Oct-20** | 133 | 2 965 | 31 903 | 0 | **35 001** | 3 150 | 609 | 0 | 31 241 | **35 001** |
| **Nov-20** | 169 | 3 780 | 26 001 | 0 | **29 951** | 2 696 | 670 | 9 677 | 16 909 | **29 951** |
| **Dec-20** | 680 | 15 196 | 132 639 | 0 | **148 516** | 13 366 | 706 | 0 | 134 443 | **148 516** |
| **Jan-21** | 378 | 8 450 | 70 477 | 0 | **79 306** | 7 138 | 685 | 0 | 71 484 | **79 306** |
| **Feb-21** | 312 | 6 968 | 72 120 | 0 | **79 400** | 7 146 | 541 | 0 | 71 713 | **79 400** |
| **Mar-21** | 312 | 6 968 | 78 575 | 0 | **85 855** | 7 727 | 483 | 0 | 77 645 | **85 855** |
| **Apr-21** | 60 | 1 334 | 39 547 | 0 | **40 941** | 3 685 | 366 | 11 229 | 25 661 | **40 941** |
| **May-21** | 0 | 0 | 17 833 | 2 432 | **20 265** | 1 605 | 287 | 18 373 | 0 | **20 265** |
| **Jun-21** | 0 | 0 | 29 500 | 0 | **29 500** | 2 655 | 229 | 23 767 | 2 849 | **29 500** |

The variance of the water balance was calculated to be 0 by using Equation 24. This was to be expected since variables have been calculated by balancing the water balance. The inflows and outflows are compared in Figure A-24.

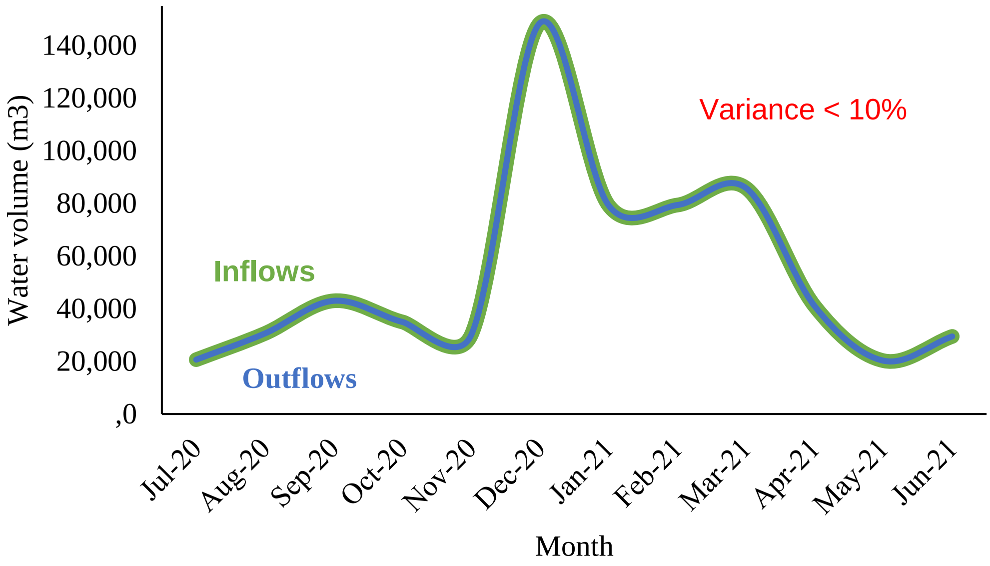


**Figure A-24: Inflows in comparison to outflows for RWD 1 in gold mining operation A.**

The variance for the water balance is 0 for 12 consecutive months, as can be seen in Figure A-24. This was expected since the water balance was solved to calculate variables which could not be quantified otherwise.

***Sensitivity analysis***

A sensitivity analysis was done to determine to which variables the variance of the water balance shows the highest sensitivity. The results for the analysis are shown in Figure A-25.

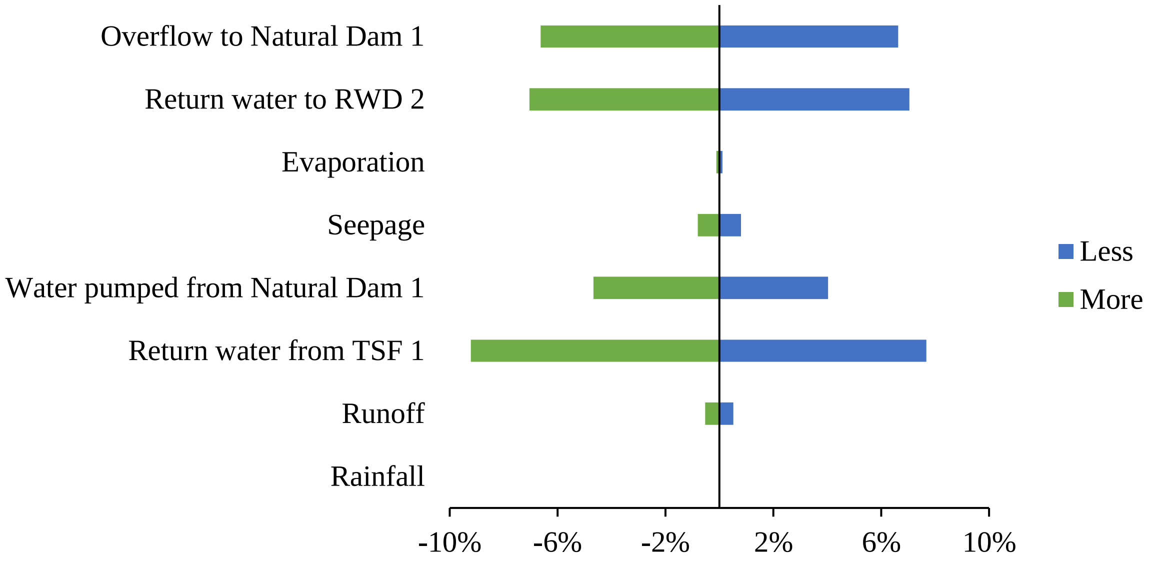


**Figure A-25: Sensitivity analysis for RWD 1 in gold mining operation A.**

The water balance variance shows the highest sensitivity to return water, overflow, and return water sent to RWD 2. Although none of the variables have an effect of more than 10% on the variance, it is advised to measure the volume of water that is pumped from pan 1 to RWD 1, as well as the volume of water that is pumped to RWD 2, as discussed previously. This will ensure that there is only one variable that will be solved by balancing the water balance and result in a more accurate water balance.

*Shaft 1 dam*

Shaft 1 dam is a concrete dam which acts as a holding dam for water abstracted from underground. The processing plant can pump water from the Shaft 1 dam as needed. The modular unit developed in Section 2.2 was used to develop the water balance over Shaft 1 dam. The level of the dam is not monitored and is therefore assumed to be unchanged. The resulting water balance is shown in Figure A-26.

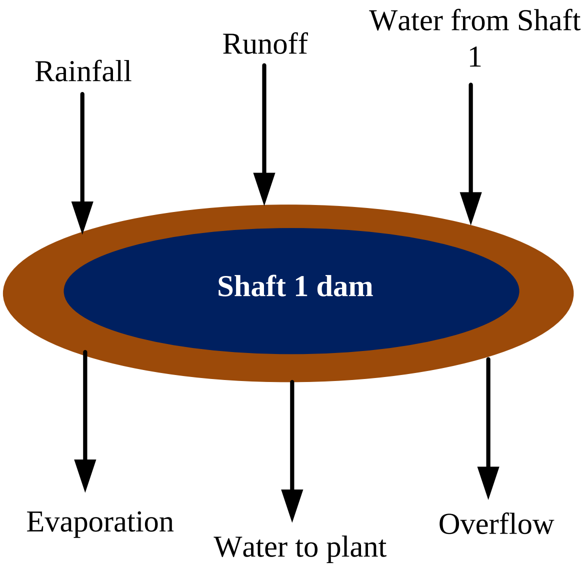


**Figure A-26: Water balance over Shaft 1 dam in gold mining operation A.**

Shaft 1 dam receives water mainly from Shaft 1, but also receives water via rainfall and runoff formed from the rainfall. The main outflow of Shaft 1 dam is water to the processing plant. A small volume of evaporation occurs from the dam surface. Shaft 1 dam overflows to a nearby natural dam which is not included within this mining operation.

***Rainfall***

The surface area of the dam is reported as 3 502 $m^2$ by the mining operation. Shaft 1 dam receives the same rainfall as that reported by the plant since they are in the same vicinity. Therefore, Equation 14 and the rainfall data from Table A-3 was used to calculate the rainfall volumes shown in Table A-53.

**Table A-53: Rainfall received by Shaft 1 dam in gold mining operation A.**

| | **Rainfall ($m^3$)** |
|---:|---:|
| **Jul-20** | 0 |
| **Aug-20** | 0 |
| **Sep-20** | 11 |
| **Oct-20** | 140 |
| **Nov-20** | 179 |
| **Dec-20** | 718 |
| **Jan-21** | 399 |
| **Feb-21** | 329 |
| **Mar-21** | 329 |
| **Apr-21** | 63 |
| **May-21** | 0 |
| **Jun-21** | 0 |

***Runoff***

Runoff is a result of rainfall on the catchment area of the dam. The catchment area for the dam is recorded as 2 821 $m^2$ by the plant. Equation 21 was used to calculate the runoff volumes received by Shaft 1 dam. These volumes are shown in Table A-54.

**Table A-54: Runoff received by Shaft 1 dam in gold mining operation A.**

| | Runoff ($m^3$) |
|---|---|
| Jul-20 | 0 |
| Aug-20 | 0 |
| Sep-20 | 4 |
| Oct-20 | 56 |
| Nov-20 | 72 |
| Dec-20 | 289 |
| Jan-21 | 161 |
| Feb-21 | 133 |
| Mar-21 | 133 |
| Apr-21 | 25 |
| May-21 | 0 |
| Jun-21 | 0 |

***Water from Shaft 1***

The volume of water from Shaft 1 that is sent to Shaft 1 dam is not measured. The total water abstracted from underground as well as the water from underground that is sent directly to the plant is measured. Therefore, the water abstracted from underground can be calculated as the difference between the total water abstracted and the water sent directly to the plant. The total water abstracted is shown in Table A-5.

while the water sent directly to the plant is shown in Table 17. The calculated water from Shaft 1 that is sent to Shaft 1 dam is shown in Table A-55.

**Table A-55: Water from Shaft 1 to Shaft 1 dam in gold mining operation A.**

| | **Water from Shaft 1 ($m^3$)** |
|---|---|
| **Jul-20** | 60 623 |
| **Aug-20** | 32 511 |
| **Sep-20** | 39 602 |
| **Oct-20** | 37 329 |
| **Nov-20** | 47 941 |
| **Dec-20** | 54 271 |
| **Jan-21** | 58 918 |
| **Feb-21** | 76 683 |
| **Mar-21** | 60 709 |
| **Apr-21** | 44 149 |
| **May-21** | 56 380 |
| **Jun-21** | 48 277 |

***Evaporation***

Evaporation occurs from the dam surface. Equation 15 together with the evaporation rates from Table 3 were used to calculate the evaporation for Shaft 1 dam. The volumes obtained are shown in Table A-56.

**Table A-56: Evaporation from Shaft 1 dam in gold mining operation A.**

| | Evaporation ($m^3$) |
|---|---|
| **Jul-20** | 274 |
| **Aug-20** | 375 |
| **Sep-20** | 514 |
| **Oct-20** | 643 |
| **Nov-20** | 707 |
| **Dec-20** | 745 |
| **Jan-21** | 722 |
| **Feb-21** | 571 |
| **Mar-21** | 510 |
| **Apr-21** | 386 |
| **May-21** | 303 |
| **Jun-21** | 242 |

***Water to processing plant***

The water that is sent to the processing plant is measured and reported by the plant. Assuming there are no leaks on the pipeline, the water pumped by Shaft 1 dam will be the same as that received by the plant. These volumes are shown in Table 17.

***Overflow***

The overflow of Shaft 1 dam is not measured. However, all the other inflows and outflows have been quantified. Therefore, the overflow can be calculated by balancing the water balance.

***Water balance***

The inflows and outflows were consolidated into the water balance shown in Table A-57.

**Table A-57: Water balance for Shaft 1 dam in gold mining operation A.**

| | Inflows | | | | Outflows | | | |
|---|---|---|---|---|---|---|---|---|
| | **Rainfall** | **Runoff** | **Water from shaft 1** | **Total inflows** | **Evaporation** | **Water to processing plant** | **Overflow** | **Total outflows** |
| **Jul-20** | 0 | 0 | 60 623 | **60 623** | 274 | 44 692 | 15 657 | **60 623** |
| **Aug-20** | 0 | 0 | 32 511 | **32 511** | 375 | 30 387 | 1 749 | **32 511** |
| **Sep-20** | 11 | 4 | 39 602 | **39 617** | 514 | 27 999 | 11 104 | **39 617** |
| **Oct-20** | 140 | 56 | 37 329 | **37 525** | 643 | 27 970 | 8 912 | **37 525** |
| **Nov-20** | 179 | 72 | 47 941 | **48 192** | 707 | 30 298 | 17 187 | **48 192** |
| **Dec-20** | 718 | 289 | 54 271 | **55 278** | 745 | 41 822 | 12 711 | **55 278** |
| **Jan-21** | 399 | 161 | 58 918 | **59 478** | 722 | 40 232 | 18 524 | **59 478** |
| **Feb-21** | 329 | 133 | 76 683 | **77 145** | 571 | 29 856 | 46 718 | **77 145** |
| **Mar-21** | 329 | 133 | 60 709 | **61 171** | 510 | 38 158 | 22 503 | **61 171** |
| **Apr-21** | 63 | 25 | 44 149 | **44 237** | 386 | 31 929 | 11 923 | **44 237** |
| **May-21** | 0 | 0 | 56 380 | **56 380** | 303 | 29 404 | 26 673 | **56 380** |
| **Jun-21** | 0 | 0 | 48 277 | **48 277** | 242 | 19 850 | 28 185 | **48 277** |

The total inflows and outflows for the water balance over Shaft 1 dam is compared in Figure A-27.

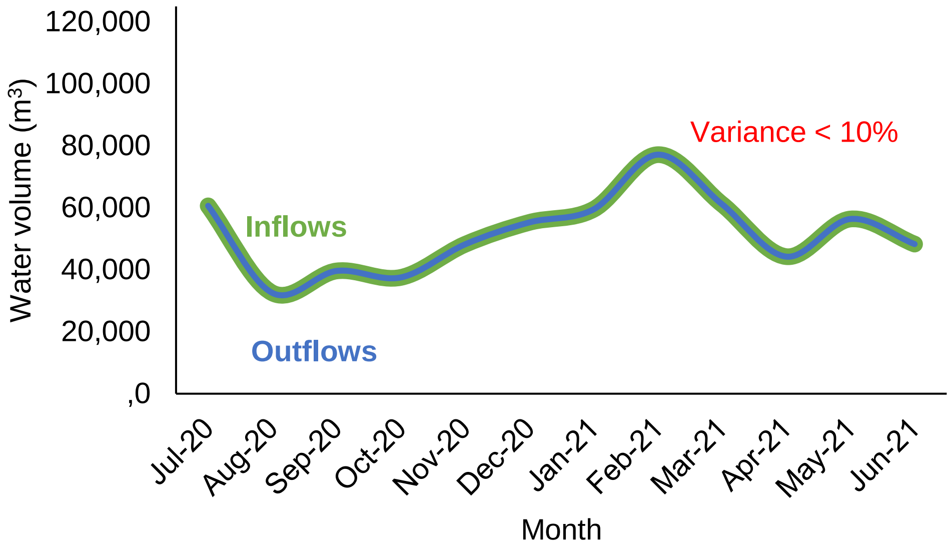


**Figure A-27: Inflows in comparison to outflows for Shaft 1 dam in gold mining operation A.**

As expected, the variance for the water balance over Shaft 1 dam is 0, as shown in Figure A-27. This is because the overflow from Shaft 1 dam was calculated by balancing the water balance.

### *Sensitivity analysis*

A sensitivity analysis was done to determine how sensitive the water balance variance is to a change in the respective inflows and outflows. The results are shown in Figure A-28.

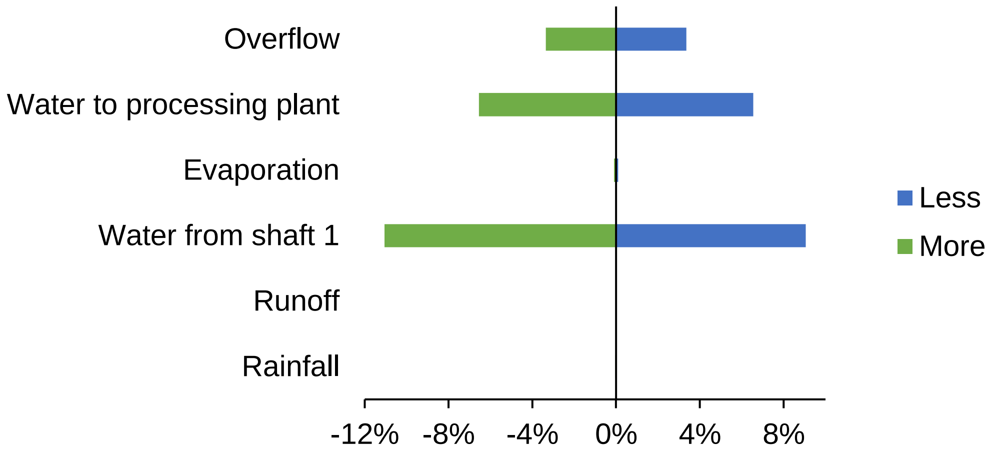


**Figure A-28: Sensitivity analysis for Shaft 1 dam in gold mining operation A.**

The variance of the water balance is very sensitive to the water from shaft 1. An increase of 10% in the volume of water received from shaft 1 results in a variance of 12% in the water balance. It is therefore advised to have the meter measuring this flow calibrated regularly to ensure the water balance remains accurate.