A Quantitative Approach in Mine Water Balances and Strategic Management

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Declaration

I, Joseph Ferdinand Willem Mostert, declare that the dissertation, "***A quantitative approach in mine water balances and strategic management***", hereby submitted by me for the Magister Scientiae in Geohydrology degree at the University of the Free State, is my own independent work and has not previously been submitted by me at another university or faculty. I furthermore cede copyright of the dissertation in favour of the University of the Free State.

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"No sustainable development of a scarce natural resource, and thus of life, is possible without understanding the resource and managing it wisely according to this growing understanding."

Ronnie Kasrils, Former Minister of Water Affairs (South Africa), 2003.

Notations and terms

Basic human need: Basic water supply means the prescribed minimum standard of water supply services necessary for the reliable supply of a sufficient quantity and quality of water to households, including informal households, to support life and personal hygiene.

Base flow: Defined by surface water specialists as the low flow component in a river. Can also be referred to as the groundwater which flow beneath a stream or river, in the base sediments and parallel to the flow of the stream or river.

Catchment: In relation to a watercourse or watercourses or part of a watercourse, means the area from which any rainfall will drain into the watercourses or part of a watercourse, through surface flow to a common point of common points.

Clean water: Water that has not been affected by pollution.

Closed water circuit: Water circuits which are not exposed to the natural environment e.g. pipes and covered tanks.

Cone of depression is a depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a borehole from which water is being withdrawn. It defines the area of influence of a borehole.

A confined aquifer: A formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.

Dirty water: Water that contains waste also referred to as contact or worked water. The Department of Water Affairs (DWA) of South Africa classifies any water which has been in contact with a disturbed area as dirty water.

Drawdown is the distance between the static water level and the surface of the cone of depression.

Effective porosity: The percentage of the bulk volume of a rock or soil that is occupied by interstices that are connected.

Efficient water use: Water used for a specific purpose over and above the accepted and available best practises and benchmarks or water used for a purpose where benefit is derived from it.

Evaporation: Evaporation occurs when the water liquid phase is changed into the vapour phase due to the addition of energy.

Facility: In relation of an activity, includes any installation and appurtenant works for the storage, stockpiling, disposal, handling or processing of any substance.

A **fault** is a fracture or a zone of fractures along which there has been displacement.

Fissure water: A common mining term in hard rock mines that refers generically to groundwater that enters the mine.

Groundwater table is the surface between the zone of saturation and the zone of aeration; the surface of an unconfined aquifer.

Hydraulic conductivity (K): The volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured perpendicular to the area [L/T]. Hydraulic conductivity is a function of the permeability and the fluid’s density and viscosity.

Hydraulic gradient: The rate of change in the total head per unit distance of flow in a given direction.

Infiltration: The movement of water through a solid medium like soil, evaporation and runoff.

Input: Volume of water which is received by the operational facility for intended use by such a facility.

Interstitial water: Subsurface water in an interstice, also referred to as pore water. The interstice is an opening or space in the soil or mine tails that is not occupied by solid matter and entrap water.

Management unit: A management unit is defined as an area or process that forms a logical individual subsystem that can be isolated and have defined boundaries for water and salt balances.

Open water circuit: Water circuits that are open to the natural environment, e.g. rivers, dams and channels.

Ore surface moisture: Layer of water on the surface of solid material.

Output: Volume of water which is removed from the operational facility after it has been through a task, treated or stored for use.

Piezometric head (ϕ) is the sum of the elevation and pressure head. An unconfined aquifer has a water table and a confined aquifer has a piezometric surface, which represents a pressure head. The piezometric head is also referred to as the hydraulic head.

Porosity: Porosity is the ratio of the volume of void space to the total volume of the rock or earth material.

Potable water: Clean water that is suitable for human consumption and may be used within a mine process.

Precipitation: The discharge of water (as rain, snow or hail) from the atmosphere upon the earth's surface.

Process water: Water that is used within the operational process.

Pumping tests are conducted to determine aquifer or borehole characteristics. Also referred to as aquifer tests.

Raw water: Raw water refers to water that is brought to or captured on site and has not been previously used for any purpose or tasks within the site.

Recharge: The addition of water to the saturated zone, either by the downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers.

Recharge area: The area where water predominantly flows downward through the unsaturated zone to replenish an aquifer.

Recycling: Recycling is when water is treated to improve its quality before it is reused.

Resource: Resource is a substance or item available for use. A natural resource is a resource that man can use but not manufacture or create.

Runoff: Surface runoff is defined as the precipitation that finds its way into the stream channel without infiltration into the soil.

Reuse: Reuse is when water from one user is passed directly to another user without transformation.

Seepage: The act or process involving the slow movement of water or another fluid through a porous material such as soil, slimes or discard.

Specific yield is defined as the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table.

Static water level is the level of water in a borehole that is not being affected by withdrawal of groundwater.

Storativity is the two-dimensional form of the specific storage and is defined as the specific storage multiplied by the saturated aquifer thickness.

Total Dissolved Solids (TDS): A concentration term used to express the total amount of dissolved solids in a solution (normally expressed in mg/ℓ).

Transmissivity (T): The two-dimensional form of hydraulic conductivity and is defined as the hydraulic conductivity multiplied by the saturated thickness.

Treated water: Water that has been treated on-site to provide water of a suitable quality for a particular purpose.

Unconfined, water table or phreatic aquifers: Different terms used for the same aquifer type, which is bounded from below by an impermeable layer. The upper boundary is the water table, which is in contact with the atmosphere so that the system is open.

Vadose zone is the zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water and capillary water. This zone is limited above by the land surface and below by the surface of the zone of saturation, which is the water table.

Water consumption: Water consumption refers to raw water that has been made unavailable for reuse in the same basin, such as through conversion to steam, losses to evaporation and seepage.

Water make-up: Mine make-up water is the component of water which is consumed or lost in the mining process.

Water stores: Facilities on site that hold and capture water.

Water table is the surface between the vadose zone and the groundwater, that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

Worked water: Water that has been through a task.

List of Abbreviations

Abbreviation	Description
a	Annum
AR	Artificial Recharge
BPGs	Best Practise Guidelines
CMB	Chloride Mass Balance
DC	Direct Current
DTH	Down the Hole
DTM	Digital Terrain Model
DWA	Department of Water Affairs of South Africa
DWAF	Former South African Department of Water Affairs and Forestry.
EM	Electromagnetic
EOH	End of Hole
EPA	US Environmental Protection Agency
FOA	Food and Agriculture Organisation
GN	Government Notice
GYMR	Groundwater Yield Model for the Reserve
h	Hours
HDTT	High Density Thickened Tailings
ICMM	International Council on Mining and Metals
IGS	Institute for Groundwater Studies
ITCZ	Inter-Tropical Convergence Zone
IWULA	Integrated Water Use Licence Application
K	Hydraulic Conductivity
kg/d	Kilograms per day
km	Kilometre
Ktpm	Kilo tonnes per month
ℓ	Litre
ℓ/s	Litre per second
LoM	Life of Mine
m	Metre
m^3	Cubic metres = 1000 litres
m^3/d	Cubic meters per day
m/d	Meter per day
MAE	Mean Annual Evaporation
MAMSL	Meter Above Mean Sea Level
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MBGL	Meter Below Ground Level

Abbreviation	Description
MCA	Minerals Council of Australia
meq/l	Mill-equivalents of solute per litre
mg/l	Milligrams per litre
min	Minutes
mm	Millimetre
mm/a	Millimetre per annum
mS/m	Milli-Siemens per meter
NWA	National Water Act of South Africa (Act 36 of 1998)
PGM	Platinum Group Metals
PWD	Process Water Dam
RDM	Resource Directed Measures
RLS	Rustenburg Layered Suite
RoM	Run of Mine
RWD	Return Water Dam
SANAS	South African National Accreditation System
SANS	South African National Standards
SAT	Soil Aquifer Treatment
SMC	Sequential Monte Carlo
SMI	Sustainable Minerals Institute
STP	Sewage Treatment Plant
SWD	Storm Water Dam
SWL	Static Water Level
T	Transmissivity
TDS	Total Dissolved Solids
tpd	Tonnes per day
TSF	Tailings Storage Facility
UFS	University of the Free State
UG	Underground
WAF	Water Accounting Framework
WGS	World Geodetic System
WHO	World Health Organisation
WL	Water Level
WMA	Water Management Agency/Area
WRC	Water Research Commission
WRD	Waste Rock Dump
WRIMS	Water Resources Information Managing System
Wt%	Percentage by weight
%m	Percentage by mass

Abbreviation	Description
~	Approximately

Table of contents

List of Figures

List of Tables

List of Equations

"All models are wrong, but some are useful."

George EP Box.

Chapter 1

1 INTRODUCTION

Due to significant climate changes, an increasing population density and poor water management, securing of water has become a global challenge (Food and Agriculture Organisation of the United Nations (FOA), 2013). While the World Health Organisation (WHO, 2013) reports that water scarcity affects one in every three people worldwide, the majority of surface water resources in sub-Saharan countries, including South Africa, will be over allocated by 2025 (Arnell and Liu, 2001). As water scarcity intensifies, developing efforts in many countries are inhibited by competition for water supply amongst different sectors, including the agricultural and mining sectors. Of principal concern is our failure to recognise and accept the fact that water is not an infinite resource and in recent years, a debate surrounding the sustainability of water use has been the focus of increasing international concern. Water scarcity will continue to be one of the greatest challenges facing mine water management as regulations by environmental authorities, along with past polluting practices, are forcing mining operations to improve and prioritise their water consumption (Postel, 2000; Gunson *et al.*, 2010). There is no simple recipe for mine water management and Anthony Hodge, president of ICMM (International Council on Mining &Metals), states that the mining sector can expect to be increasingly required to demonstrate leadership through water use management (ICMM, 2012). In a study conducted by the Sustainable Minerals Institute (SMI), Cote and Moran (2008) refer to a water balance as a tool aiding in strategic mine water management and sustainable use, as part of the solution.

1.1 Background and validation

The Department of Water Affairs (DWA) of South Africa (1996) considers a water balance to be one of the most important and fundamental water management tools available for mining operations. AGES (2013) states the importance of using a water balance as guidance for planning purposes. An accurate water balance can be described as a powerful tool to optimise water need, assisting in minimising the requirement for make-up water by maximising recycling (Idrysy and Connelly, 2012). American statistician and author, William Edwards Deming (1900-1993), once said: “You cannot manage what you cannot measure”, emphasising the significance of quantification within a system before implementation of management and mitigation measures. This view is supported by Howard (2013) with the argument that it is impossible to manage water resources effectively if it is not properly measured and monitored. Accordingly, water management on mining operations begins with a basic understanding of where water is sourced from and where it is utilised. In his attempt to simplify mine water balances, McPhail (2005) considers two essential elements of an accurate water balance as a basic accounting system; and the use of efficiency techniques in the interest of reducing risk and costs.

A mine water balance should be based on a systems model approach, as defined by Checkland (1981). This shifts the major focus to the system as a whole, with an appropriate relationship between the required level of complexity in the model structure, available data as well as the purpose of the model (Cote *et al.*, 2010). In the United States Environmental Protection Agency's (EPA) guidelines for hard-rock mining (EPA, 2003), van Zyl *et al.* (1998) highlights that a mine water balance entails two water systems. These water systems can be categorised as water consumed in the process system as well as water forming part of the natural system, encompassing the intrinsic hydrological cycle. An investigation conducted by Pulles *et al.* (2001) revealed that the overall state of mine water balances is poor with water from the natural system often disregarded and underestimated due to uncertainties and indefinable flow paths. This can however significantly impact on mine water usage (Pulles *et al.*, 2001; EPA, 2003) and decision making and management options should consequently be based on the evaluation of the system as a whole. Thus inclusion of the natural system as a component of the mine water balance is imperative for accurate quantification and prediction of site conditions.

The natural system includes a surface water environmental circuit as well as a groundwater environmental circuit. Historically, surface and groundwater resources were managed separately, but more than ever before, interaction between these two systems are required to facilitate effective resource management and decision-making (Parsons, 2004). Cogho (2012) supports this statement by pointing out that components of hydrology as well as hydrogeology must not be viewed in isolation from each other and the mine water balance. Mining activities potentially have a major effect on the hydrological regime and mining-induced fracturing increases the hydraulic conductivity and porosity of strata and host rock, enhancing hydraulic connections between aquifer zones (Ouyang and Elsworth, 1993). Vermeulen and Usher (2006) found that extracted rock and ore are replaced by spoils which increase the hydraulic conductivity and recharge dramatically. Water sourced from mine dewatering is an important driver of a mine water balance as fissure water ingress into mine workings can serve as an economical alternative to sourcing external make-up water (AGES, 2013; Idrysy and Connelly, 2012). Singh and Atkins (1984) state the significance of predicting water inflows into mine workings and the integration thereof in mine water control systems.

Poor water management poses an operational risk to mining operations as it can cause breaches of the regulatory framework which in turn, can lead to financial implications and calls for innovative thinking (Cote *et al.*, 2009). Accordingly, the mining sector has developed novel ways to respond to water issues in differing circumstances and has illustrated the ability to turn risk into opportunity (Kenrick, 2011). Now, more than ever, special measures are needed to identify options for life-of-mine strategies and initiatives for water conservation and management (Kenrick, 2011).

This dissertation seeks to investigate the quantification of mine water balances for base-metal operations, with influences from the natural system incorporated, to be implemented as a tool, aiding in effective mine water management. A literature review provides an overview of the main drivers of mine water balances, development of water loss assumptions, quantification and formulation of water balance inputs and outputs and integration of groundwater as part of the natural system. A comparison between a conventional mine water balance and an adapted mine water balance, incorporating all aspects of natural system water, is discussed. To conclude, novel water use efficiency techniques are investigated as part of a strategic mine water management approach. A case study of a typical base-metal mining operation in South Africa is conducted with the output aimed at developing an analytical mine water balance framework for the mining industry, to quantify operational water requirements and to demonstrate the concepts under investigation.

1.2 Terms of reference

1.2.1 Objectives

The objectives of this dissertation include:

1. Provide an overview of fundamental water balance principles;
2. Evaluate mine water balance components based on a systems model approach and investigate different water systems involved;
3. Assess the significance of groundwater and surface water interaction within a mine water balance, and incorporate the influence and quantification of the natural system into the model;
4. Investigate novel water use efficiency techniques as part of a strategic mine water management approach;

5. Investigate the current status quo of mine water balances within the industry and compare current methodologies against best practice standards as set out in literature; and
6. Develop an adapted analytical mine water balance to aid in mine water management and demonstrate concepts under investigation by applying principles to a case study.

1.2.2 Scope of work

The scope of work for this study is summarised as follows:

1. Literature review on published works, qualified reports and academic research conducted on mine water balances and elements influencing such, with an overview of novel water use efficiency techniques, including the current status of mine water balances;
2. State a mine water balance methodology to aid in the compilation of an integrated mine water balance and representation of acquired data;
3. Data analyses and interpretation;
4. Case study and applications; and
5. Conclusions and outlook.

1.2.3 Dissertation layout

The conceptual dissertation layout is:

1. Chapter 1: Introduction;
    a. Background and terms of reference stating study objectives and scope of work;
2. Chapter 2: Literature review;
    a. Overview of fundamental water balance principles, mine water balance; components and assumptions;
    b. Incorporating natural system water as a component into the mine water balance by investigation of the environmental surface water circuits as well as environmental groundwater circuits and quantification thereof;
    c. Strategic water management focussing on novel water use efficiency techniques;
    d. Status quo of existing mine water balance methodologies, and
    e. Summary of statutory and regulatory requirements.
3. Chapter 3: Data
    a. Methodology;
    b. Data collation and collection;

4. Chapter 4: Data analyses and interpretation and application of data by a case study demonstration;
5. Chapter 5: Conclusions;
6. References;
7. Appendices.

Chapter 2

2 LITERATURE REVIEW: A QUANTITATIVE APPROACH IN MINE WATER BALANCES AND STRATEGIC MANAGEMENT

2.1 General concepts

Water science is based on quantitative methods to evaluate and understand water resources (Basson *et al.,* 1994) and the main objective of determining water quantities[1] and qualities[2] is to serve as planning or design purposes (Vivier, 2011). To successfully manage water from mine sites, a precise understanding of water systems is required and an accurate water balance, incorporating both surface and groundwater influences, is imperative for effective mine water management (EPA, 2003; Parsons 2004).

A model represents our thinking about reality rather than reality itself and can be defined as a theoretical construct that begins with a concept which can be portrayed diagrammatically in the form of a flow diagram (Nordstrom, 2012). The National Research Council (2007) defines a model as a simplification of reality while Sterman (2002) reports that the purpose of modelling is not to model a physical problem with zero defects, but rather to perform simulations for the purposes of decision-making and management. A mine water balance can be viewed as a model which can be used to elevate the level of information extracted from data and can be implemented as a tool aiding in decision making (Vivier, 2011) (Figure 2-1).

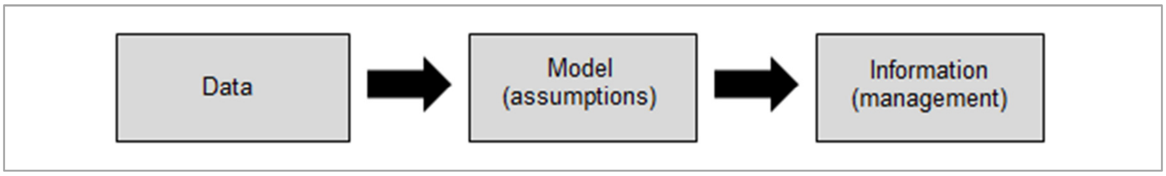

Figure 2-1 Modelling data for output information (After Vivier, 2011).

2.1.1 Principles of mass conservation

A water balance is based on the principles of mass conservation in which the inflows to a system are balanced by the sum of outflows and a change in storage. This principle was first outlined by Mikhail Lomonosov in 1748 (Shiltsev, 2012) and later reiterated by Kampf and Burges (2009), stipulating that the mass of water that enters a system must equal the mass of water that exists the same system and a change in storage, under natural conditions. Key

[1] Water quantity refers to the sustainable volume of water required for any given operation and can be represented by the mine water balance and flow volumes.
[2] Water quality refers to the chemical, physical and biological characteristics of water and can be represented by the mine mass balance.

to the analyses of a water accounting system is that water moving through an operating unit does not disappear, but rather continues to exist in one form or another (Moran, 2006). Pulles and van Rensburg (2006b) define an operating unit as a section, area, or process which can be isolated from any logical individual sub-system. A general water balance equation can be applied to any unit within specified boundaries and can be given by the following equation:

$$\mathbf{Total}_{\mathbf{Water\ input}} = \mathbf{Total}_{\mathbf{Water\ output}} + \mathbf{\Delta Storage}$$

Equation 2-1

Where:

Losses represent any water that is taken out of the system and is accounted for by a change in storage.

2.1.2 Systems model approach

There is a requirement for a management tool which emphasise the system[3] as a whole and a simple systems model can be implemented as an appropriate instrument to improve planning and management (Cote *et al.,* 2010). A suitable balance should exist between the required level of complexity in a model and the purpose of the model, therefore the number of parameters should be minimised as to simplify the calibration process (Cote *et al.*, 2010). Systems modelling makes use of analytical or mathematical techniques to quantify environmental problems (Vivier, 2011) and can be defined as the understanding of how components in complex systems influence each other as a whole (Sterman, 2000). Nooteboom (2007) mentions that a systems approach is increasingly used for decision making in terms of sustainable development.

The development of a mine water balance can be based on two approaches namely, a traditional engineering approach and an adapted environmental approach. The engineering approach to describing mine water systems is to represent all catchments, storages, reticulation and pumps, along with the operational rules that dictate transport rates in the distribution system, and usually only focuses on metallurgical processes (McIntosh *et al.*, 2003). This structure is not well adapted to the requirements of a systems approach and tends to concentrate on water stocks explicitly; therefore not representing water tasks as such (Cote *et al.,* 2010). The environmental approach covers the components outside the

[3] Checkland (1981) describe the root definition of a system as a set of elements, connected together, which form a whole; this showing properties which are properties of the whole rather than of its components parts.

mine e.g. tailings storage facility, storm water and the resource from where the water is obtained. It differs from an engineering approach in that it focuses on the make-up water[4] and environmental requirements, rather than total flows required for plant and mining processes (AGES, 2012). This reductionist influence created by environmental investigations, can however limit the ability to model the interconnected nature of reality (Nordstrom, 2012).

Flow volumes in the engineering approach are typically reported in litres/h whereas the environmental approach reports volumes in m^3/d. The purpose of an environmental water balance is to integrate all flow components of mine water management and planning, with emphasis on regulatory requirements. On the contrary, engineering water balances, as described by McIntosh *et al.* (2003), rather focus on mine water inventories and detailed planning. Accordingly, in order to cater for strategic mine water management, a new model must be developed with emphasis on a system approach, taking in consideration the main interactions, feedbacks and functional relationships between the various parts of the entire system, without excessive detail.

2.1.3 Data uncertainty

Water management on mining operations is intrinsically associated with uncertain parameters of the larger hydrological cycle and includes parameters such as precipitation, runoff, evaporation, recharge, infiltration, seepage, entrapped water and fissure water ingress into mine workings (Ogola *et al.,* 2011). Constructed flow paths are usually easily definable, while natural and uncertain flow paths, as listed above, are more difficult to define (Pulles and van Rensburg, 2006b). It is important to ascertain areas and operating units within the circuit representing the highest variability and uncertainty (McPhail, 2005). The existence of uncertainties is confirmed by Kuczera and Mroczkowski (1998), which states that it should be managed in an on-going basis and it is important to implement techniques to incorporate uncertainty into hydrological models. Model uncertainties can arise not only from input data, but also from uncertainties in the model configuration (Kampf and Burges, 2009). Celeux *et al.* (2000) note that simulating physical processes by using models to represent the underlying physics holds challenges when defining the appropriate parameter values from limited data. Moran *(*2006) however iterates that this occurrence should not discourage a water balance and account framework for reasonable estimations and assumptions. In the absence of perfect information, assumptions have to be made and can be useful if implemented in the correct context (Vivier, 2011). In reality, assumptions are

[4] Mine make-up water is the component of water which is consumed or lost in the process (AGES, 2013).

based on data collection and entail an interpretation process (Vivier, 2011). Marinelli and Niccoli (1999) state the significance of carefully comparing assumptions to known or inferred site conditions, maintaining that it is important that assumptions be made relevant to each specific study site. Due to a lack of scientific information conservative assumptions should be used, following a precautionary and conservative principle catering for worst case scenarios (Vivier, 2011).

The selection of appropriate statistical analysis techniques and the accuracy of predictions are linked to data representativeness and should be carefully considered (Ward *et al.*, 1990). Environmental and water management requires statistical methods which are considered a more appropriate approach, as most natural environmental processes are described by variability and probability (Basson *et al.*,1994). Statistical procedures best corresponding to population characteristics should be identified and used for analysis and incorporation of variability and uncertainty into the water balance model. This can be done making use of a probability distribution[5] approach (also known as statistical or stochastic methodologies) where there are gradations of probability between zero and one (Palisade Corporation, 2010; EPA, 2003). Vivier (2011) also suggest following a probabilistic approach and state that due to the high degree of variability related to natural events, probabilistic methods are used to evaluate data.

Common parameter assumptions, which do not apply for hydrological models, include the independence of observations, the absence of seasonal independence, homogeneity of variance over the recording period as well as formation of probability distributions e.g. normal or non-normal (Ward *et al.*, 1990). Accordingly, statistical characterisation of hydrological data should be used for mine water balance calculations, incorporating time series plots to test for normality. For many hydrological variables, the data does however not configure to a normal distribution and it is not realistic to expect such, because data is commonly correlated and non-normally distributed with variance changing over time (EPA, 2003). By using Monte Carlo[6] simulation techniques, uncertainty within natural systems can be represented and effectively modelled (Griffiths *et al.,* 2009). Sequential Monte Carlo (SMC) samplers are effective in posterior distribution sampling with non-linear dependency structures and it is well suited for implementation and representing inherent uncertainties associated with data (Jeremiah *et al.,* 2012). Bayesian interference offers an ideal platform

[5] Probability is defined as a numerical measure of the likelihood of an event occurring and can be used as a measure of the degree of uncertainty associated with historical events (Williams *et al., 2006*).

[6] Broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The modelling method where statistical distributions are sampled in a simulation is used for risk assessments, is known as the Monte Carlo Method (Bear, 1979; Spitz and Moreno, 1996). The Monte Carlo simulation is a computerized mathematical technique that account for risk in quantitative analysis and decision making (Palisade Corporation, 2010).

to assess parameter uncertainty and variability for complex water balance models which is ideally suited for environmental decision-making, such as water management (Vivier, 2011). Bayesian statistics accept that statistical variation such as the mean, median and standard deviation can be inferred based on known information or a prior judgement (Vivier, 2011). On the contrary, Bredehoeft (2003; 2005) warns that probabilistic sampling parameter sets do not necessarily compensate for uncertainties and should be considered carefully.

A sensitivity analysis is a process whereby values of a model input are altered while keeping all other inputs unchanged, and by doing so determining the relative influence of the changed input on the model simulation results (Golder Associates, 2011). Sensitivity analyses are used to determine the impact of any changes in the model input (Golder Associates, 2011). Results from an uncertainty analysis are summarised by extracting the relevant percentiles from output distributions. To incorporate extreme conditions, *i.e.* data limits, data percentiles are determined, and are useful when periods of floods or draughts are taken into consideration for different scenarios as depicted in Figure 2-2. The p^{th} percentile is a value such that at least p percent of the observations are less than or equal to this value and at least (100-p) percent of the observations are greater than or equal to this value (Williams *et al.,* 2006).

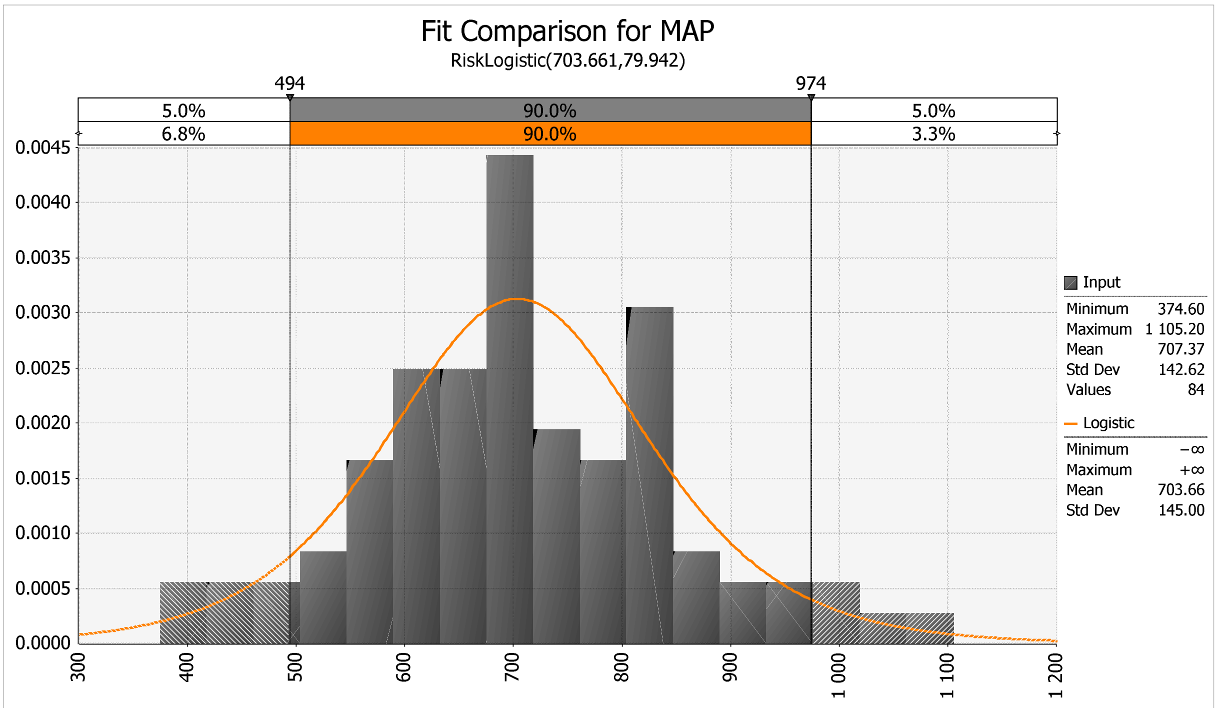

Figure 2-2 Incorporating extreme events by means of percentiles.

2.1.4 Water balance categories

Water balances are constantly evolving in terms of complexity, representativeness and accuracy. One of the basic aspects for a reliable and appropriate water balance is not only to get the water balance right, but also to get the right water balance. McPhail (2005) categorised three types of water balances as listed below:

2.1.4.1 Basic water balance

A basic water balance comprises of a spread sheet format in which the number of columns represent the flows to and from the operating units encompassed in the mine water circuit. The unknown, harmonising flow is calculated by balancing across the operating unit accounting for all inflows, outflows and a change in storage. The basic water balance can be applied to perform simple water balance exercises for example, specific operating units within an integrated system.

2.1.4.2 Predictive water balance

This type of water balance is also referred to as a deterministic, predictive water balance. In order to improve water management, it is necessary to introduce control measures. Control logic is an essential component of predictive water balances, and incorporation thereof into the model allows for strategic management of water resources and optimization. This water balance can include start and stop pumps or the introduction of supplementary storage capacity. Deterministic water balances require a set of input values e.g. average annual precipitation (Brown *et al.,* 1997; EPA, 2003). A predictive water balance can be used to incorporate potential management changes, combined with relative simple control logic modifications, and is limited only to definite input parameters.

2.1.4.3 Probabilistic predictive water balance

The probabilistic, predictive water balance enables the incorporation of uncertainty and variability into the water balance, linking these parameters with management and control logic functions. Uncertain parameters occur as a result of random events or sporadic operating conditions including natural events such as rainfall events, evaporation rates, water seepage and percolation, or unnatural events such as production rates, equipment failures and maintenance schedules (McPhail, 2005). Probabilistic approaches result in a better understanding and design of retention facilities and can also reveal potential design weaknesses (Brown *et al.*, 1997; EPA, 2003). Probabilistic models make use of stochastic data in the form of probability distributions to explicitly represent uncertainty and variability within the model (Golder Associates, 2011) and the input is sampled from probability distributions, e.g. annual precipitation probability (Brown *et al.*, 1997). This type of water balance is therefore ideally suited for complex and integrated water balance models such as mine water balances, applying it as a tool aiding in strategic mine water management.

2.2 Mine water balances

In his attempt to simplify mine water balances, McPhail (2005) considers two essential elements of an accurate water balance:

i. A basic water accounting system to assess how much water is needed for a given operation; and
ii. Improvement of water use efficiency techniques in the interest of reducing risk and costs.

A mine water balance comprises a flow diagram in which flow rates between various mine components are reflected for different production scenarios throughout the year (Idrysy and Connelly, 2012). The water balance illustrates the relationship between water inputs, *i.e.* sources, and water outputs, *i.e.* sinks, incorporating the influence of natural events on mining activities (Idrysy and Connelly, 2012). Between the input and output components, a processing and usage unit is represented in which water can be retained, reused, treated or recycled (Idrysy and Connelly, 2012; Pulles and van Rensburg, 2006b).

Typical water sinks on mining operations can be ascribed to water losses within the tailings circuit, mine service water, evaporation, water shipped off with the product, water being discharged, water for human consumption, water used for dust suppression and seepage losses (Gunson *et al.*, 2010; Pulles and van Rensburg, 2006). Distinctive water sources on mining operations include water from external sources *i.e.* board water as well as raw surface water, groundwater, fissure water resulting from mine dewatering, moisture in run of mine (ROM) ore and precipitation (Gunson *et al.*, 2012). Figure 2-3 represents a simplified mine water balance model as adapted from Gunson *et al.* (2012). Water in the base-metal mining sector is mainly related to ore processing, residue transport and domestic water supply (Idrysy and Connelly, 2012). This statement is supported by Kemp et al. (2010) stating that water in the mineral industry is used for processing and transport of ore and waste, minerals separation, dust suppression, washing of equipment and human consumption.

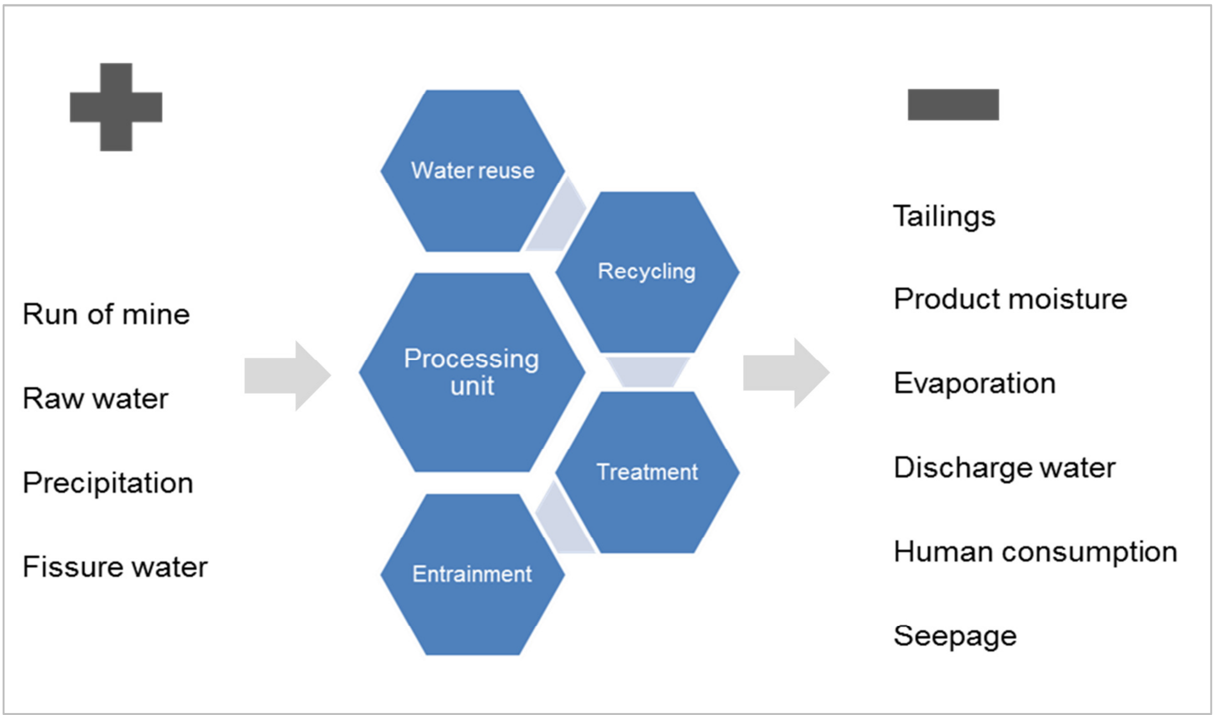

Figure 2-3 Simplified mine water balance model (Adapted from Gunson, 2012).

Water use in the context of so-called hard rock mining, refers to process water which is necessary for routine functioning of the mine-milling complex. This description is iterated by Mavis (2003) who classifies mine water as being involved in three production-related areas, namely: mining or mine workings, processing and beneficiation into a sellable product and conveyance in the form of mine tailings to be disposed of at a residue facility. Operations typically requires water for production drilling, and any associated size reduction facilities which is assumed to consist of crushing, wet screening, semi-autogenous grinding and rod mills (Mavis, 2003).

A clear distinction should be made between units consuming water and units using water. A water consumer can be defined as a unit which requires water, be it available for re-use or not, while a water user is a unit utilising water which is available for reuse and recycling after the task has been completed (Gunson *et al.,* 2010). Water consumers include mill and compressor cooling water, pump gland seal water, wash water, dust suppression water, reagent and dilution water and production drilling water (Gunsen *et al.*, 2010). Major consumers on site must be identified with a description of the required water quantity and quality per facility and can be calculated from engineering guidelines such as Perry and Green (1997).

A simplified process flow sheet, describing a generic base metal mining operation, is indicated in Figure 2-4. Ore is extracted from the ore body, be it an underground or open pit operation, transported and processed through the beneficiation plant to produce a saleable product. Tailings and waste material are then deposited at a Tailings Storage Facility (TSF) and a Waste Rock Dump (WRD) (Gunson *et al.,* 2010).

The make-up water requirement for typical base metal mining operations comprises a total volume of 0.3 m^3 to 0.7 m^3 of water per tonne of ore processed (Gunson *et al.,* 2012). Brown (2003) also reported that the average mine water use for base metal mines currently ranges from 0.4 m^3 to 1.0 m^3 per tonne of ore processed. Ore processing usually requires a constant supply of water while water consumption for the remaining components in the circuit will vary seasonably (Gunson *et al*., 2012).

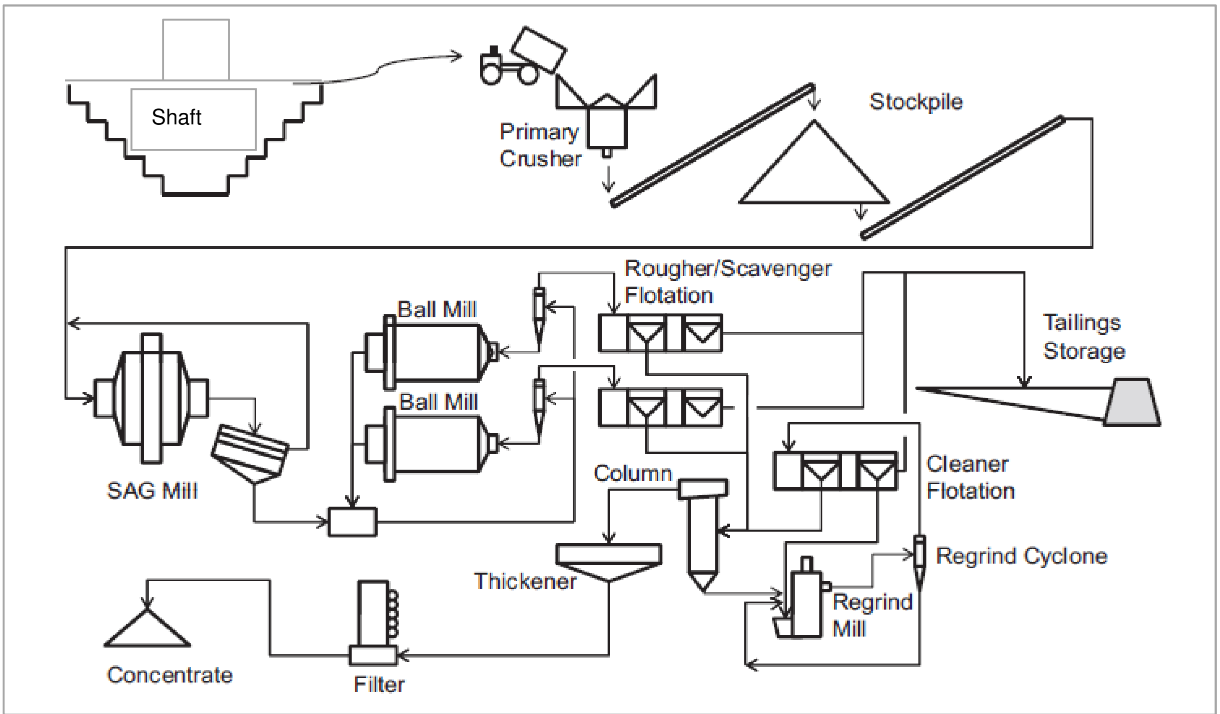

Figure 2-4 Process flow of a generic base metal mining operation (Modified from Gunson *et al.,* 2012).

2.2.1 Components and operating units

Mining operations tend to evolve into large, complex reticulation systems and it is important to identify the main drivers for water usage. The Best Practice Guidelines (BPG G2) as set out by the DWA (Pulles and van Rensburg, 2006b) advice grouping water balance systems into main components or operating units. A typical base-metal[7] mine site consists of the following components as described by Gunson *et al.* (2010): Underground and/or open pit

[7] Base metal refer to certain common metals such as copper, lead, zinc, tin and **ferrochrome** as distinct from the precious metals, gold, silver and platinum (Ashton, 2003).

operation, metallurgical processing and beneficiation plant, mine residue deposits such as tailings storage facilities (TSF) with supporting infrastructure, waste rock dumps (WRD) as well as change houses and administration offices, all of which have a direct or indirect influence on the overall mine water consumption. Miscellaneous water uses such as dust suppression or mining related water needs which may arise, should also be incorporated into the mine water balance. These components make up the main drivers influencing the water balance and along with external water from the natural system, entailing precipitation, evaporation, seepage, runoff, recharge and fissure water ingress into mine workings, comprise the overall mine water balance reticulation system.

Make-up water use per component, *i.e.* water losses, is reflected as a percentage of the total mine make-up water requirement and was derived from literature reviews on published articles and qualified investigations from similar operations as illustrated in Figure 2-5. Accordingly, the main drivers in a mine water balance, contributing to more than 90% of the make-up water requirement, include water losses to the tailings circuit, water consumption in mining related processes as well as water used for dust suppression (Figure 2-6). Corresponding values are approximations for researched base-metal operations only and can be applied for conceptual purposes; however, predicting mine water flows for detailed investigations may require the use of specialised models.

This investigation is aimed at developing a management model for the purposes of decision-making and does not aim at determining the exact balances or status as it is in the field, as this is deemed an impossible task. A systems model approach is the focus, with each component contributing to the system as a whole and an accuracy level of 10 – 15% for the overall mine water balance, taking into account measurement errors, is considered adequate (Pulles and van Rensburg, 2006b). It is important to verify values by regular updates as part of a dynamic calibration process, with close collaboration between plant, mining and tailings engineers (Idrysy and Connelly, 2012).

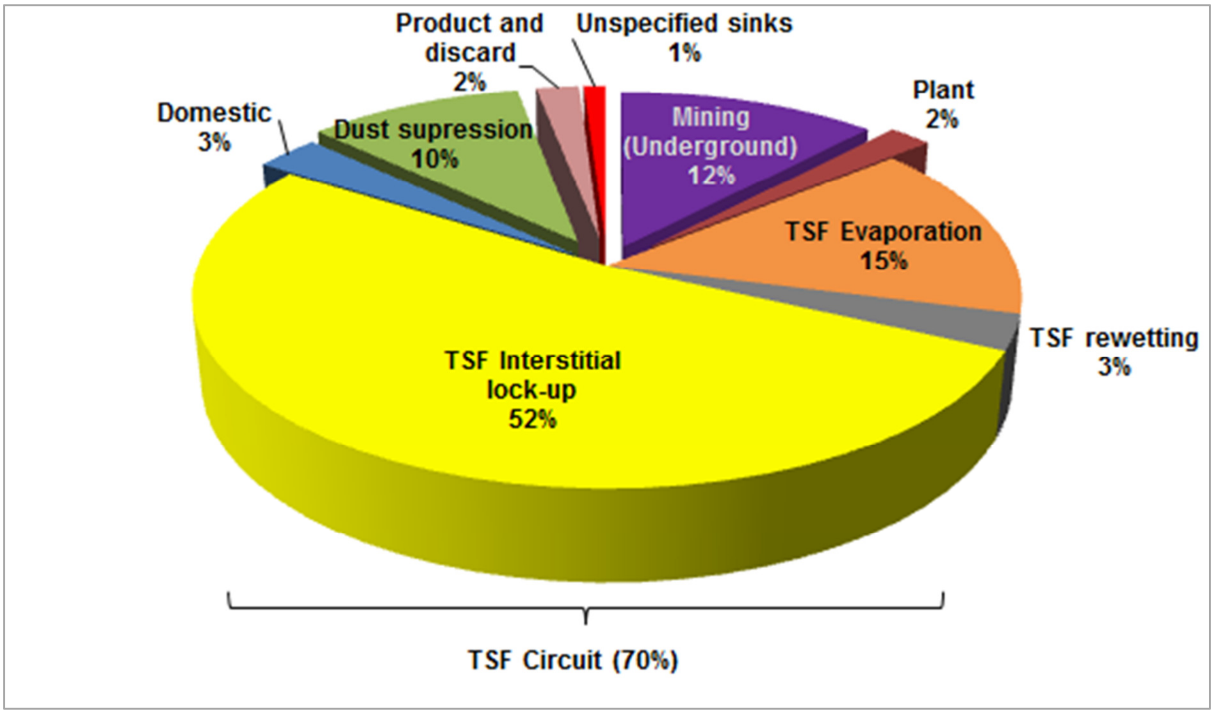

Figure 2-5 Approximation of water losses per component.

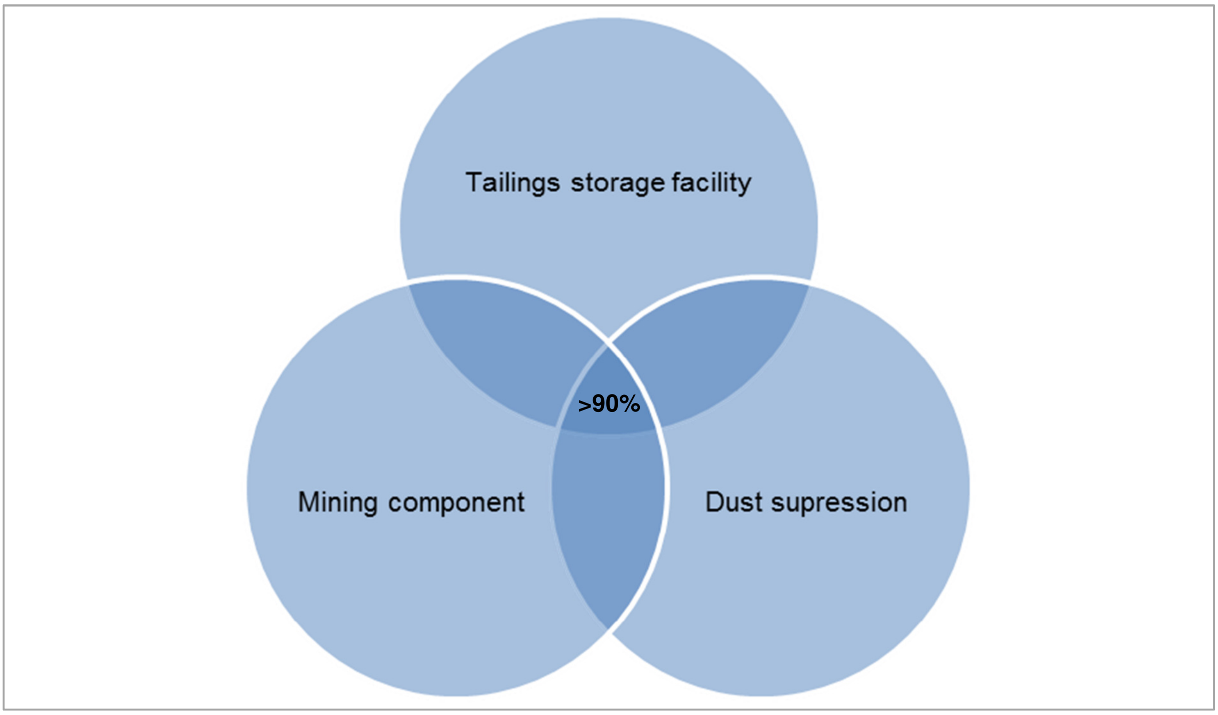

Figure 2-6 Major drivers contributing to >90% of total mine water make-up requirement.

2.2.1.1 Mining component

The mining component consists of an open pit and/or underground operation with supporting water reticulation infrastructure such as raw water reservoirs, worked water dams, settling or clarifier ponds and storm water containment facilities. Water requirements for the mining component encompass approximately 10% to 15% of the total water use (Gunson, 2012; Golder Associates, 2011). Major water circuits comprise the following: Losses to evaporation, including shaft ventilation losses, seepage losses, ore moisture and water losses to mine service and cooling water, fissure water ingress into mine workings, precipitation and water entrapped in ore (Figure 2-7). Figure 2-8 indicates a probability distribution of water loss percentages for this component, with an average loss of 11.6%. Mine make-up water requirements for an open pit operation are usually less than make-up water for an underground operation. This is due to influences of ventilation losses and underground services and cooling water which do not play such an important role in an open pit scenario, but should be taken in consideration.

2.2.1.2 Plant component

The plant component consists of the beneficiation and metallurgical processing plant with supporting water reticulation infrastructure, such as raw water reservoirs, potable water reservoirs, fire water tanks, process and plant water dams and storm water containment facilities. Mining operations with beneficiation plants use considerably more water than operations without beneficiation plants and are therefore required to apply better water management principles (Pulles and van Rensburg, 2006b). Water requirements for the plant component encompass approximately 2% to 5% of the total water use (Gunson, 2012). This component comprises the following major water circuits: Chemical make-up water, ore surface water moisture, evaporative circuit losses, gland service water consumption, plant water consumption, product moisture, seepage losses, surface water runoff, tailings discharge, tailings return water as well as water consumed at the workshop (Figure 2-9). Figure 2-10 indicates a probability distribution of water loss percentages for this component, with an average loss of 2.48%.

2.2.1.3 Tailings component

If all the physical processes influencing water movement are to be considered, the development of the tailings storage facility (TSF) water balance is a challenging task and the TSF is the operating unit with the most variability (Wels and Robertson, 2003; McPhail, 2005). The TSF circuit is considered the main driver of a mine water balance and it is consequently vital to focus on getting the TSF water balance right (McPhail, 2005). This facility encompasses the following major water circuits as depicted in Figure 2-11 and Figure 2-19: Tailings discharge to TSF, evaporation, beach rewetting, retained interstitial lock-up water, seepage losses, precipitation onto the TSF surface area as well as surface water runoff. Supporting reticulation infrastructure includes return water dams (RWD), seepage collecting trenches and sumps. Make-up water requirements for the tailings component encompass approximately 50% to 80%, depending on metallurgical processes, deposition techniques and the moisture content of discharge tails (McPail, 2005, Wiid, 2013). Figure 2-12 indicates a probability distribution of water loss percentages for this component, with an average loss of approximately 70%.

2.2.1.4 Domestic component

The domestic component consists of the domestic water reticulation system, including the change house, office and administration blocks and potable water provisions for the plant, workshop and mining operations (Figure 2-13). A centralised sewage treatment plant treats all sewage to a re-useable quality and international best practice states that treated effluent should be recycled back to the main circuit which forms part of this component (EPA, 2003). Most of the solids in wastewater received by the sewage treatment system are concentrated into thick slurry, which has a volume of less than 1% of the total water received (Mara, 2003). It is estimated that 20% - 30% of the total water input gets lost to evaporation and treatment processes, with the remainder of the treated effluent recycled back to the main circuit for reuse as stipulated. Make-up water requirement for the domestic component encompass approximately 1% to 6% of the total water use, but is highly dependent on the number of employees at the site operation (CSIR, 2000). Figure 2-14 indicates a probability distribution of water loss percentages for this component, with an average loss of 3.33%.

2.2.1.5 Waste Rock Dump component

The waste rock dump (WRD) component is not classified as one of the main drivers for water consumption, but it is however deemed necessary to include this component into the water balance model for management purposes. This component comprises the following major water circuits: Waste rock surface moisture, evaporation, precipitation on the waste rock dump surface area, surface runoff as well as seepage and infiltration (Figure 2-15). Waste rock dumps have the ability to capture large quantities of water and although runoff and seepage water captured from this facility contain high salt concentrations and are characterised as poor quality water, this component can have a definite influence on the overall mine water balance and should be incorporated in the site water management plan accordingly. Waste rock surface moisture originating from inert conditions as well as water entrapped in the rock, is not credited, for it is assumed to be lost to evaporation and interstitial lock-up preventing water release. In order to determine the quantity of waste rock to be disposed of at a given facility, it is necessary to assume the stripping ratio[8] of ore; waste and accordingly calculations should be based on this ratio. Supporting infrastructure includes pollution control dams intersecting water from toe seepage as well as runoff from waste rock dumps.

2.2.1.6 Environmental component

The environmental component represents the most data variability and uncertainty of a mine water balance and includes a surface water environmental circuit as well as a groundwater environmental circuit. This component is often neglected and is vital to be taken into consideration for an accurate representation of site conditions (Pulles and van Rensburg, 2006b).

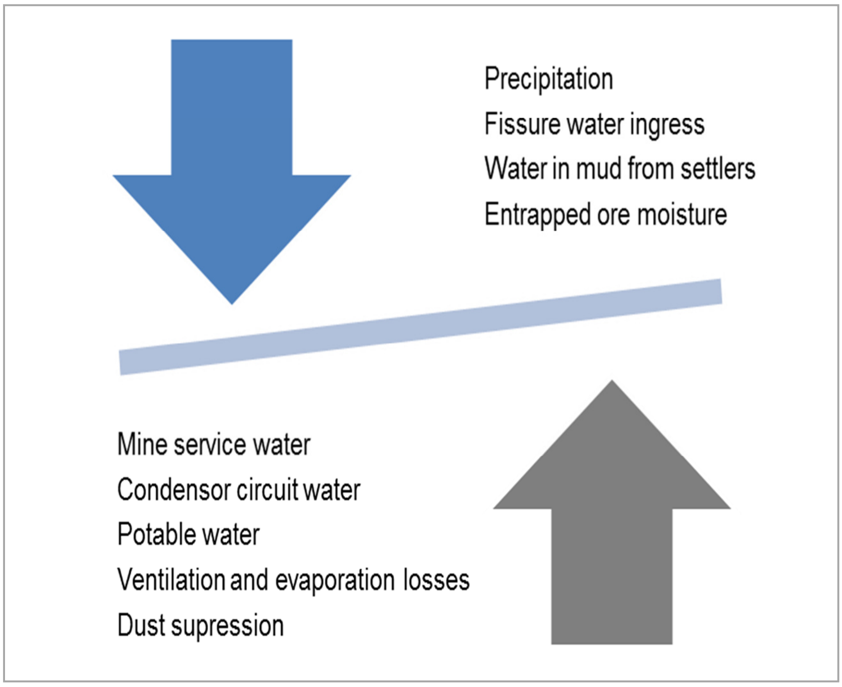

Figure 2-7 Mining component major water circuits.

[8] In mining, stripping ratio or strip ratio refers to the ratio of the volume of overburden (or waste material) required to be handled in order to extract some volume of ore. For example, a 3:1 stripping ratio means that mining one cubic meter of ore will require mining three cubic meters of waste rock (Hartman, 1992).

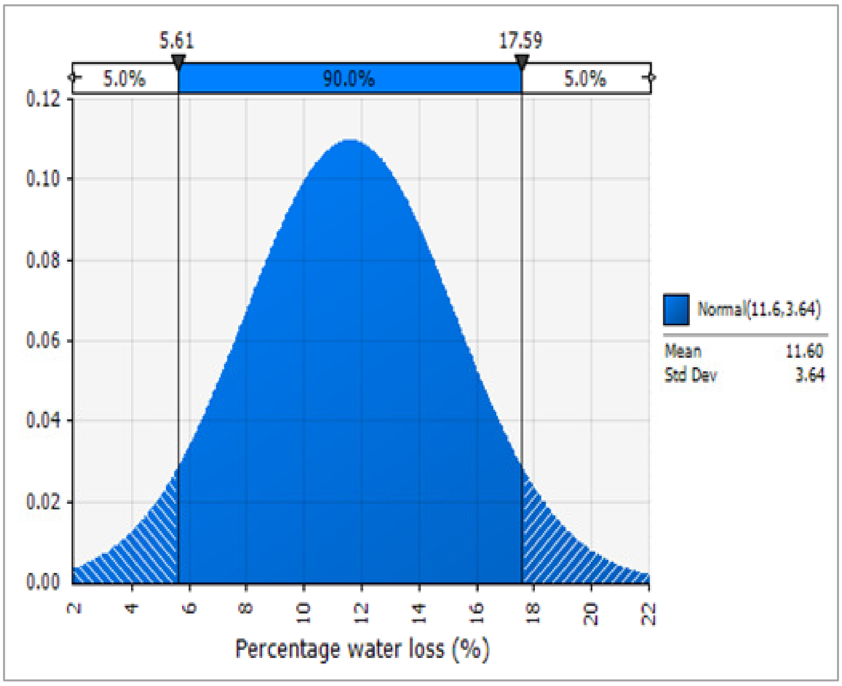

Figure 2-8 **Mining component water loss probability distribution.**

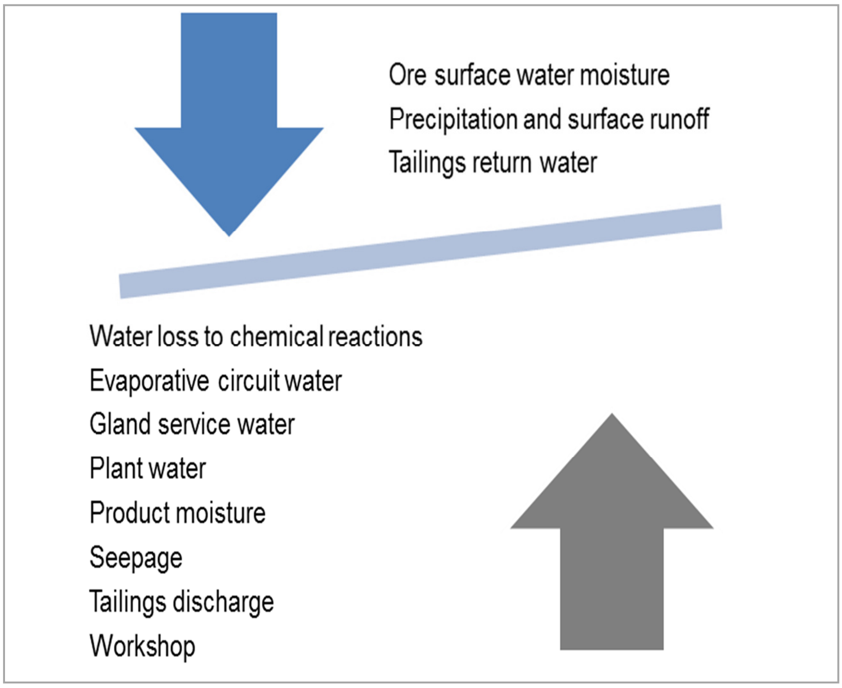

Figure 2-9 **Plant component major water circuits.**

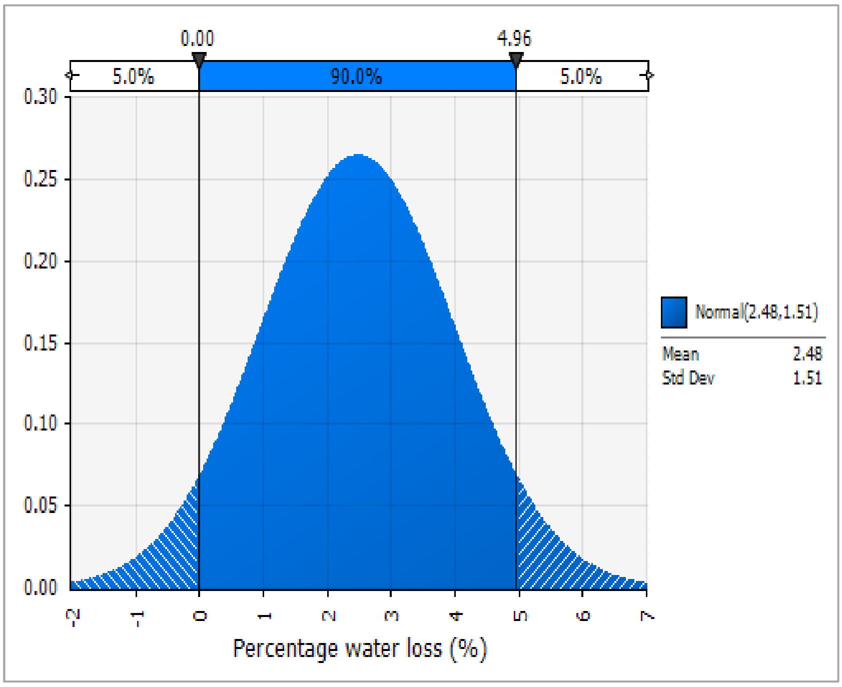

Figure 2-10 Plant component water loss probability distribution.

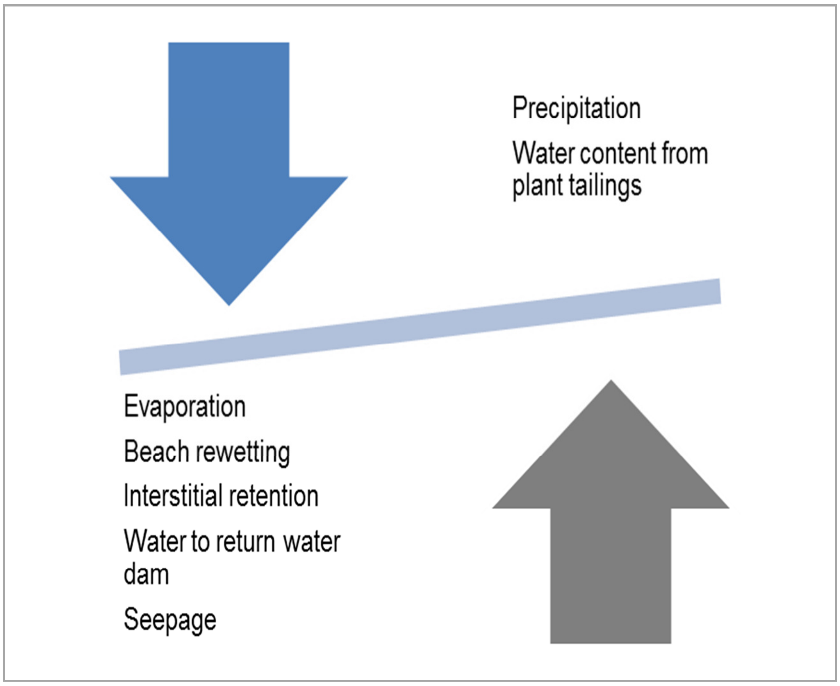

Figure 2-11 TSF component major water circuits.

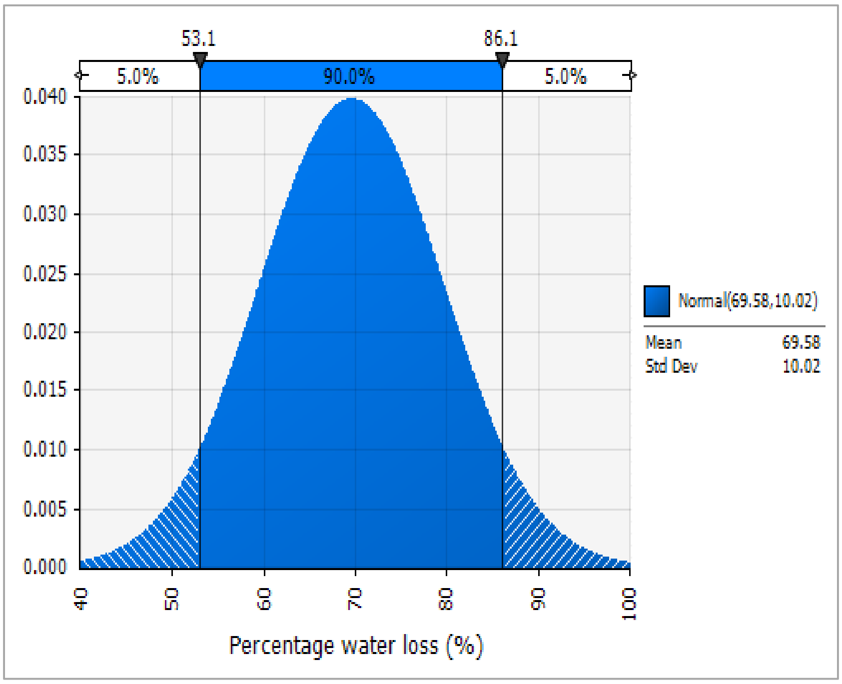

Figure 2-12 TSF component water loss probability distribution.

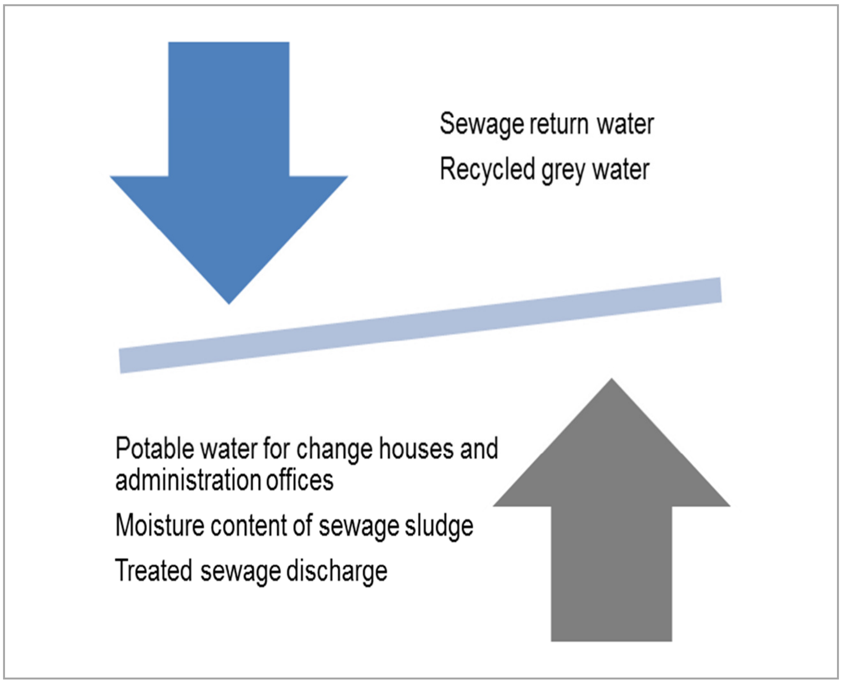

Figure 2-13 Domestic component major water circuits.

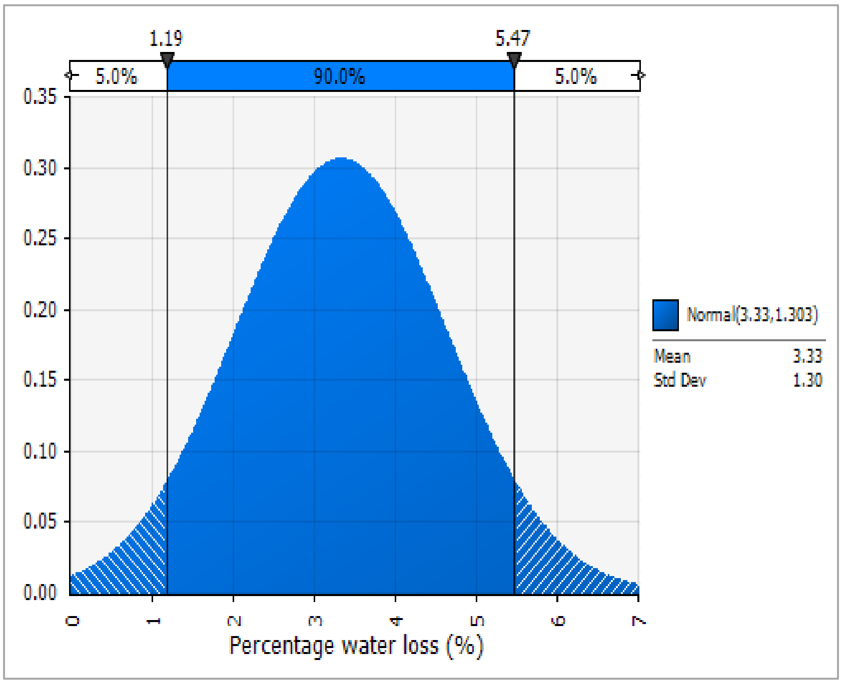

Figure 2-14 Domestic component water loss probability distribution.

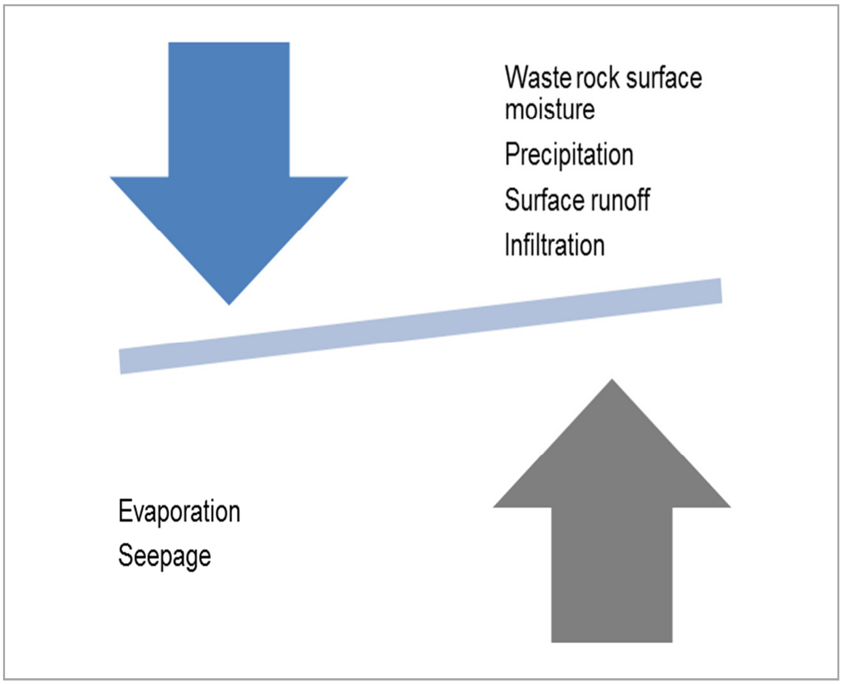

Figure 2-15 Waste Rock Dump component major water circuits.

2.3 Water balance systems

A water balance for a typical mining operation encompasses two water systems, namely water from the process system and water from the natural system (EPA, 2003). Process system water accounts for all site water and mining related water while water from the natural system is associated with the intrinsic hydrological cycle. These two water systems are superimposed by an integrated surface and groundwater balance, accounting for all waters (EPA, 2003).

2.3.1 Process system water

Water from the process system accounting for site make-up water and generally include water losses to retention, water entrapped in tailings, ROM ore moisture, product and concentrate moisture, chemical reagent water, operational start-up water, water used for dust suppression as well as water consumed for domestic purposes (Cote *et al.,* 2010). Water balance components, forming part of this system include the mining component, plant component, tailings component and the domestic component. Following is a brief overview of major water losses encompassing the process system and quantification thereof.

2.3.1.1 Tailings water retention

In his research on tailings and paste management, McPhail (2005) calculated the water to be lost to the TSF as up to 80%. Tailings water recovery is controlled by a complex interplay of various physical processes, including tailings deposition and consolidation, evaporation, rewetting and seepage (Wels and Robertson, 2003). The mined product and tailings can be transported through a pipeline as aqueous slurry to a storage facility some distance away and the water use depends on the rheological[9] properties. McPhail (2005) also reported that tailings retention and interstitial lock-up water values are dependent on various physical properties of mine tailings. Therefore, an allowance of approximately 15% mass of water per dry mass of solids should be subtracted. The average moisture content of newly placed tailings is estimated at approximately 30 - 50% of mass of water per dry mass of solids (McPhail, 2005). As discussed, it should be noted that interstitial lock-up assumptions can differ from one operation to another and water retention tests should be done as part of the validation process. Retention tests were done on tailings samples derived from the case study with interstitial water lock-up for the tails measured at 30%.

[9] Rheology is the study of the flow of matter, primarily in the liquid state under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force. It applies to substances which have a complex microstructure, such as muds, sludge and suspensions (W. R. Schowalter,1978).

2.3.1.2 Ore water retention

Moisture content is an important factor to bear in mind when calculating losses due to entrapped water. Water entrapment encompasses the capability of ore to consist of an inert water bearing ability. The ROM ore for base metal mining operations typically has a moisture content of 2.0 percentages by mass (%m) to 5.0 %m (Gunson *et al.,* 2010). SMI (2012) confirms this value and states that, in the absence of the above mentioned information, a reasonable estimate can be assumed as 2.0 %m to 3.0 %m. The volume of entrapped water in ore can be calculated by this equation:

$$\mathbf{V_{Ent}} = \mathbf{1000} \times \mathbf{P} \times \mathbf{m}$$

Equation 2-2

Where:

V_{Ent} = Volume of entrapped water in ore;

P represents incoming ore processed (m^3); and

m represents the moisture content as a fraction.

2.3.1.3 Product moisture

The final product or concentrate consists of moisture content of less than 1.0% by weight (Gunson *et al.*, 2010), while the average water content determined for the final sellable product in the case study is 5.9% by weight. The moisture content *i.e.* water loss from the product is highly dependent on the beneficiation process and the final produce and product moisture determination tests should be conducted on a regular basis.

2.3.1.4 Dust suppression

Aside from minor water uses for personnel, equipment maintenance and miscellaneous uses, the main secondary water use on mining operations is for dust control (Mavis, 2003). A major impact of any mining operation is the impact on air pollution due to the formation of dust particles caused by associated activities. This effect can be mitigated by the moistening of dust forming areas with water or any environmental friendly suppressant. Dust suppression is needed in pits, underground workings, at conveyances, on roads and in industrial areas (Cote *et al.,* 2010). Usually worked water is utilised as part of the management strategy, with the amount of water used for wetting varying between 0% and

15% of the total water used at the mine, depending on site conditions (Crane-Murdoch, 2010). Dust control consumes about 20 litres per ton of ore produced and the volume required is modelled as a function of the amount of rainfall received by the site (Cote *et al.,* 2010). Cote *et al.* (2010) supports this statement by noting that mine sites generally water roads if the rainfall does not exceed 10mm over a period of 24 hours and can be implemented as part of the strategic management process. Accordingly, it is important to calculate the dust control surface areas for planning purposes (Golder Associates, 2011).

2.3.1.5 Domestic water usage

In his study of wastewater usage, Destatis (2009) considered a mean water consumption of 126 litres per day per capita. During monitoring of the operational phase for a mining operation in South Africa, it was determined that 100 litres of potable water/person/day is consumed (SLR, 2013). The South African Department of Water Affairs Guidelines for Human Settlement Planning and Design requires that a minimum of 25 litres of potable water be provided per person per day (CSIR, 2000).

2.3.2 Natural system water

The other water system entailing a mine water balance is the natural system, associated with the intrinsic hydrological cycle[10] (Figure 2-16). The natural system consists of a surface water environmental circuit, made up of precipitation, runoff and evaporation (including transpiration) as well as a groundwater environmental circuit, made up of seepage, recharge and fissure water ingress into mine workings (EPA, 2003; van Zyl, 1998). Water balance components forming part of the natural system entail the environmental component which is often disregarded, and can significantly impact on mine water usage and losses (Pulles *et al.*, 2001; EPA, 2003). Decision making and management options should be based on the evaluation of the system as a whole and the inclusion of the natural system as a component of the mine water balance is imperative for accurate prediction of site conditions, hence management. Figure 2-17 and Figure 2-18 provide a schematic representation of the conventional approach in compiling a mine water balance compared to an adapted approach of incorporating environmental influence as part of the natural system. It is clear that it is important to include the natural system as a component of the mine water balance for accurate quantification.

[10] The hydrological cycle is a continual circulation and distribution of water through all the elements of nature (EPA, 2003).

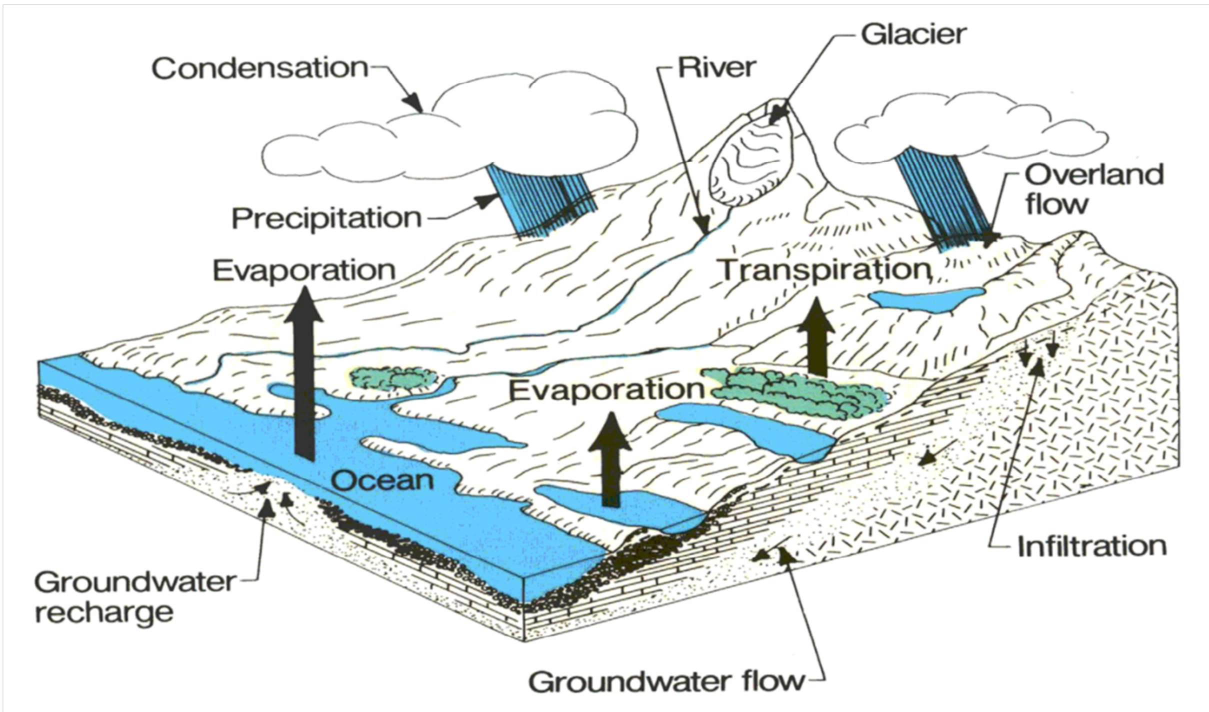

Figure 2-16 Hydrological cycle (After Ward, 1990).

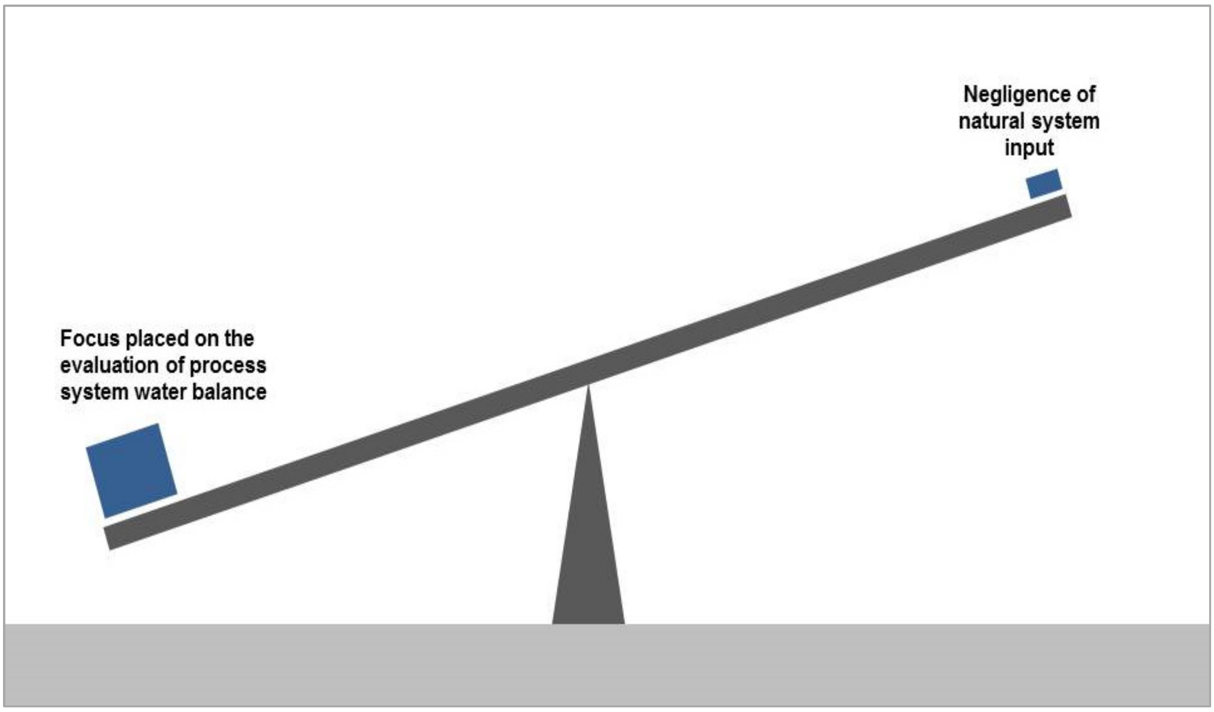

Figure 2-17 Schematic representation of an imbalanced approach in compiling mine water balances.

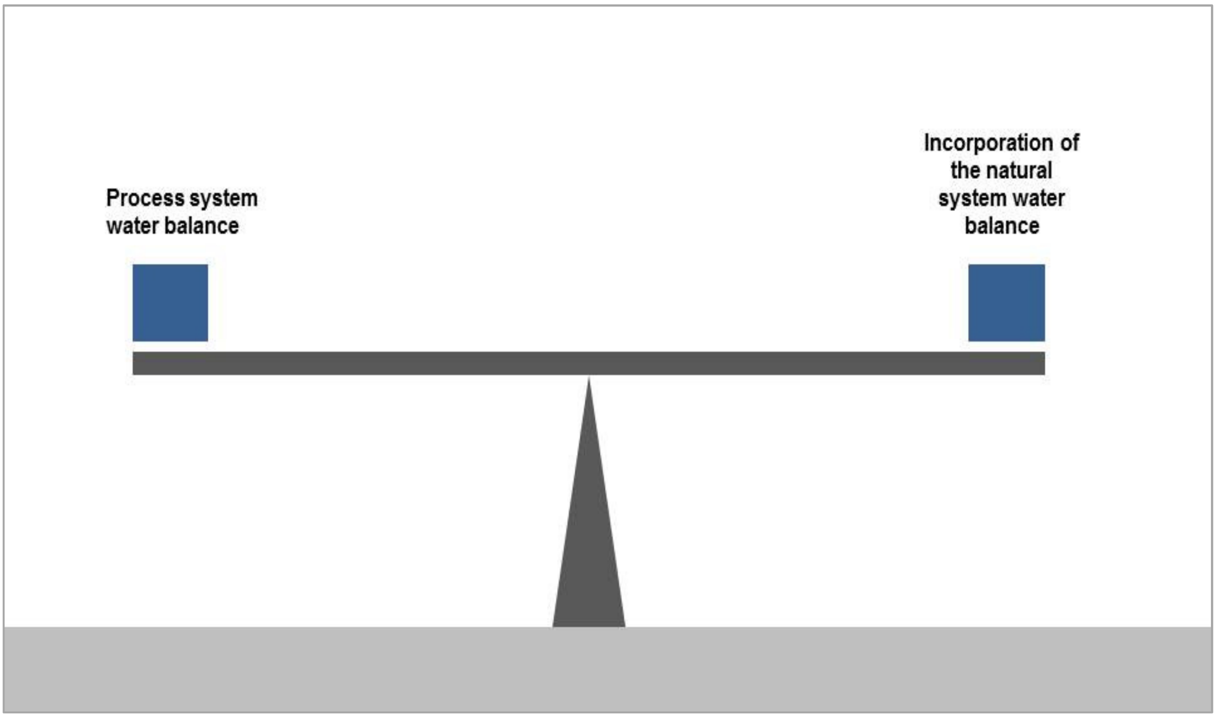

Figure 2-18 Schematic representation of a balanced approach incorporating external influences.

Following is a brief overview on underlying aspects of natural system water and quantification thereof. The first section will discuss the surface water environmental circuit.

2.3.2.1 Precipitation

Precipitation events can significantly impact mine water usage and can determine whether a system will have a net gain or loss of water (EPA, 2003). Mine make-up water depends greatly on seasonal variations in rainfall (Younger *et al.,* 2002; Vermeulen and Usher, 2006) and rainfall is regarded as an important driver in a mine water balance (AGES, 2013). Utilisation of proper historical climatic records is important in order to reflect seasonal changes throughout a typical year and a key aspect of a water balance is long-term variability of precipitation volumes, intensity as well as duration of rainfall events (Idrysy and Connelly, 2012; EPA, 2003). In order to provide insight into such events to occur within a specific timeframe, the water balance should compute for average, wet and dry conditions (Brown, 1997; EPA, 2003). Pulles and van Rensburg (2006a) validates this statement by stating that seasonal changes can be accounted for by dividing the hydrological year into wet and dry seasons and statistical calculations can determine the 5th percentile[11] (dry conditions), 50th percentile (mean) as well as the 95th percentile (wet conditions) accordingly. A water balance is also required to size storm water containment facilities which should be

[11] A percentile provides information about how data is spread over a specific distribution and is a measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall.

designed to accommodate additional water flows due to extreme precipitation events. This can be obtained using long-term climate data and seasonal rainfall behaviour (EPA, 2003; Cote *et al.,* 2010). The dynamic calculation of a site water balance is associated with varying seasonal water demands, and is often poorly understood by plant managers. Therefore, excessive costs can result from both poor understanding of water resource availability, incomplete information relating to water consumption and resulting water management decisions (Griffiths *et al.,* 2009).

2.3.2.2 Runoff and runoff coefficients

Run-off volumes are calculated from rainfall data using monthly volumes and a volumetric run-off coefficient. These volumes are derived through analyses of historical values computed from regional data (Middleton and Bailey, 2005). Coefficients are determined for areas that are vegetated and undisturbed, or non-vegetated, disturbed areas, which display an increased run-off of 50% (Cote *et al.,* 2010). This is confirmed by Boughton (2003) based on the analyses of runoff predictions for the Australian Water Balance Model. Most runoff is caused by individual intense rainfall events and not necessarily by the volume of rainfall recorded (Ogola *et al*., 2011). McPhail (2005) estimated the runoff on tailings to be 50% to 65% of the mean annual rainfall. Tailings dam particles exhibit a small distribution in size, with the majority of particles uniform in size and deposited in a layered form (Rosner and Boer, 1996; Rykaart *et al.,* 2003). Accordingly, the TSF area serves as a catchment for rainfall which is higher for valley impoundments. Surface water stores must hold maximum stocks to ensure water security, but the mine must also have sufficient storage capacities to contain all runoff during wet seasons. The volume of rainfall incidents on facilities including waste rock dumps, tailings storage facilities and other facilities can be calculated by means of:

$$\boldsymbol{V_{Rainfall} = 0.001 \times R \times SA_{R.M}}$$

Equation 2-3

Where:

$V_{Rainfall}$ = Volume of rainfall (m^3/d);

R = Rainfall measured during the reporting period (mm); and

$SA_{R,M}$ = The surface area of facility (m^2).

Rainfall runoff volumes can be calculated by applying the following equation:

$$\mathbf{V}_{\textbf{Rainfall Runoff}} = \mathbf{0.001} \times \mathbf{R} \times \mathbf{A} \times \boldsymbol{\beta}$$

Equation 2-4

Where:

$V_{\text{Rainfall Runoff}}$ = Volume of rainfall runoff (m^3/d);

R = Rainfall measured during the reporting period (mm);

A = Undisturbed/disturbed catchment area ratio (m^2); and

β = Volumetric rainfall/runoff factor.

2.3.2.3 Evaporation

Evaporation losses are responsible for large volumes of water losses to a permanent sink and are viewed as the most uncertain component of the natural system (Kampf and Burges, 2009). Any water body subjected to an open water circuit is susceptible to evaporation and should be determined and evaporation calculated for management purposes (Gunson, *et al.,* 2012). As evaporation of the TSF circuit is responsible for one of the largest losses on mining sites, calculation and estimation of this component will be discussed in more detail; the basic principle however remains the same for any open-air water-containing facility. It is important to determine the areas of wet, damp and dry beaches when calculating the evaporation losses for the tailings component (McPhail, 2005). Pond evaporation, along with all other open water circuits, will usually take place at the full evaporation rate with a lake correction factor of 0.8. Wet beaches evaporate at a rate of 0.6 – 0.8 while damp beaches evaporate at a rate of 0.4 – 0.6. A lake correction factor on dry beaches can be assumed as 0 – 0.2 depending on the rate of rise for the TSF (McPhail, 2005). In their investigation on the status of mine water balances, Pulles *et al.* (2001) indicated that water losses by evaporation can reach volumes of up to 31%. Pulles *et al.* (2001) also stated that a comparison between underground mining operations[12] versus open cast operations revealed a difference in evaporation losses compared. It can be subscribed to ventilation of underground workings having an impact on evaporation rates. Evaporation can be calculated by applying the following function:

[12] In their research Pulles *et al.* (2001) specifically refer to underground bord and pillar mining conditions as investigated.

$$\mathbf{V}_{\mathbf{Evap}} = \mathbf{0.01} \times \mathbf{S}_{\mathbf{Evap}} \times \mathbf{Pan}_{\mathbf{Evap}} \times \boldsymbol{f}$$

Equation 2-5

Where:

V_{Evap} = Volume of evaporation (m^3/d);

S_{Evap} = The average surface area (m^2) occupied by water within facilities during the reporting period; and

Pan_{Evap} = The value of measured rates of pan-evaporation during the reporting period;

f = Correction factor to convert measurements of pan evaporation into evaporation losses.

The following sections will focus on the groundwater environmental circuit and elaborate on the quantification measures and assumptions of incoporation of this circuit in the overall mine water balance.

2.4 Incorporating the Groundwater balance

Surface and groundwater resources were historically managed separately, but more than ever before, an understanding of the interaction between these two systems is required to facilitate resource management and decision-making (Parsons, 2004). Both components of hydrology as well as hydrogeology, must not be viewed in isolation from each other, but incorporation of groundwater as part of the natural system should be considered (Cogho, 2012). With all aspects taken into consideration, groundwater and surface water interaction can become a complex application and entails elements of the unsaturated zone, the surface water balance as well as the groundwater balance. It is necessary to calculate areas of drainable surplus, which can be defined as the quantity of water flowing into the groundwater reservoir in excess of water flowing out (Boonstra and de Ridder, 1994). Under predevelopment conditions the groundwater system is in long-term equilibrium and water is constantly being added to the system by recharge from precipitation, and leaving the system as discharge to surface water and as evapotranspiration (USGS, 2013). The fundamentals in compiling a groundwater balance are also based on the principles of mass conservation, which is often referred to as the water budget. Groundwater catchment boundaries, such as topographical no-flow boundaries and regional drainages, should be delineated for calculation purposes. Boonstra and de Ridder (1994) proposed the following simplified equation:

$$\textbf{Inflow} = \textbf{Outflow} + \textbf{Change in Storage}$$

Equation 2-6

2.4.1 Seepage

Seepage is an important element of a mine water balance and should be incorporated into all assumptions and calculations. In their investigation on the status of mine water balances, Pulles *et al.* (2001) indicated that only 25% of mining operations surveyed included seepage as a parameter within the water balance model. Upon filling a newly constructed facility initial seepage rates may be as great as 10 mm/day. However, seepage rates decrease due to the plugging of conducting pores in the bed material by microbial slimes and colloidal soil materials (Madramootoo *et al.*, 1997). It should be kept in mind that seepage loss will occur at any earth-lined or unlined facility. Once more, as the TSF circuit is responsible for the largest loss on mining sites, calculation and estimation of seepage losses to this component will be discussed in more detail. Seepage[13] losses during discharge of fresh tailings onto older, desiccated tailings beaches can contribute to large quantities of water being lost. The rate of seepage is governed by the hydraulic conductivity of the sub-strata (Vermeulen and Usher, 2006). This statement is supported by McPhail (2005) who also reported that seepage from the TSF will occur at a rate governed by the hydraulic conductivity of the tailings or the base foundation, whichever is the lowest. An increased surface area from blasting and crushing of ore material results in increased weathering, and a coarser particle size generally results in more rapid infiltration of rainfall to the base of the tailings and the generation of seepage (Wels *et al.,* 2003). A water table mounding occurs in the vicinity of deposition tailings which is often an area of groundwater recharge (Jambor and Blowes, 1994). Process water and precipitation infiltrating the tailings, migrates downwards into the underlying groundwater flow system (Jambor and Blowes, 1994) which, according to Wels and Robertson (2003), can represent an annual recharge rate of 30% of the Mean Annual Precipitation (MAP).The infiltration of moisture from tailings materials placed in the discards area is also referred to as rewetting and is a function of the quantity, grading, moisture content, the compaction of placed material, the drainage system employed, the height of the material in the dump, the rainfall on the surface area as well as the storage capacity of surface water on the contained surface (Bigen, 2011). The ratio between infiltration and runoff depends on various factors such as the properties of the slurry, the discharge rate, the duration of discharge, the permeability of the deposited tailings, the presence of reaction

[13] Seepage reflects losses at the foundation of the tailings facility to the sub-strata while rewetting refers to infiltration into the bear surface of the tailings (Brixel and Caldwell,2011).

cracks as well as the position of the phreatic level (Engels, 2001).

Darcy (1856) formulated an equation considering the factors controlling groundwater flow. This formula is known as Darcy's Law and may be considered as the first principle of groundwater science. Seepage losses can in view of this be calculated by application of Darcy's formula:

$$\mathbf{Q = KAi}$$

Equation 2-7

Where:

Q = quantity of water per unit of time (m^3/d);

K = hydraulic conductivity (m/d);

i = hydraulic gradient ($i = \Delta h/L$); and

A = area (m^2).

Groundwater flow is governed by a hydraulic gradient which can be determined by using the following equation:

$$\boldsymbol{i = \frac{h_1 - h_2}{L}}$$

Equation 2-8

Where:

i = groundwater flow gradient (dimensionless);

$h_1 - h_2$ = difference in groundwater elevation between any two given points (mamsl); and

L = distance between the two given points (m).

Figure 2-19 provides an illustration of the application of Darcy's formula on a tailings storage facility, quantifying foundation seepage (Q). The calculation is based on the assumption that the entire base of the TSF area is susceptible to seepage and that any seepage occurs vertically downwards, *i.e.* $L = h_1 - h_2$; i=1, if the hydraulic conductivity of the matrix is greater than the hydraulic conductivity of the tailings. Particle sorting towards the supernatant pond of the tailings storage facility creates an increase in hydraulic conductivity within this area and consequently a depression of the phreatic surface (Zandarin *et al.,* 2009). The phreatic surface is essentially the water table in the tailings and is defined as the position between the zone of saturation and the zone of aeration (Jambor and Blowes, 1994). The exact level at which the phreatic surface resides is the point where the water rises have pressure equal to that of the atmosphere (Anglo Gold, 2004).

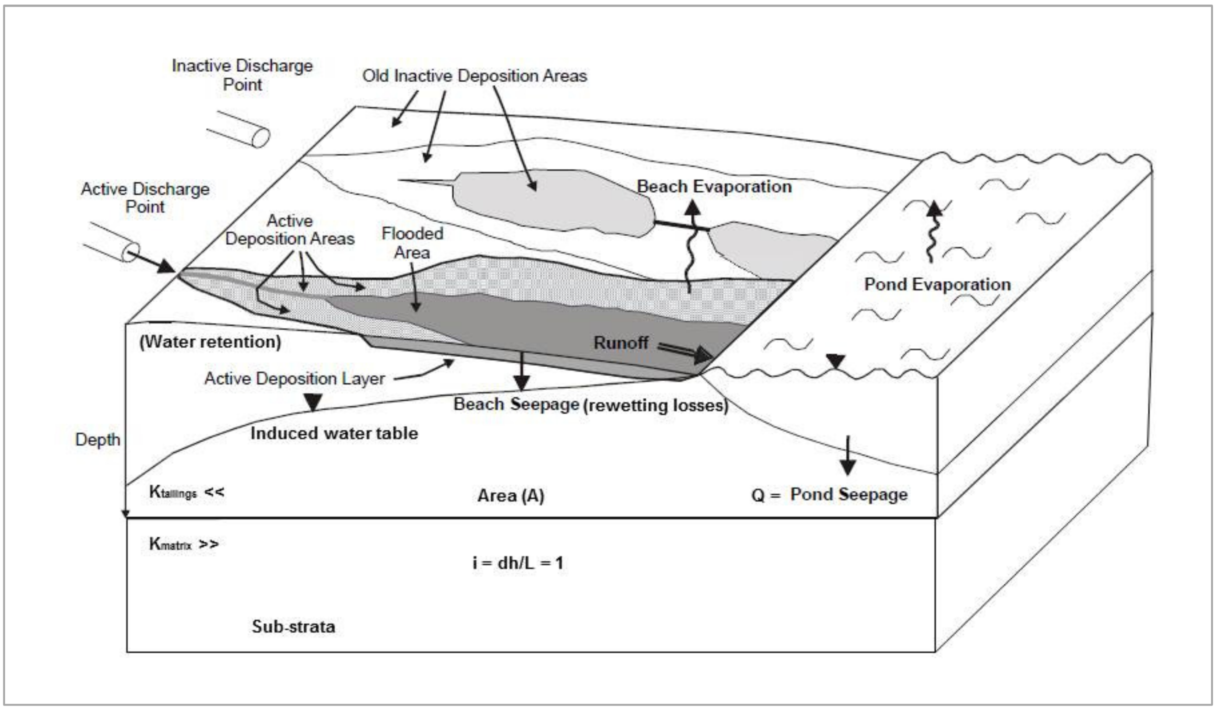

Figure 2-19 Schematic diagram of tailings deposition and associated water balance components (Modified from Wels and Robertson, 2003).

2.4.2 Groundwater Yield Model for the Reserve (GYMR)

Bredehoeft (2003) referred to the “water budget myth” as the assumption that the pre-development water budget can be used to calculate the water available for consumption (USGS, 2013). This statement is however not entirely correct and is an oversimplification of the information that is required to understand and develop a groundwater system (USGS, 2013). RDM (2010) provide a framework for the determination of a catchment based groundwater balance by applying the Groundwater Yield Model for the Reserve (GYMR) Method. In the GYMR model a distinction is made between natural and unnatural inflow and outflow components. The purpose of the model is to calculate the volume of groundwater in storage given that the total volume of water required by natural systems is allocated for (RDM, 2010). If the assumption is made that, in a natural, steady-state situation, outflow to and inflow from deep aquifers balance each other e.g. a null effect, the groundwater balance equation for the model is given by:

$$\Delta \mathbf{GV_{ST}} = \mathbf{Q_R} - \mathbf{Q_{GETL}} - \mathbf{Q_{GBF}}$$

Equation 2-9

In an unnatural groundwater system, as is the case for mining operations, the groundwater flow balance per time step is given by:

$$\Delta \mathbf{GV_{ST}} = \mathbf{Q_R} + \mathbf{Q_{DS}} - \mathbf{Q_{BH}} - \mathbf{Q_{LSF}} - \mathbf{Q_{BHN}} - \mathbf{Q_{IRR}} - \mathbf{Q_{MDW}} - \mathbf{Q_F} - \mathbf{Q_{AVEG}} - \mathbf{Q_{WLD}} - \mathbf{Q_{RVEG}} - \mathbf{Q_{SF}} - \mathbf{Q_{GETL}} - \mathbf{Q_{GBF}} - \mathbf{Q_{EWR}}$$

Equation 2-10

Where:

Q_R = Recharge from rainfall;

(Where L equals length and T equals time)

Q_{GETL} = Groundwater flow (evapo-transpiration) losses;

Q_{DS} = Inflow from seepages;

Q_{IRR} = Return recharge from irrigation;

Q_{AVEG} = Alien vegetation;

Q_{GETP} = Evapo-transpiration losses;

Q_{MDW} = Mine dewatering;

Q_{SF} = Spring flow;

Q_{GBF} = Groundwater base flow;

Q_{WLD} = Wetland fed by groundwater;

Q_{RVEG} = Riparian vegetation;

Q_{EWR} = Ecological Water Requirement (component of groundwater base flow);

Q_{BH} = Abstraction from boreholes e.g. well fields for water supply;

Q_{LSF} = Abstraction from boreholes for livestock farming;

Q_{BHN} = Allocation for basic human needs and communities;

Q_F = Forestry groundwater use; and

GV_{ST} = Volume of groundwater in storage.

As discussed above, for the purposes of integration and completeness, a highly simplified groundwater balance (Figure 2-20) will be incorporated in the mine water balance model with an appropriate relationship between the required level of complexity in the model structure, available data and the purpose of the model. Factors influencing the groundwater balance are briefly discussed below.

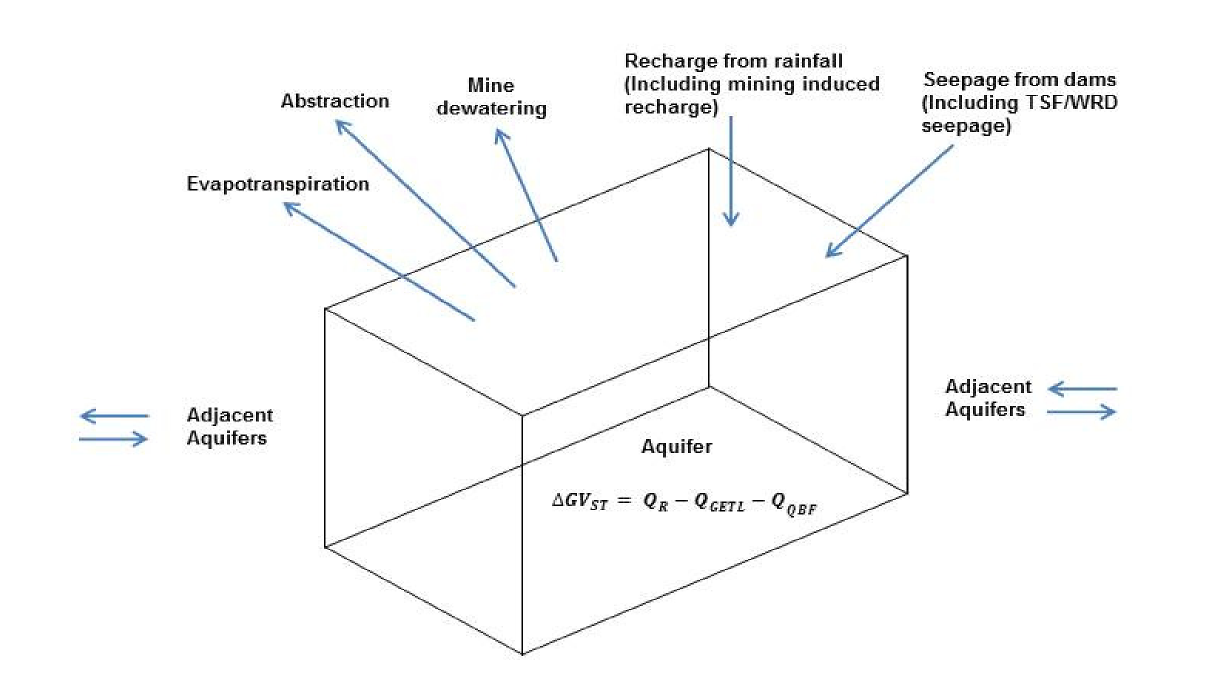

Figure 2-20 Simplified representation of a groundwater budget for a mining operation.

2.4.3 Modification of the hydrogeological regime

A modified hydrological system should be evaluated and potentially higher zones of recharge, also referred to as mining induced recharge, should be incorporated into an integrated groundwater and surface water management approach (Cogho, 2012). According to the BPGs of DWA (Pulles and van Rensburg (2006c), water is typically the prime environmental medium affected by mining activities with mining operations substantially altering the hydrological regime, subsequently affecting surface runoff, recharge and groundwater behaviour. Mining activities have a major effect on the hydrological regime and Ouyang and Elsworth (1993) found that mining-induced fracturing increases the hydraulic conductivity and porosity of strata and host rock which enhances hydraulic connections between aquifer zones. Changes concerning hydrological conditions are a process of learning to adapt to such changes and if managed from a strategic perspective, mining operations can adapt to the newly created hydrogeological characteristics (Rossi, 2009). By investigating and understanding such alterations, these conditions can be of great benefit to operations with water scarcity challenges as will be demonstrated.

2.4.4 Recharge

Water balances are of overriding importance when groundwater recharge and water losses need to be determined (Vermeulen and Usher, 2006). Evaluating a mining site in terms of potentially higher zones of recharge can proof valuable for water management purposes, especially in the determination of water fingerprinting and managing inflows into operations (Wolkersdorfer, 2005). Where geological conditions are prone to accepted water qualities, thus water generated is of acceptable quality, the potential to utilise so called spoil water for industrial applications exists (Wunsch *et al.,* 1999*;* Botha and Maleka, 2011). In his research on striving towards a "zero effluent mine", Cogho (2012) mentioned that it is important to note that significant portions of mined out open-casts, accumulate large quantities of water which is governed by rainfall recharge. Factors influencing recharge include geology, permeability, topography and vegetation as well as rainfall (Cogho and van Niekerk, 2009). Potential higher zones of recharge include the following disturbed areas:

2.4.4.1 Mining spoils

The increased permeability and porosity of broken rock materials, or spoils[14] replacing pre-existing solid rock, significantly increases the recharge and storage potential of the aquifer. In their investigation of groundwater movement in large mine spoil areas, Wunsch *et.al.* (1999) estimated a porosity of 20%. A distinction should be made between un-rehabilitated and rehabilitated spoil areas. The latter represents an area where disturbed conditions have been returned to stable, self-sustaining conditions (Wunsch *et al., 1999*) with suggested recharge rates as provided by Hodgson *et al.* (2006) as 8% of precipitation. Recharge on disturbed or un-rehabilitated spoil areas can range from 20% of rainfall for levelled areas, to 60% rainfall recharge for un-rehabilitated spoils (Cogho, 2012). In an investigation into recharge in South African underground collieries, Vermeulen and Usher (2006) confirm these recharge values. In contrast with coarse permeable zones of recharge, relatively impermeable and compacted zones are also produced within mining areas (Wunsch *et al.,* 1999). These zones include final compacted graded land surface, access and haul roads, which can inhibit water from infiltrating and recharging the phreatic water level.

2.4.4.2 Rehabilitated mining voids

Vermeulen and Usher (2006) estimated recharge percentage of rehabilitated opencasts as between 14% – 20% of the precipitation. The Australian Department of Industry, Tourism

[14] Mining spoils refer to waste material brought up during the course of an excavation or a dredging or mining operation and can accumulate large quantities of groundwater (Wunsch *et al.,* 1999).

and Resources (2006) also reported that the mean annual recharge for reclaimed ground is more than double that of undisturbed areas. Botha and Maleka (2011) estimated the porosity of backfilled mining voids at 30% and state that blasting and breaking of backfilled material, the effective porosity is close to the porosity ratios determined at 25%.

2.4.4.3 Waste rock dumps

Waste rock dumps refer to deposits formed by waste residue deposits and are characterised by dominantly coarse grained materials (Ogola *et al.,* 2011). Waste rock by nature is highly heterogeneous and its intrinsic physical properties are relatively well documented in literature (Smith *et al.,* 1995; Noël and Ritchie, 1999; Wunsch *et al.,* 1999). The hydraulic conductivity parameters considered for unsaturated scenarios such as waste rock dumps, are characteristically dominated by large uncertainties (Noël en Ritchie, 1999). Rapid underground water movement occurs at waste rock dumps after periods of high rainfall and the net drainage recorded at dumps amounted to 40% of the precipitation (Ogola *et al.,* 2011). Noël and Ritchie (1999) reached a similar conclusion and stated that the response time of a given waste rock dump *i.e.* time required for a water flux at the bottom of a waste pile to react to a change in flux at the top is relatively short, and can be observed within a couple of weeks. Smith *et al.* (1995) concluded that the internal response of the system is governed by the type of fluid flow regimes operating within the waste rock dump. Fluid flow within a waste rock dump is dominated by flow through a channel system and a partially saturated, porous matrix (Smith *et al.,* 1995). Studies carried out by Smith *et al.* (1995) are suggestive of rapid infiltration of water through waste rock piles, calculated at 50% of precipitation with a 5% porosity based on the relative response of water levels to precipitation. On the contrary, the Australian Department of Industry, Tourism and Resources (2006) estimated the porosity of fresh, coarse grained waste rock dumps as 25% and those of weathered, well-graded waste rock dumps as up to 60%. Golder Associates (2011) also suggest elevated recharge caused by spatial distribution of waste rock dumps. Wunsch *et al.* (1999) reported an estimated porosity of 20% for waste rock dumps and state that recharge occurs through macro pores at the spoils surface. The hydraulic conductivity will initially be low as percolation is limited by low hydraulic conductivity of the unsaturated zone (The Australian Department of Industry, Tourism and Resources, 2006). As the degree of saturation, aided by preferential seepage paths rises, so does the hydraulic conductivity and the ability to pass water. Infiltrated water discharges from the waste rock dump either as basal toe seepage collected in ditches and accumulated in a ponding system or enters the groundwater system beneath the dump (Morin *et al.,*1995). Low intensity rainfall events of less than 15mm are stored within the fine material of the waste rock dump with higher intensity events of more than 15mm being discharged (Botha and Maleka, 2011). An operating waste rock dump closes off any surface evaporation, while still allowing rainfall infiltration (Australian Department of Industry, Tourism and Resources, 2006). Rainfall infiltration is initially dominated by channelled flow after which, when saturation occurs, continuum flow will take over (Williams *et al.*, 2006). Rainfall infiltration will go into storage within voids and excess water infiltrating will emerge as toe seepage.

2.4.4.4 Chloride mass balance

Water catchment data is affected by large uncertainty, arising from sampling and modelling, which makes predicting groundwater recharge difficult (Diodato and Ceccarelli, 2006). Various methods for the estimation of recharge exist with the following methods to be applied with greater certainty in arid and semi-arid Southern African regions: Chloride Mass Balance (CMB) - based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface; Cumulative Rainfall Departure - based on the premise that water level fluctuations are caused by rainfall events; Extended model for Aquifer Recharge and moisture Transport through unsaturated Hardrock; Water Table Fluctuation; Groundwater Modelling - predict the aquifer piezometry under various groundwater stress situations and Saturated Volume Saturation. These methods have in common that they estimate recharge based on linking specific information from the atmosphere, unsaturated and saturated zones (Xu and Beekman, 2003). Due to its adaptability and simplicity, the CMB method for estimating recharge within the study area, was selected for the purposes of this investigation.

Since being initially proposed by Eriksson and Khunakasem (1969), the CMB method has been applied during recharge investigations worldwide in recent time (Edmunds and Gaye, 1994; Wood and Sanford, 1995; Bazuhair and Wood, 1996). For a steady state between the chloride flux at the surface and the chloride flux beneath an upper zone where evapotranspiration and mixing of rainfall and pore water takes place and excluding runoff and run-on, a site specific moisture flux can be calculated for the unsaturated zone (Eriksson and Khunakasem, 1969). The chloride method has been applied in different regions in South Africa and results from chloride profiles in the unsaturated zone portray a surprisingly consistent relationship between rainfall and potential recharge. A recharge flux can be determined as follows:

$$\boldsymbol{R\ (sm)\ =\ \frac{P \times C\ell\ (p)+D}{C\ell(sm)}}$$

Equation 2-11

Where:

R_{sm} = The moisture flux (mm/a);

P = Rainfall (mm/a);

$C\ell_p$ = Chloride concentrations in rainfall (mg/ℓ);

$C\ell_{sm}$ = Chloride concentrations in soil moisture (mg/ℓ); and

D = Total atmospheric chloride Deposition.

Recharge can be expressed in various forms, e.g. as a percentage of annual rainfall, or in mm/year (Beekman *et al.*, 1999). It can be determined by applying the following equation:

$$\textbf{Recharge volume} = \textbf{Area} \times \textbf{MAP} \times \%\ \textbf{Recharge}$$

Equation 2-12

Where:

MAP = mean annual precipitation (mm/a).

2.4.5 Mine dewatering

In his work, *De Re Metallica*, Georgius Agricola (1556) noted that excessive ingress of fissure water[15] was one of the main reasons for mine abandonment (Vermeulen and Usher, 2006). Dewatering plays a major role in providing a suitable and safe environment for the continuation of mining activities (Vermeulen and Usher, 2006). Mines operating below the water table are required to dewater around mine workings and this water is generally suitable for use, commonly utilised for process water (Gunsen *et al.,* 2012). Mine dewatering can significantly impact on water usage and is regarded as an important driver in a mine water balance (AGES, 2013). There exists an interaction between mine water supply and dewatering, and it is important to estimate and quantify groundwater inflow into mine workings for incorporation thereof into the mine water balance model (AGES, 2013). Effective mine water supply can determine the success and viability of any project and fissure water can serve as an economical alternative to sourcing external water for make-up requirements (Idrysy and Connelly, 2012). A key area of uncertainty for a mining operation is water supply, especially if a significant contribution can be obtained from mine dewatered

[15] Fissure water refers to groundwater accumulation and movement within joints and fractures of the matrix host rock.

water (Griffiths *et al*., 2009). Accordingly, hydrogeological investigations must be integrated with the overall mine water balance planning to obtain maximum benefit. Gunson *et al.* (2010) listed water resulting from mine dewatering as a typical external water source. Singh and Atkins (1984) also emphasise the significance of predicting water inflows into mine workings during the feasibility phase and the necessity for efficient design of mine water control systems. The water inflow during the life of mine (LoM) can be traced from groundwater seepage into the mine workings and the assumption is made that ingress of fissure water is dependent on groundwater recharge (Hanna *et al.,* 1994), however, groundwater inflows from storage can also make a significant contribution.

2.4.5.1 Analytical approach

Simple analytical equations for groundwater inflows can be informative during initial stages and an analytical approach in determining groundwater recharge can be used to get an estimate of recharge volumes to the mining area (Marinelli and Niccoli, 1999; Boshoff, 2012). Analytical as well as numerical models are based on mathematical calculations, with an analytical approach implemented for more simple scenarios. Although Singh and Atkins (1984) stated that analytical models are not as versatile as numerical models, Anderson and Woessner (1991) suggested considering an initial analytical based model rather than a more complex and labour intensive numerical model for estimating water flows for planning purposes. However, at more advanced levels of an investigation such as feasibility and detailed mine design, an analytical solution can be too simplistic and not accurate enough. A numerical approach and an analytical method are relatively similar (Hampton, 2013), while Fitts (2013) states that both solutions combine physical principles (e.g. Darcy's Law) with conservation of mass or volume. To get head values, numerical approximations are used in both approaches and are based on mathematical models which represent reality. For example, the Theis solution is analytical, but must be solved numerically. Many complex situations can best be addressed using numerical models, but using analytical models in conjunction with numerical models can ensure that important elements of the problem have been captured.

2.4.5.2 Assumptions and site specific conditions

When using an analytical method, assumptions are often made and usually provide a broad overview of what can be expected (Dennis, 2008). Singh and Atkins (1984) list the following idealised conditions which are valid for analytical techniques estimating groundwater ingress into mine workings: The extent of the aquifer is seemingly infinite; the aquifer is homogeneous, isotropic and uniform in thickness, the aquifer is pumped at a different discharge rate and the variations in diameter of the well do not affect draw-down and that the entire project area consists of a porous medium (Marinelli and Niccoli, 1999). In investigations on mining activities operating within the Bushveld Complex, Witthuser *et al.* (2009) characterise the regional aquifer system as a shallow weathered aquifer and a deeper fractured bedrock aquifer. This consequently places a limitation on the application of the above mentioned equations.

2.4.5.3 Flow equations

Several studies have historically been conducted to determine groundwater inflows into mine workings, evaluating numerous scenarios using analytical approaches. In their publication on idealised analytical techniques for predicting mine water inflows, Singh and Atkins (1984) refer to various equations for the estimation of dewatering volumes which are presented in Singh and Reed (1988), Hanna *et al.* (1994), Marinelli and Niccoli (1999) and Aryafar *et al.* (2007). Singh and Atkins (1984) also discuss analytical techniques to model groundwater inflows for different scenarios and aquifers.

(i) Case study scenario: Underground dewatering of a semi-confined aquifer

Aquifers within the Bushveld Complex are characterised by a shallow, perched aquifer and a deeper, semi-confined aquifer (Witthuser *et al.,* 2009). Singh and Atkins (1984) proposed the following equations for estimating underground water inflows for semi-confined aquifers:

$$\mathbf{Q} = \frac{\mathbf{2KLD}}{\mathbf{ln}(\frac{\mathbf{R}}{\mathbf{r}})}$$

Equation 2-13

$$\frac{\mathbf{R}}{\mathbf{r}} = \mathbf{0.88} + \mathbf{11.8}\ (\frac{\mathbf{B}}{\mathbf{r}})$$

Equation 2-14

$$\boldsymbol{B} = \sqrt{\boldsymbol{KLL'/K'}}$$

Equation 2-15

Where:

B = Leakage factor (m) = $\sqrt{(KLL'/K')}$;

D = Draw down (m);

K = Aquifer permeability or hydraulic conductivity (m/d);

K' = Hydraulic conductivity of aquitard (m/d);

L = Thickness of formation being dewatered (m);

L' = Aquitard thickness (m);

Q = Quantity of inflow (m^3/d); and

r = Radius at which draw down is required (m).

Transmissivity is the product of the hydraulic conductivity and the saturated thickness of the aquifer and according to Fetter (2001) can be given by the following equation:

$$\mathbf{T = bK}$$

Equation 2-16

Where:

b = Saturated thickness of the aquifer (m);

K = Hydraulic conductivity (m/d); and

T = Transmissivity of the aquifer (m^2/d).

2.5 Mine salt balance

A salt balance can be viewed as a management tool assisting in the determination of the mass of salts carried in a dynamic system and is also referred to as a mass balance. Changes in water management can involve changes in water quality, especially when the management strategy comprises water recirculation (McPhail, 2005). Water quality management by means of salt balances forms an essential part in strategic management and increased recirculation implies a lower dilution, hence the importance of determining the impacts on processing plant efficiency due to the higher salt loads (McPhail, 2005). Consequently, it is important not to implement water saving strategies purely on consideration of volume, but also to keep water quality in mind as inappropriate water qualities can result in mineral processing difficulties and delays (McPhail, 2005). Integrated water management must therefore not only be based on quantitative methodologies, but also include incorporation of qualitative methodologies. A lack of adequate linkages between water and salt balance modelling formulations has traditionally been seen as a major limitation in management plans developed for water quantity and quality assessment of mining projects (Golder Associates, 2011). The former approach, establish the baseline for qualitative salt balance integration. Under normal circumstances, when determining water balances, reference is made to the hydraulic balance, *i.e.* accounting for the total input and output volumes entering and leaving the system. Opposed to this system, a salt balance use the hydraulic balance to account for dissolved solids carried in flows.

The salt concentration may either refer to the total dissolved solids (TDS) or alternatively a specific chemical constituent, depending on the objectives of the salt balance. Cote *et al.* (2007) identified different water quality standards and assigned them to specific categories of inputs and outputs. Tasks tend to be grouped according to a broader purpose and are usually aggregated to simplify operating units and flows (SMI, 2012). Frequent water quality testing should, where possible, be taken over a long period of time to allow for seasonal variations (Gunson *et al.,* 2010). This approach is supported by the DWA BPGs (Pulles and van Rensburg, 2006a), applying the same basic principles to determine salt balances, *i.e.* salt load, which represent the conservation of mass across a system:

$$\textbf{Total}_{\textbf{Salt load in}} = \textbf{Total}_{\textbf{Salt load out}} + \textbf{Losses}$$

Equation 2-17

Where:

Salt load (kg/day) = Flow (m^3/day) x 0.001 x Salt concentration (mg/ℓ).

The following sections will elaborate on strategic water management and novel water use efficiency techniques for practical implications on mine sites.

2.6 Strategic water management

The second element considered by McPhail (2005) in simplifying mine water balances, is the improvement of water use efficiency techniques in the interest of reducing risk and costs. More stringent legislation and increased competition for available water, as more mines become operational or expand, are limiting the volume of water available in many areas with water use efficiency becoming progressively demanding (Howard, 2013). Effective mine water supply and management are components which can determine the success and viability of a project as poor water management poses an operational risk and can cause breaches of regulatory frameworks leading to financial implications (Idrysy and Connelly, 2012). Griffiths *et al.* (2009) validate this statement, mentioning that conservation of water has to be an important factor for costs, environmental management as well as corporate image. An effective mine water management system is defined as one that meets all operational constraints, maintains appropriate salt concentrations for worked water and adopts novel strategies leading to less water being used and more water being recycled (Cote *et al,* 2010). Water management strategies can be simulated by varying storage capacities, water imports, fraction of worked and fresh water at the intake of any task and salt tolerances (Cote *et al.,* 2010). Water management problems often arise after a 20–30 year mining period due to a lack in storage capacities (Vermeulen and Usher, 2006), which is caused by an increase of recharge and poor water quality. The core of better systems design revolves around two key concepts: Operating all processes at the highest solids density ratio possible and supplying all processes with the poorest acceptable quality water (Bagajewicz, 2000). These concepts should be managed and implemented without negatively impacting on the process performance.

Strategic management continue to be one of the greatest challenges facing mining operations and with little technical, high-level leadership regarding water saving strategies and management, solutions are left to individual mines (Bennett, 2009). Consequently, little information is available for the mining industry on best practise water use, or methods for maximisation of water use efficiency (Howard, 2013). This view is supported by the CERES investor coalition (2010) which state that the vast majority of leading companies working in water-intensive industries have weak water use management systems in place (Lambooy, 2010).The improvement of water system design and practice are key strategic requirements in moving towards a more sustainable mining industry (Gunson *et al*, 2012). In an investigation on achieving sustainable water use for mining operations, Gunson *et al.* (2010) stress that the first step towards improving mine water systems is to develop a good understanding of the existing system in place and the implementation of effective water metering technologies. This, together with an accurate mine water balance, is considered critical aspects (ERS, 2008; Mayer *et al.*, 2008; ICMM, 2012; Pulles and van Rensburg, 2006a). No effort should be undertaken in improving a mine water system until an accurate water balance has been developed (Gunson *et al.*, 2012).

2.6.1 Hierarchy of decision making

The South African Department of Water Affairs provides an excellent best practice guideline on mine water management, in which the authors, Pulles and van Rensburg (2006a), call for mines to optimally match water uses with required water quantity and quality. The water management hierarchy as set out in the DWA BPGs is based on the decades-old waste management hierarchy and establishes a clear priority order in which applicable management options must be considered. This forms the basis of implementing water management on mines with this approach to be considered as international best practice (Cogho, 2012). The priorities in terms of water management principles are keeping clean water clean; containing impacted water with low risk of spillage; maximising the re-use of impacted water within the mining environment; treatment of impacted water where it cannot be re-used without treatment; and finally discharge of water to the environment as permitted by local authorities (Cogho, 2012). Further investigation indicated that the key principle of effective and efficient mine water management is the requirement that all water conservation as well as pollution prevention options should initially be considered and exhausted before a shift is made to impact minimisation measures, water reuse and reclamation and ultimately, treatment and discharge as the last option (Pulles and van Rensburg, 2006c). These principles are supported by Bagajewicz (2000) and correspond closely to the concepts of the National Water Conservation and Water Demand Management Strategy as set out by the South African Department of Water Affairs (2004), which is based on the hierarchy of water management namely (Figure 2-21):

- Pollution prevention: Seek to reduce water where possible through efficiency measures, with waterless option;
- Re-use and reclamation: Seek to re-use and recycle water where possible in accordance with applicable regulations;
- Treatment: Treatment of impacted water where it cannot be re-used; and
- Disposal/Discharge: Seek to ensure that disposal and/or discharge of water does not cause degradation of the receiving environment.

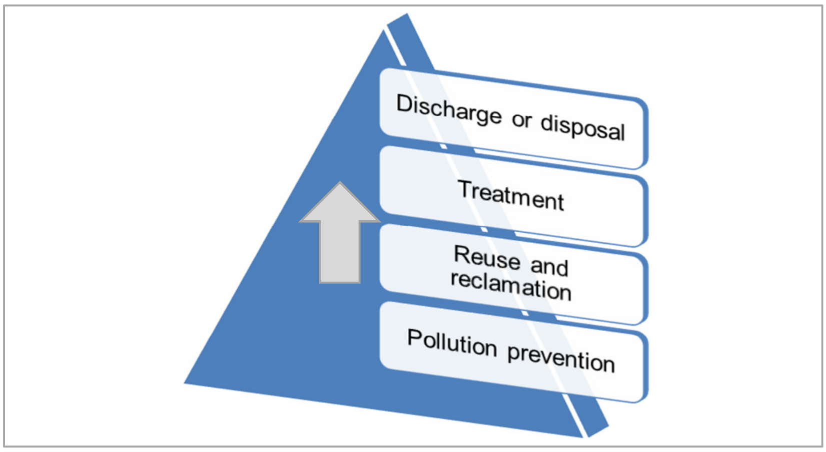

Figure 2-21 DWA hierarchy of decision making.

To follow is a brief overview on each level of the hierarchy as well as novel water use strategies to be implemented for each element.

2.6.1.1 Pollution prevention

According to the DWA hierarchy of decision making (Pulles and van Rensburg, 2006b), pollution prevention through reducing water usage should be considered as the highest ranking option. In their efforts to reduce mine water requirements, Gunson *et al.* (2012) recorded a number of options available for reducing mine make-up water use. By reducing the wet/open area of the TSF, Chambers *et al*. (2003) recorded significant water savings with careful management of the wet pond placement. Barrera and Oritz (2010) introduced the installation of underflow drains at the TSF and recorded a substantial reduction in water losses. Reducing concentrate moisture content as proposed by Soto (2008) results in improving filter performance to lower water losses and reduces concentrate shipping costs. Soto (2008) and Mayer *et al.* (2008) investigated the minimisation of evaporation through floating covers and results presented indicated a decrease in evaporation. General Electric (2006) reported dust suppression water savings of between 67% - 90% when making use of organic binders, while Kissel (2003) found that dust suppression by foam and fogging systems can dramatically lower water consumption. Thompson and Minns (2003) as well as ERS (2008), reported on studies where mining operations implemented of-the-shelf water saving techniques such as low water shower and toilet facilities and the effectiveness thereof. The above mentioned options can be applied with a high success rate, decreasing mine water consumption and consequently, decreasing the potential of pollution.

2.6.1.2 Reuse and reclamation

As mentioned before, there is an increased competition for water usage within the mining industry and steps towards more sustainability should involve the promotion of poor-grade water usage which agriculture and municipalities do not want (Kenrick, 2011). Kenrick (2011) discusses areas of concern for sustainable water management within the mining sector and lists maximising of water reuse as one of the greatest challenges of mine water management. With severe draughts and over-allocations of water imposing on mines to reduce their fresh water consumption, alternative water sources have been sought, including worked water. Recycling water to the mine reduces the overall water consumption and may also decrease the overall water treatment costs (Gunson *et al.*, 2012) with arid environments already considering reused waste water as a valuable resource according to Pedrero *et al.* (2010). Patrick McKelvey, Principal Hydrogeologist at Schlumberger Water Services, agrees with this statement, highlighting that the water management industry in mining is beginning to make use of non-optimal water *i.e.* saline instead of fresh water (Kenrick, 2011). Rio Tinto has taken the lead in this area, with well thought-out water management policies and has a group-wide water efficiency target of 6% reduction in fresh water used per tonne of product between 2008 and 2013 (Gunson *et al.,* 2012). Operations with beneficiation plants recycle approximately 26% of the total water budget (Pulles *et al.,* 2001). A barrier to increasing the use of worked water is caused due to a lack of information on its impacts. Increases in the salt concentration, which arise when recycling water, require effective water quality management (Cote *et al.,* 2010) as also reiterated by Bartosiewicz and Curcio (2005). Careful management must be applied to balance corrosion costs associated with using worked water, against the costs of treating water or alternatively, importing fresh water (Cote *et al,* 2010.). Little evidence exists of any relationship between mine production and the use of fresh or worked water and there are often no major process impediments to using recycled water (Cote *et al.,* 2010; Gunson *et al.,* 2010). Many water uses are insensitive to water quality and merely require a nominal volume of water with which to perform essential operations; however, for mineral concentration based flotation processes, a certain minimum quality must be maintained to recover economic percentages of mineral values at sufficient grade and keep the mine profitable (Mavis, 2003). Modern operations often recycle all their water and metal mines in Canada recycle a higher ratio of water than any other industry (Statcan, 2008). This high rate of reclamation is not a function of the required water per operational unit, but rather dependant on the volume of water lost to offsite waste water. Recycled water should therefore be considered as a less expensive alternative to water supply, substituting fresh water (Gunson *et al.,* 2010). Cooling water can be reused for a wide variety of water consumers and should not be discarded (Roberts *et al.,* 2008). Grey water can be reused as washing utilities in toilets or for watering of green space around the site with great success (Thompson and Minns, 2003). The effectiveness of reuse can be given by the following function:

$$\textbf{Reuse Efficiency} = \frac{\textbf{Sum of Worked Water Flows to Tasks}}{\textbf{Sum of All Flows to Tasks}}$$

Equation 2-18

2.6.1.3 Treatment

A general assumption can be made that the dirtier the source water and the more pure the required water, the higher the capital and operating cost of the treatment system to be installed (Gunson *et al.,* 2010). To prevent salt load build-up in the system, treatment of impacted water is inevitable, but more sustainable and environmentally friendly options to conventional treatment should however be considered. In his vast research on the topic of active treatment versus passive treatment, Walkersdorfer (2005) states that active treatment is cost and labour intensive and mines must therfore aim to decrease the time during which active treatment must be used. Though it is widely reported that extremely polluted mine water cannot be properly treated by passive treatment, the latter process can be implemented with high success rates (Brown, 2003). It is essential to determine when to make the transition between active and passive treatment processes from a strategic and cost benefit perspective (Mayes *et al.,* 2009). Until recently, active treatment dominated the mining sector due to its precise control, efficiency and relative minimal space required. Principal processes include oxidation dosing with alkali and sedimentary processes. Passive treatment technologies only developed within the past two decades and entail aerobic, compost and reducing alkalinity wetlands (Younger *et al.,* 2005). Although the more economical option, in contrast with active treatment, passive treatment processes usually take up space in order to function sufficiently (Younger *et al.,* 2005). Johnson and Younger (2006) have successfully applied the wetland passive treatment method for co-treatment of coal mine water and tertiary sewage effluent. This method of treatment has gained more popularity with regulating authorities because of wider environmental benefits, such as habitat creation and biodiversity. However, the argument of Quener and van Lanen (2001) in which they state that the effects of storing water in shallow wetlands have to consider evapotranspiration, must be evaluated to implement an appropriate strategy. The effectiveness of recycling can be given by the following function:

$$\textbf{Recycling Efficiency} = \frac{\textbf{Sum of Treated Water Flows to Tasks}}{\textbf{Sum of All Flows to Tasks}}$$

Equation 2-19

2.6.1.4 Disposal and discharge

The balance between the available storage of storm water retention facilities to handle flood events, and to sustain periods of low flow and management thereof, is vital (Thomas *et al.,* 2011). It is considered best practise to allow for discharging of storm water to a certain extent in order to conserve water for ecological needs (Pulles and van Rensburg, 2006a). Excess water to be discharged as a last option should be managed appropriately, ensuring that discharge qualities conform to water quality limits as specified by local environmental authorities.

2.7 Innovative thinking

Water demand has outgrown supply, and innovative thinking towards sustainable water management has become the benchmark. The mining sector have developed innovative ways to respond to water issues in differing circumstances which has illustrated the ability to turn risk into opportunity (Kenrick, 2011). This argument is supported by Medelin-Azuara *et al.* (2008) who state that changes caused by a dryer climate forced recent adoption of optimisation of water management systems. To follow is a brief overview of innovative management strategies and possible implementation of such strategies at mining operations. While not all of these options are suitable for every mining site, these scenarios outline how the industry could work towards significantly reducing its water requirements by creative thinking towards the future (Gunson *et al.*, 2012).

2.7.1 High density thickened tailings

In a comprehensive analysis on the physical perspectives of mine water by Younger *et al.* (2005), one of the main disadvantages seems to be the complex low-density sludge of by-product and techniques to increase sludge density (dewatering) are therfore adopted. In his published article on mitigating environmental impacts of tailings storage facilities, Fourie (2009) acknowledges the fact that high-density thickened tailings (HDTT) provide significant water savings when compared to conventional approaches[16]. This is due to lower seepage losses and groundwater contamination as a result of less moisture present in the deposited tailings and generally no supernatant pond. Thickened tailings or HDTT involves the mechanical process of dewatering low solids concentrated slurry (Fourie, 2003). Thickened tailings should not be confused with paste tailings, which comprise dense slurry that is pumped to its final storage facility using positive displacement pumps and which is usually a much more expensive method.

According to Fourie (2003) as well as McPhail and Brent (2007), HDTT provide significant water savings, at costs not entirely prohibitive compared to conventional approaches. In an attempt to determine what water saving benefits there lie in using thickened tailings technology, Anglo Platinum Limited initiated a campaign to demonstrate a pilot-scale project at the Anglo Mogalakwena South Concentrator Plant in South Africa. In results presented by Boshoff *et al.* (2010), it is indicated that for the Mogalakwena tailings substantial water savings can be achieved by discharging thickened tailings directly to the TSF. Conventional methods produce tailings with a solid content of 35 %m leading to an increase in water loss

[16] Conventional approaches of tailings disposal encompass slurry densities of 20-40 wt% and contain much larger water to solids ratios (Jambor and Blowes, 1994).

due to interstitial lock-up (Boshoff *et al.*, 2010). With thickening technology, a solid content of >65%m is achieved, leading to improvement of water consumption as the active pool size and hence the improvement of evaporation losses (Fourie, 2009). It should be stated that Boshoff *et al.* (2010) also indicated that thickening beyond a solid content of 70%m results in the recovering of incremental volumes of free water and has an insignificant effect on savings. This technology has been implemented worldwide from as early as the 1990's and the main advantages claimed for the technology include: Improved water recovery; improved TSF structural stability and reduced seepage to groundwater (Williams *et al.,* 2006). HDTT storage will become much more prominent in future as environmental regulations will tighten with increased pressure on the mining industry to become more sustainable (Welch, 2003).

2.7.2 Water reduction model

Gunson *et al.* (2010) describe potential water savings by applying key water reduction options and currently available off-the-shelf mining technology. The process can be summarised as follows: Ore is pre-sorted, rejecting more than 20% of ore and retaining a purer form. The flotation tailings are filtered to a solids content of approximately 80% and an organic binder is applied to all haul and access roads. All grey water derived from site is collected and directed to the process water tank. Dust suppression at the primary crushers is done by means of a fog system. Water tanks, concentrate thickeners and flotation cells are covered and tiles are placed on the tailings thickener, reducing evaporation by 95%. Lastly, concentrate is filtered to 93% solids by mass, minimising water losses. Installation of this combined system reduces mine water loss by approximately 74% (Gunson *et al.,* 2012).

2.7.3 Artificial recharge

The use of artificial recharge (AR) stores to counter decreasing water availability has been a practice for several thousands of years (Pandey *et al.,* 2003). Konikow and Kendy (2005) highlight a great need for and the potential to recharge depleted aquifers for the use of subsurface reservoirs. Introducing artificial recharge through infiltration basins has a positive effect on the groundwater available from storage (Wunsch *et al., 1999*). A site water management plan should include directing of runoff into infiltration basins, which will also help to minimise sedimentation of surrounding streams (Wunsch *et al.*, 1999). Bouwer (2002) and Dillon (2005) reviewed specific artificial recharge techniques and stated the increasing importance of this method due to the ability to store water for a long term period with fewer evapotranspiration losses compared to any surface bodies. Another advantage of artificial recharge is further purification taking place as soil aquifer treatment (SAT) (Ternes *et al.,* 2007). On the contrary, Dillon (2005) expresses some limitations of this technique in that it requires excess water to be infiltrated into sub-strata as well as available space for infiltration ponds and wells. It would be favourable to synergise storm water retention and managing artificial recharge (Martin-Rosales *et al.*, 2007; Tredoux *et al.*,1999). Botha and Maleka (2011) demonstrate the application of a man-made aquifer in an investigation on platinum mines in South Africa, whereby a backfilled mining void is used as an artificial aquifer to enhance water security. Major advantages includes cleaner water which requires less filtering as well as reducing electricity and water purification costs (Botha and Maleka, 2011). Further advantages include an increase in the assurance of supply, minimising evaporation and decrease of dirty water discharges. Mining activities alter the regional hydrogeological behaviour substantially (Pulles and van Rensburg, 2006c) and if backfilling is done correctly, old mining voids may in near future become major water reservoirs, easing the pressure on diminishing surface water resources (Botha and Maleka, 2011). The aim is to change the way the mine manages its groundwater and to bring groundwater into mining as a sustainable partner (Botha and Maleka, 2011).

2.7.4 Catchment management approach

A catchment management plan, collecting site precipitation and reusing surface runoff water, also referred to as rainwater harvesting, can significantly reduce offsite water requirements (Thomas *et al.,* 2011). Barrick's Buzwagi gold mine recently constructed a 75 ha high-density-polyethylene (HDPE) lined area for rainwater harvesting (Mayer *et al.,* 2008). Local catchments acting as basins for capturing rainwater are referred to as meso-scale catchments (Exbrayat *et al.*, 2010; Niehoff *et al.*, 2002) with a catchment being recognised as a natural unit for water resource management (Heathcote, 1998). In their generic water balance for coal mines, Pulles *et al.* (2001) state that rainwater harvesting can account for up to 3% of input water sourcing. The increase of sealed areas within mine sites influences low flows, which should be directed to facilities in order to contain water within the catchment (Thomas *et al.*, 2011). Although Keller *et al.* (2000) and van der Zaag and Gupta (2008) highlight several reasons against the establishment of large reservoirs, the variability in precipitation will increase, causing the need for excess water during rain events to be managed (Karamouz and Araghinejad, 2008).

2.8 Regulatory requirements

A mine water balance should be adapted to assess the performance of water management systems and by applying an environmental approach emphasis is put on regulatory requirements (Cote *et al.*, 2010). A mine water balance can be applied for auditing purposes as well as the assessment of licence conditions. It is important that water management be conducted in conjunction with local legislation and regulatory frameworks and as a result, the water balance and reticulation flow diagram should be integrated with regulatory frameworks (McPhail, 2005; Pulles and van Rensburg, 2006b). By doing this, compliance with authorisation conditions in terms of constraints such as discharge qualities and capacities, abstraction volumes and other licensing requirements can be assessed. Pulles and van Rensburg (2006b) considers a water balance as a vital part of any water use authorisation process and requires that all relevant information in terms of technical input to the authorisation process be included. An accurate water balance flow diagram, reflecting all relevant technical information necessary for the evaluation of a licence application, will consequently expedite and facilitate the authorisation process and provide a conceptual perspective of water uses to be authorised. As the case study is South African based, local water management regulations and statutory requirements will be discussed.

The Bill of Rights in the Constitution of the Republic of South Africa, 1996 (Act 108 of 1996) enshrines the concept of sustainability; specifying rights regarding the environment and water access, information and administrative action. The latter are further legislated through the National Water Act (NWA) of 1998 (Act 36 of 1998), forming the primary statute in providing the legal basis for water management in South Africa. This legislation has to ensure ecological integrity, economic growth and social equity when managing and using water. The use of water for mining and related activities is also regulated through regulations which were updated after the promulgation of the NWA (Refer to Government Notice No. 704 dated 4 June 1999) (Pulles and van Rensburg, 2006b).

2.9 Application and status quo

A mine water balance can be applied to achieve the following management measures as stated by McPhail, 2005; Pulles and van Rensburg, 2006b:

- Providing essential information assisting in defining and driving water management strategies;
- Auditing and assessment of water reticulation systems;
- Evaluating storage design to minimise the risk of spillage;
- Assisting with water management decision-making processes by means of simulation of various water management strategies before implementation thereof;
- Supporting the optimisation of water usage by identifying possible areas of loss;
- Pointing out wastage and inappropriate water utilisation;

- Identification of operating units where there's a shortfall in management practices and thus scope for improvement;
- Simulation of management options before implementation, pointing out the effects be it positive or negative;
- Assisting in water use optimisation and identification; and
- Localising and quantifying seepage, leakage or evaporation losses from potential pollution sources.

Limitations of a water balance model are dependent on the type of water balance selected for the specific purpose. In their investigation on the current status of mine water balances on South African mines, Pulles *et al*. (2001) found that there is a lack of detail contained in evaluated mine water balances. Pulles *et al.* (2001) established that incompleteness of water balances is reflected by the investigation's large percentage of water losses to unspecified sinks. The absence of good water balance data makes it difficult to draw meaningful conclusions about water usage patterns on mining operations and the state of mine water balances is poor with insufficient detail provided. This causes an equivalent problem with the status of water management on operations (Pulles *et al*., 2001). Primary problems include an inadequate consideration of the effects of seepage and evaporation losses as well as the effect of rainwater as an input to the water balance model (Pulles *et al*., 2001). Furthermore, the lack of appropriate water balances is believed to be a serious hindrance to effective mine water management and needs to be addressed as a matter of priority. Additional findings revealed that water balances are not being updated regularly and as an operational concern and reluctance from mines to provide data results in repeated requests for information. Generally inadequate water balances provided by mining operations require extensive manipulation of data by the project team and result in large percentages of unspecified water sources and sinks.

It is believed that mining operations will benefit greatly from a simplistic, computerised water and salt balance model, capable of easy updating data reflecting a change in reticulation patterns (Pulles and van Rensburg, 2006). Jack Caldwell (2006) from the InfoMine Mining Intelligence &Technology Group in the USA compiled a checklist for a water balance model from an industry perspective and summarised crucial aspects as the following: (i) Model: It is important to have an effective and calibrated water quality and quantity (volumetric flow) model which is easily updated and adjusted. This will lead to a better understanding of complex relationships between infrastructures, resulting in an accurate prediction of water changes; (ii) Measurement: An effective sampling system must be in place to keep the quantity and quality up to date and continuously evaluate the effectiveness of applied assumptions. The significance of accurate flow measurements is highlighted with Mayer *et al.* (2008) also emphasising the importance of effective water metering technologies to be in place; (iii) Calibration: The model should be calibrated and monitored on a monthly basis on discrepancies between reality and the model outcome, accordingly investigating any discrepancies; (iv) Management: All actions to be taken to minimise water quantity and quality must be fully appreciated and implemented when pre-specified levels are reached. Taking ownership of a water balance is vital with McPhail (2005) referring to a water balance-owner or custodian, required to compile and maintain an accurate water balance model. In future, proposed pricing strategies and waste charges will force mining operations to manage water resources responsibly (Pulles and van Rensburg, 2006b) and if mining operations are to maximise the benefit of a water balance model, a skilled owner need to be matched to the specific water balance models (McPhail, 2005).

Basic water balances falls well within the skill and capabilities of environmental officers while a predictive water balance require more experienced environmental personnel, depending on the complexity of the model. Predictive water balances can easily be compiled by a person with an engineering background, again depending on the detail required for the model. Probabilistic, predictive water balances, requires a person comfortable with statistics as well as probabilities, due to the variability of the model setup. Mining companies often choose to outsource this task due to capacity and time constraints (McPhail, 2005). In his conclusion on tailings and paste management, McPhail (2005) focuses on the aspect of an appropriate water balance owner, ensuring that succession planning has the water balance being transferred from a generation of owners, updating and implementing the water balance recommendations.

2.10 Discussion: Chapter 2

This chapter provided an overview of published literature concerning the quantification of mine water balances, with emphasises on what influences from the natural system can be expected and how it should be incorporated into an adapted mine water balance methodology. From the literature review, it has become apparent that an accurate water balance is considered imperative for mine water management, with a systems modelling approach, focussing on the system as a whole, forming the basis of an effective management strategy.

It is identified that mining operations encompass two water systems, namely: process system water, representing all site water, and natural system water, associated with the intrinsic hydrological cycle. The main argument is that natural system water is often disregarded and underestimated during calculations and estimations, however can significantly impact on mine water usage and losses. Accordingly, it is recommended that decision making and management options should be based on the evaluation of the system as a whole, and inclusion of the natural system as a component of the mine water balance is imperative for accurate quantification and predictions of site conditions. The natural system is furthermore considered and it is highlighted that, although this system encompasses a surface water environmental circuit and a groundwater environmental circuit, components of hydrology and hydrogeology must not be viewed in isolation from each other, as interaction between these systems is required to facilitate effective resource management. The latter can determine the success and viability of any project and even with a comprehensive understanding of the interaction and dependency of different systems, inadequate water management poses an operational risk to mining operations. The key principle pertaining effective mine water management is to implement novel water use efficiency techniques with innovative thinking towards sustainability.

The following chapter provides a step-by-step methodology for the development of an adapted mine water balance, with incorporation of water from the natural system, a description and evaluation of data input to the water balance as well as applicable data sources used.

Chapter 3

3 DATA

Data acquisition and collation, facilitating the development of a mine water balance, are extensive processes due to the number of variables taken into consideration. It cannot be overstated that the integrity and accuracy of a water balance is dependent on the accuracy of data. The current state of mine water balances is poor with insufficient detail provided, and accordingly it is important to collect accurate field data and make use of reliable techniques for effective water management. This chapter will elaborate on data collection and a methodology for developing an adapted mine water balance model, quantifying and incorporating water from the natural system, is discussed. A list of data sources and descriptions is also provided.

3.1 Objectives

The objective of the data acquisition phase is to gather and prepare data for interpretation, aiding in the compilation of an overall mine water balance.

3.2 Methodology

3.2.1 Mine water balance

The Minerals Council of Australia (MCA) initiated a water accounting project that has been undertaken as part of a research assignment in conjunction with the Sustainable Minerals Institute (SMI) (2012) at the University of Queensland (2007-2011). This allows for mining sites to not only account for, but also report and compare site water management practices from a water balance approach (SMI, 2012). Parallel to the Water Accounting Framework (WAF), the DWA of South Africa has published Best Practise Guidelines (BPG G2) which also set out the general principles to consider when developing a water and salt balance (Pulles and van Rensburg, 2006b). Following is a brief overview on a step-by-step methodology in developing an adapted mine water balance.

3.2.1.1 Define water balance objectives

The initial step in compiling a water accounting framework is to define the objectives of the mine water balance. Important aspects to consider include model boundaries, level of detail required, target areas as well as the type of water balance for the operation.

3.2.1.2 Define system boundary and operating units

It is imperative to develop a clear understanding of the boundaries of the system under investigation and to provide an accurate representation of all water supply facilities and reticulation. Model boundaries must be evaluated from a systems approach and expanded to incorporate influence from the natural system due to a modified hydrological regime.

3.2.1.3 Facility and flow representation

According to Golder Associates (2011) a flow diagram is an essential component in developing a water balance model. Water circuits and waste facilities should be presented schematically as a dynamic flow diagram representing the reticulation system and all water flow paths. This diagram will help to identify simulation building blocks required to represent water management infrastructure and will also assist with the authorisation process. It is necessary to assign each water flow within the reticulation system to a status of raw, worked or treated water. By doing this, the reuse and recycling efficiency can be determined. Water flows represented within a flow diagram are based on a conventional colour coding system:

- Clean/raw water is coloured blue;
- Dirty/worked water is coloured orange;
- Tailings/sludge is coloured brown;
- Treated water/effluent is coloured purple;
- Entrapped water in ore/product is coloured black;
- Precipitation is presented as a dotted, blue line;
- Evaporation is presented as a dotted, orange line; and
- Seepage is presented as a dotted, green line.

Facilities are represented as follows:

- Closed component facilities (not exposed to seepage and/or evaporation) are represented by solid boundaries; and
- Open component facilities (exposed to the atmosphere with evaporation and seepage influencing storage volumes) are represented by dotted boundaries.

3.2.1.4 Data collection and monitoring

As stipulated by Gunson *et al.* (2010), typical data collection for the compilation of a mine water balance includes the determination of the RoM tonnage, ore and product water content (verified through sample testing and analyses), rheological properties of tailings, employee numbers, recorded flow rates (input and output volumes), capacity and areas of facilities, seepage/evaporation determination (including water losses in tailings), historical precipitation distribution, site characterisation in terms of disturbed/undisturbed areas and hydraulic parameters as well as site and water quality for specific identified circuits. In order to provide a more representative reflection of the natural system, climatic data should be subjected to probability distributions before input.

3.2.1.5 Accounting for data uncertainty

Data uncertainty is accounted for by statistical analyses and probability distributions. Site specific assumptions are also made to aid in quantifying uncertainties arising.

3.2.1.6 Balance per unit

Each task performed within the mining operation will either be grouped together, or kept separately as an operating unit. Assign the input and output values to specific units and develop equations for solving of the separate water balances.

3.2.1.7 Water quality description

In order to integrate water quality assessment, a salt balance must be developed. Assigning water quality categories to each input and output within the system will provide the means to compile a salt load distribution. TDS can be used as a measure for general water quality, while specific chemical constituent concentrations can be used depending on the application of the balance.

3.2.1.8 Incorporating natural system water

Decision making and management options should be based on the evaluation of the system as a whole and the inclusion of the natural system as a component of the mine water balance is imperative for accurate prediction of site conditions, hence management. Thus water from both the process and natural systems should be incorporated as part of an integrated approach. Apply water balance assumptions and quantification formulations for an accurate representation of site conditions.

3.2.1.9 Operational efficiency

Efficiency is a function of the proportion of reused and recycled flows in relation to the total flow/input into a specific task and can be calculated by applying Equation 2-18 and Equation 2-19. By doing so, a water use efficiency range can provide an indication of water management.

3.2.1.10 Contextual statement

Background on water resources, facility and climatic conditions and any other conditions which may impact on the management thereof, should be recorded in a contextual statement along with the water balance model. This can include a brief description of the geographical terrain, catchment details, climatic conditions, assumptions and water policy details and allocations if applicable.

3.2.1.11 Model calibration

In order to use the water balance model as an accurate water management tool, data validation and model calibration is imperative. Predictions can only be substantial if simulations correspond to and reflect real time on-site conditions. Calibration is obtained by comparing estimated results to measured data and by using the least squares method in calculating a correlation coefficient in order to compare representativeness and accuracy ($R^2 > 0.9$). Calculated water balance mine make-up water requirement for each component of the reticulation system must therefore be compared to the data ranges and actual flow meter data in order to calibrate water balance input data as part of an on-going process.

3.2.1.12 Integration of strategic management

As mentioned before, strategic water management can determine the success and viability of a project as poor management poses an operational risk and can cause breaches of regulatory frameworks leading to financial implications. Accordingly, integrating strategic management with the mine water balance will produce a powerful tool aiding in guidance for planning purposes.

3.2.2 Checklist

Cote and Moran (2010) issued a water accounting framework checklist aiding in mine water management and compiled a complete list of the information required in order to develop such an account or water balance, as indicated below (SMI, 2012):

- Flow charts for water flows;
- Information on water storage and capacities;
- Flow volumes and qualities;
- Surface areas, including proportion of undisturbed and disturbed areas;
- Task list with average water demand;
- List of water sources, including volumes and quality;
- Discharge volumes and quality of any water leaving the site boundary;
- Tonnage of ROM to the concentrator with the ore moisture content; and
- Estimates, simulations or measurements for uncertain parameters including seepage, rainfall, runoff and evaporation.

3.3 Data collection

Site characterisation is necessary to determine aquifer parameters for input into dewatering predictions as well as recharge calculations. Field investigations conducted include a geophysical survey for borehole siting, drilling of two site characterisation boreholes within disturbed and undisturbed areas as well as aquifer testing of suitable boreholes.

3.3.1 Geophysical survey

Suitable drilling positions for site characterisation boreholes were located by means of a geophysical survey followed by analyses and interpretation. Methods used for this investigation included the electromagnetic (EM) method as well as the direct current (DC) resistivity method as prescribed according to the South African National Standards (SANS 10299-1:2003).

The Electromagnetic method measures the conductivity of host rock. The application in groundwater exploration can be found in the fact that there is a relationship between the conductivity of a formation and the porosity thereof, the connection between pores, the volume of water in the pore and the conductivity of the water in the pore (Macmillan, 2004). The Geonics EM34-3 geophysical apparatus was used with a 20 m coil separation in order to measure and determine the apparent conductivity.

The direct current resistivity method is based on the behaviour of the flow of an electrical current in the subsurface of the earth’s crust. The resistivity meter comprises two current probes, and two voltage probes. An apparent resistivity can then be calculated using the voltage and the induced current values. A Wenner array was used with a 5 m electrode spacing.

3.3.2 Drilling

Drilling was done according to the SANS standard (SANS 10299-2:2003). Air percussion drilling was used as the drilling technique utilised to compress air to transport rock cuttings to surface. A percussion hammer attached to the drill string pulverises the rock or material below, and then blows it back up the annular space of the borehole to the surface. Boreholes where water strikes were encountered were cased and developed accordingly.

3.3.3 Aquifer test analyses

Boreholes which indicated adequate blow yields were subjected to aquifer testing in order to determine aquifer parameters. Aquifer testing is conducted by means of a pumping test which is a practical, reliable method of estimating well performance, well yield, the zone of influence of the well and aquifer characteristics (*i.e.*, the aquifer's ability to store and transmit water, aquifer extent, presence of boundary conditions and possible hydraulic connection to surface water). A pumping test entails the pumping of groundwater from a well, usually at a constant discharge rate, and measuring water levels in the pumped well and any nearby wells (observation wells) or surface water bodies during and after pumping. Accordingly, this data is used to plot drawdown and recovery graphs for interpretive evaluation (Sterrett, 2007) (Refer to Appendix B3).

3.4 Data sources

A summary and description of data sources are provided in Table 3-1. Data was acquired from Xstrata Eastern Mines Ltd. as well as from external sources.

Table 3-1 List of data sets and sources.

Data set	Source	Description
Rainfall data	WRIMS Database (DWA, 2005).	Rainfall data from 1904 to 2014 for weather station 0548280W, Lydenburg.
Evaporation data	DWA Internal Strategic Perspective – Olifants WMA, Report no. PWMA04/000/00/0304.	Overview of water resource management of the Olifants WMA and applicable data sets.
Runoff coefficients	WRC2005 Report (12/2008).	Evaluation of water resources of South Africa compiled by the Water Research Commission.
Recharge coefficients	Institute for Groundwater Studies (IGS), UFS, Report no. 2006/012/FDIH.	Investigation conducted by Hodgson, F, Lukas, E, and Vermeulen, D on recharge of disturbed areas.
Geological data and maps	Geological survey, Council for GeoScience.	1:250 000 Geological map sheets 2430 Pilgrim's Rest.
Aerial images	Google™ Earth.	Aerial images and a birds-eye view of the greater study area.

Data set	Source	Description
Topographical GIS data	Chief Directorate of Surveys and Mapping.	1:50 000 map sheets and data for 2430.
Digital terrain model (DTM)	Digital data (AGES (Pty) Ltd).	DTM data (XYZ format) for 20m contour intervals.
Site characterisation data	AGES (Pty.) Ltd. Technical report no. AS-R-2008-12-08.	Technical report on site characterisation including geophysical data, drilling data and aquifer testing analyses.
Site layout and reticulation	Xstrata Eastern Mines Limited conceptual layout drawings.	Layout of site infrastructure and reticulation.
Surface water management plan	Xstrata Alloys: Thorncliffe Mine surface water planning, RedCo 2008.	Evaluation and assessment of a site storm water management plan.
Groundwater monitoring data	Client monitoring database AGES (Pty) Ltd.	Macro- and Micro chemistry and Microbiological parameter data and Water levels from June 2008 to June 2012.
Product moisture content	Xstrata Eastern Mines Limited data provided.	Estimation of moisture content of concentrated metallurgical grade and lumpy chrome product.

3.5 Data description

3.5.1 Precipitation

Historical rainfall records were retrieved using the Water Resources Information Managing System (WRIMS) Rainfall Model provided by the DWA. Rainfall data was sourced for station reference 0554786, situated in Lydenburg and covering a period from the year 1904-2012 (Figure 3-1) as listed in Appendix A. The analysis of data was conducted by applying risk analysis and simulation add-in packages for Microsoft Excel®, @Risk®. The result of the @Risk® Monte Carlo probability simulation of the data is a distribution of data within the 90% probability limits, which equates to statistical confidence limits of 95%, as indicated in Figure 3-2. Accordingly, data was used to evaluate rainfall trends and simulate extreme periods of flooding and drought events. The mean annual precipitation (MAP) is 646 mm, with the maximum rainfall of 1 076 mm in 1939 and a minimum of 236 mm recorded during 2007. The standard deviation is 171 mm/a, which is 27 % of the average, indicating that rainfall data is variable. The data set was also used to calculate dry and wet cycles for one in twenty year events, representing the 5th and 95th percentiles respectively. The upper 95% assurance level indicates a 0.95 certainty that 95% of the values fall below this level whereas for the lower 95% assurance level, 95% of the annual values fall above this level. The one in twenty year drought event was calculated at 374 mm/a, with the one in twenty year flood event calculated at 913 mm/a. As expected of a summer rainfall region, months contributing most to rainfall volumes include December to March (Figure 3-3). Results for the statistical analysis of rainfall data are shown in Table 3-2.

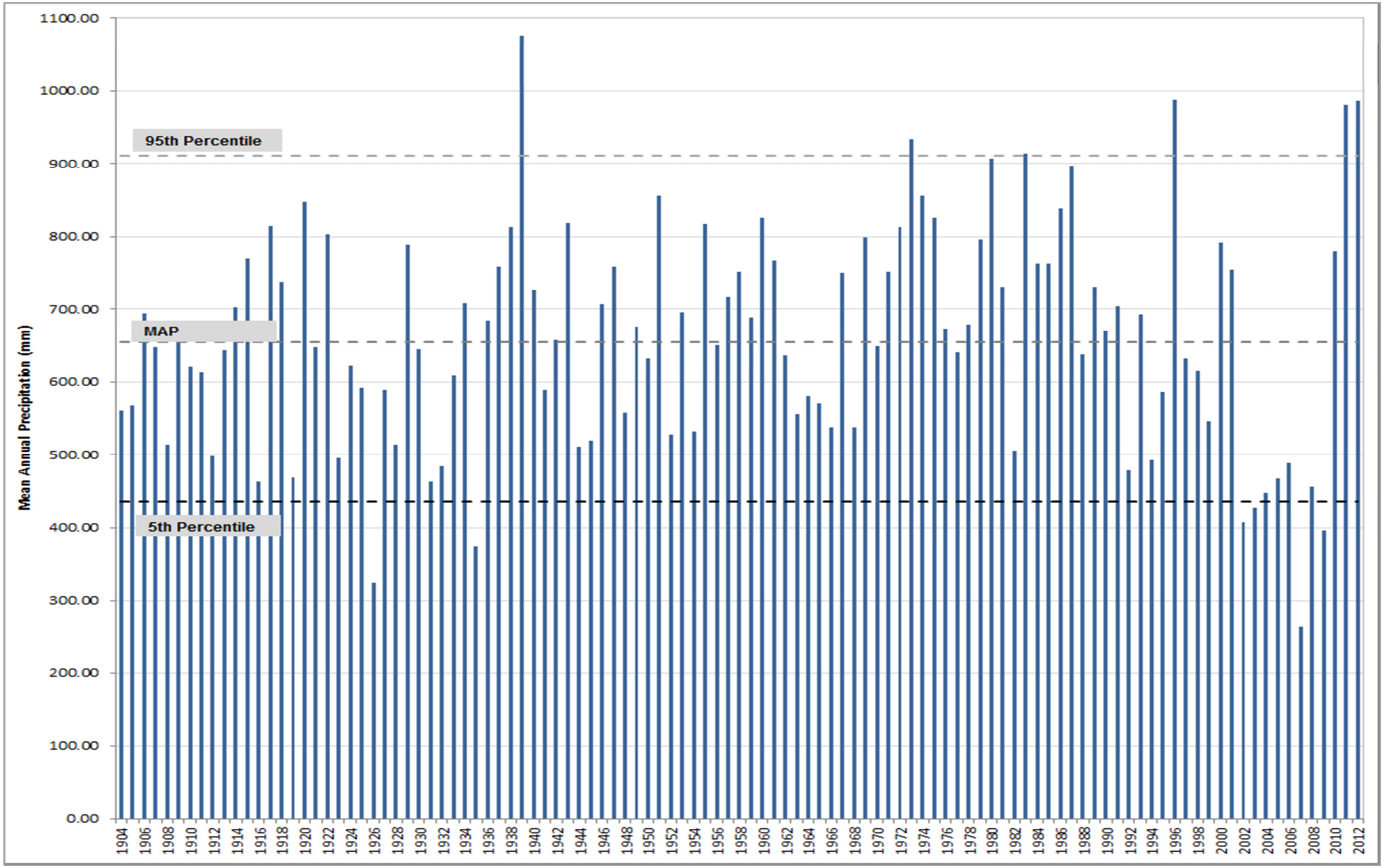

Figure 3-1 Distribution of annual rainfall data recorded (1904 – 2012).

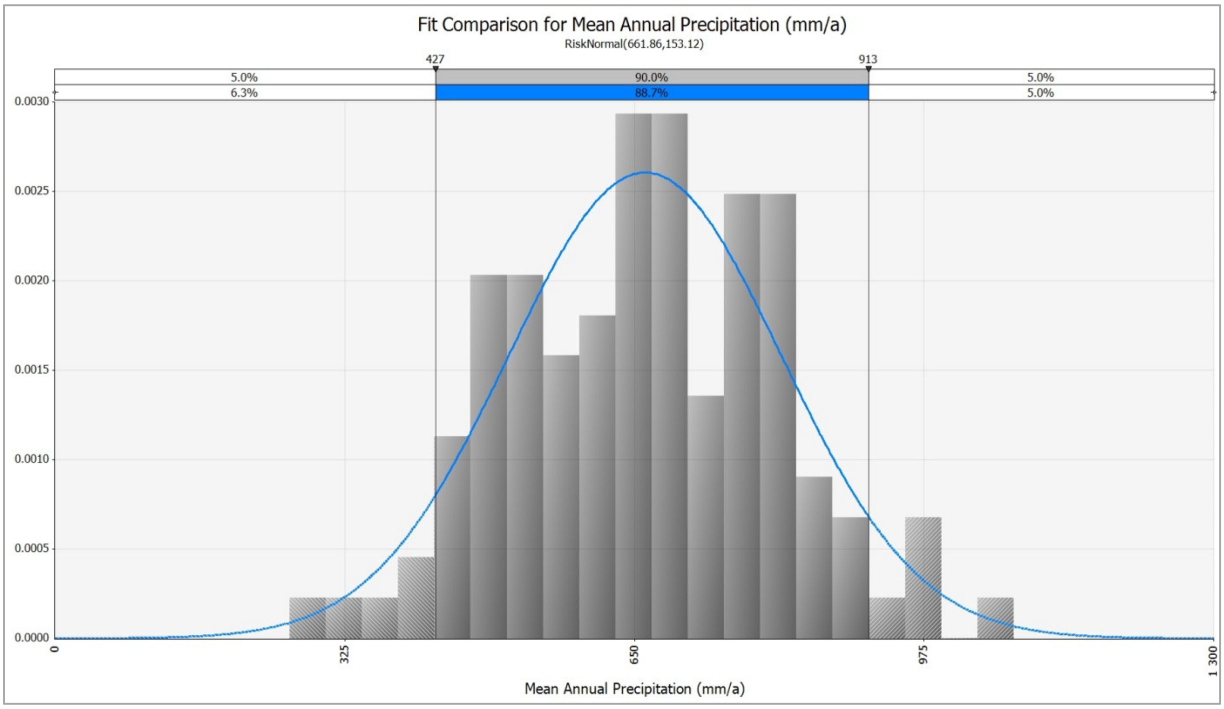

Figure 3-2 Annual rainfall data distribution (1904 – 2012).

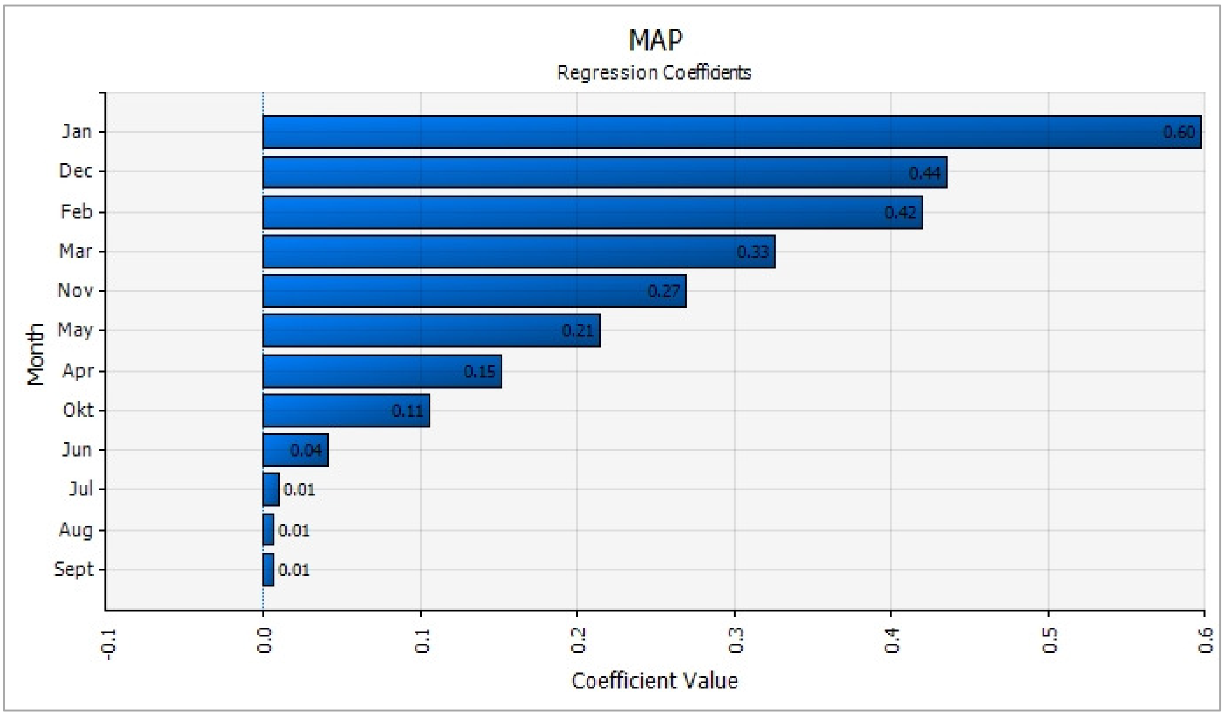

Figure 3-3 Monthly rainfall data regression coefficients (1904 – 2012).

3.5.2 Evaporation

Monthly evaporation data per quaternary catchment (Table 3-3) was obtained from the International Water Management Institute (IWMI) (2004) and was developed as part of a benchmark basin study (Molle 2002). The mean annual evaporation (MAE) is 1 957 mm, with the maximum monthly evaporation of 200 mm occurring in December and the minimum of 107 mm recorded in June. Results for the statistical analysis of evaporation data are shown in Figure 3-4. This figure also allows for a comparison between monthly rainfall values and monthly evaporation values. The MAE is more than three times the MAP and it is clearly visible why evaporation is considered one of the main drivers for a water balance and should definitely be taken into account. The purpose of the statistical analyses is to constrain the MAP and MAE, or base case to which the flood and drought events can be compared. Using a Monte Carlo probabilistic statistical model, rainfall distributions are used in the calculation of rainfall volumes on specific surfaces, runoff and seepage, rather than single values. Therefore, the 95% confidence levels are contained in the data distribution of the calculated results. These probability simulations were used to determine data range boundaries.

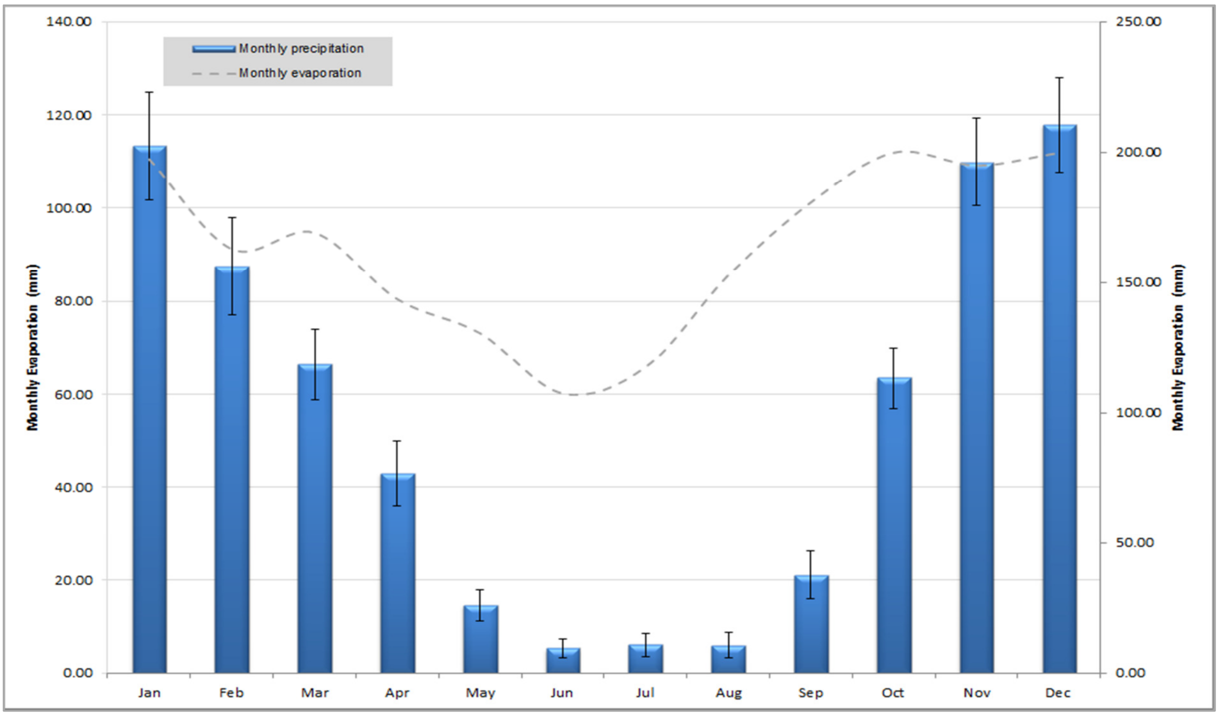

Figure 3-4 Monthly evaporation data corresponding to rainfall distribution.

Table 3-2 Monthly rainfall statistics.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	310.40	292.10	193.30	166.80	73.50	62.40	75.20	100.60	140.80	170.40	279.50	294.10
Minimum	13.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.80
Average	113.40	87.43	66.40	43.00	14.67	5.29	6.10	5.92	21.18	63.44	109.92	117.92
Standard deviation	60.85	54.45	39.88	36.53	16.77	10.45	12.99	14.48	26.48	34.02	49.36	53.23
1:20 year flood	227.66	183.84	142.04	117.06	51.04	27.82	30.56	29.28	80.64	116.12	195.02	228.64
1:20 year drought	35.76	16.70	15.66	0.40	0.00	0.00	0.00	0.00	0.00	14.10	38.70	44.58

Table 3-3 Monthly evaporation statistics (Schulze *et al.*,1997).

Month	A-Pan Evaporation (mm)
Jan	197.40
Feb	162.90
Mar	169.10
Apr	143.60
May	130.60
Jun	107.40
Jul	117.50
Aug	152.80
Sep	180.80
Oct	199.90
Nov	195.00
Dec	199.90
Total	**1956.90**
Max	**199.90**
Min	**107.40**
Average	**163.08**
Standard deviation	**33.00**

3.5.3 Site characterisation

3.5.3.1 Groundwater levels

Water level data is relevant to determine the flow regime of the local groundwater system and movement within the substrata. Twenty six (26) on-site water levels were recorded of which 24 represented static water levels (SWL) measured (data used to determine average regional water levels) and two being dynamic due to abstraction (Figure 3-5). As indicated, a distinction can be made between a shallow, weathered aquifer (0 - ~18 metres below ground level (mbgl)) and a deeper, fractured aquifer (>18 mbgl) with a maximum water level of 56.5 mbgl recorded for BHMS2 and a minimum water level of 2.26 mbgl recorded for BHMS4. A mean regional water level was calculated at 11.27 mbgl with a standard deviation of 12.9 mbgl. Hydraulic head elevation was compared to topographic elevation and indicates a good correlation (R^2>0.9) (Figure 3-6). Water levels were measured during a site visit and a distribution of regional hydraulic head contours as well as expected groundwater flow directions, are indicated in Figure 3-7.

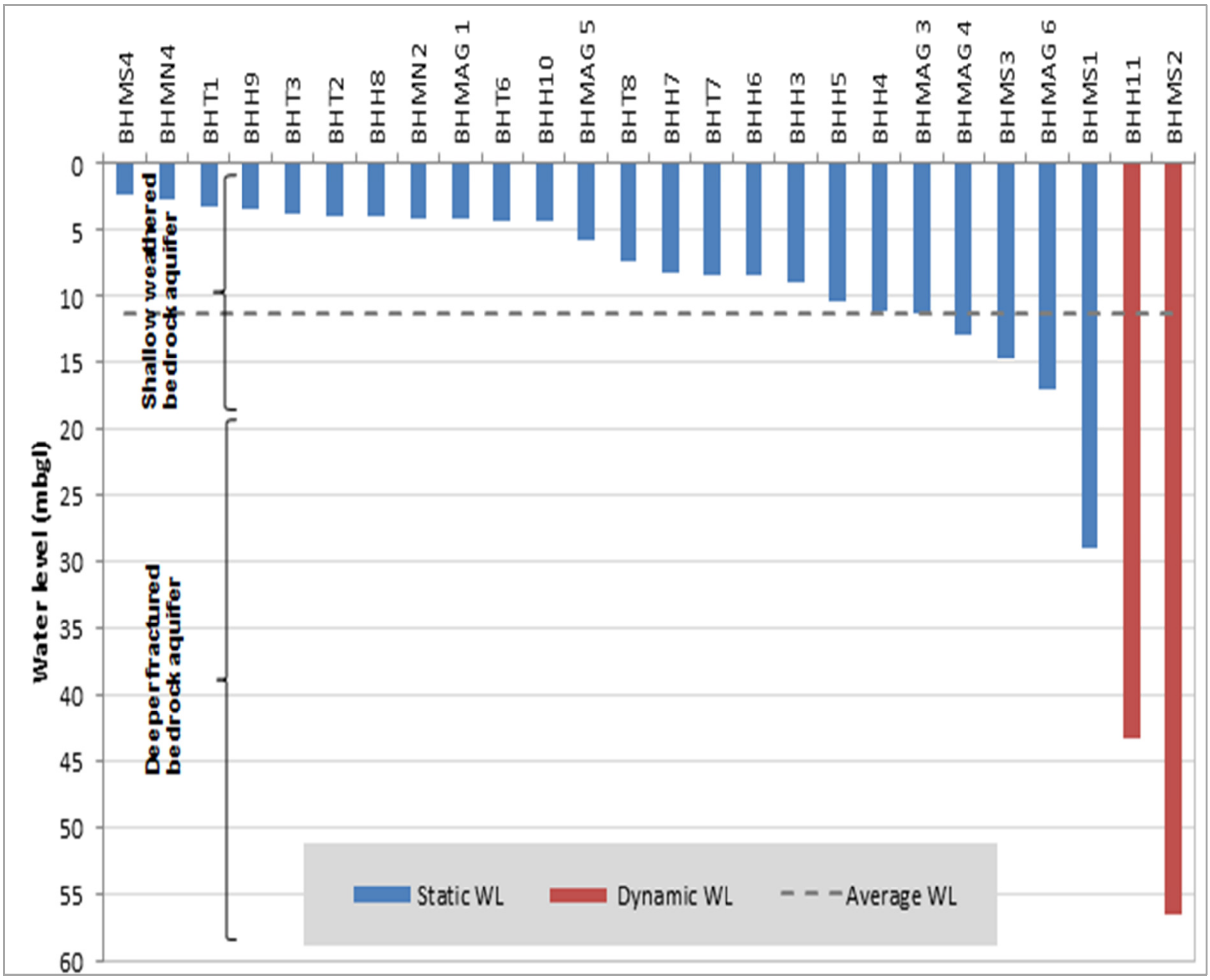

Figure 3-5 Distribution of regional groundwater levels.

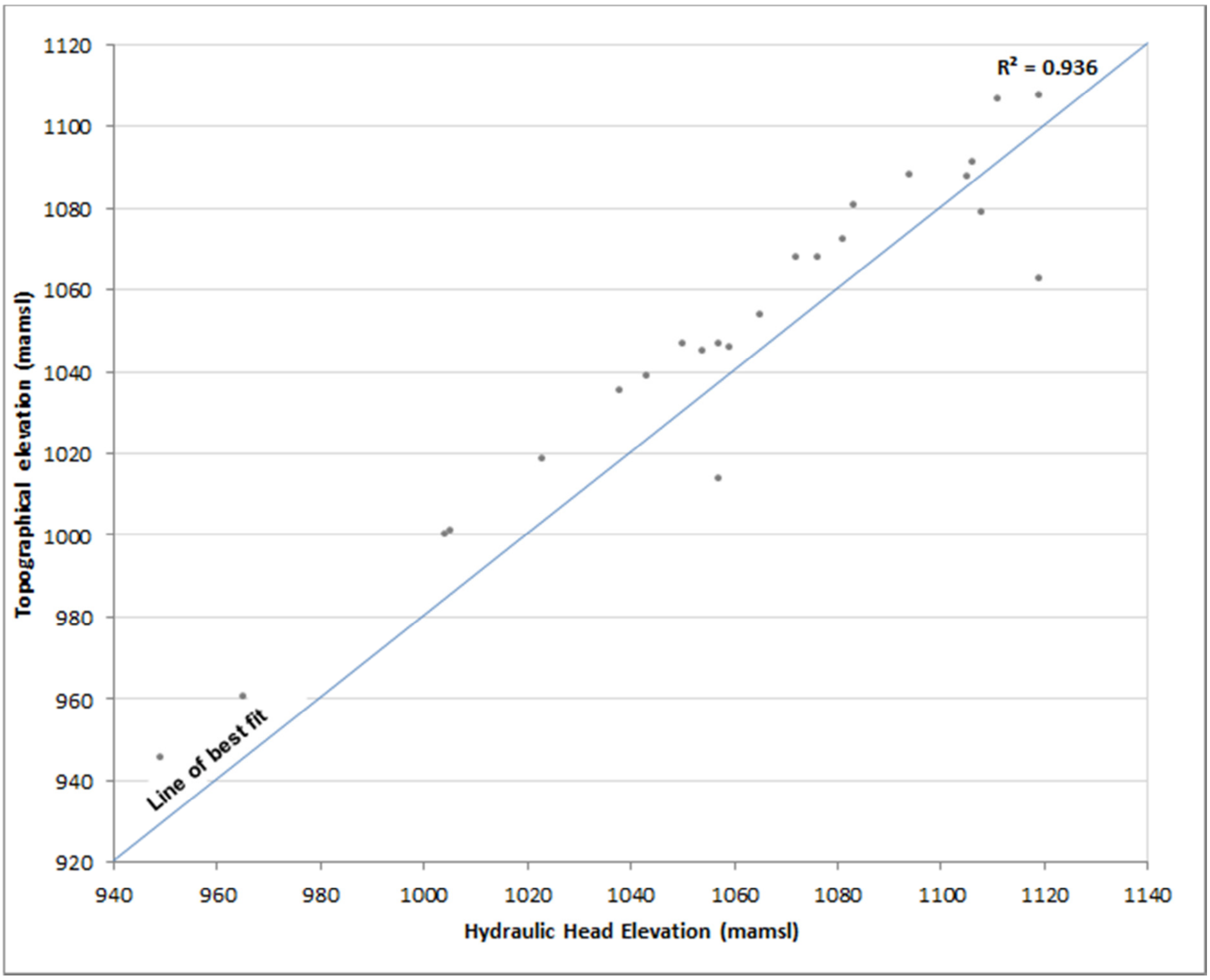

Figure 3-6 Correlation of hydraulic head elevation vs. topographic elevation.

3.5.3.2 Geophysical survey

A geophysical survey was conducted to determine suitable drilling positions for site characterisation and monitoring purposes. Five geophysical traverses were conducted using electrical soundings as well as DC resistivity methods (Figure 3-8). BHT6 was cited on line 1, station 13, on the northern perimeter and weathered zone of structural activity represented by a high resistivity zone (Figure 7-1) and BHT7 was cited on line 2, station 6, in a low resistivity zone represented by the backfilled area (Figure 7-2). No drilling sites were identified on lines 3 to 5 (Refer to Appendix B1).

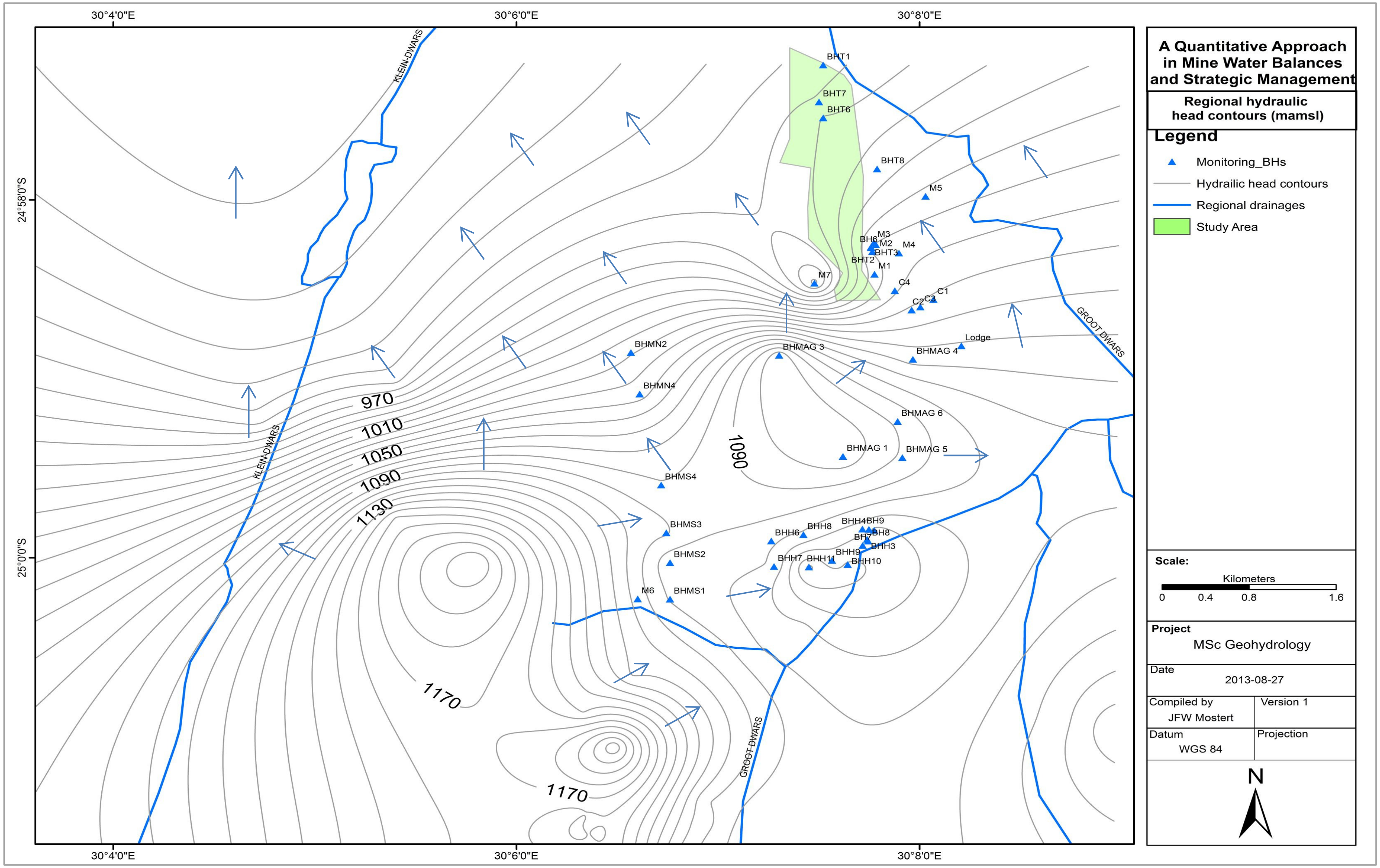

Figure 3-7 **Regional hydraulic head contours for the greater study area with groundwater flow directions.**

3.5.3.3 Drilling

Boreholes were sited at targets as illustrated in Figure 3-9. The boreholes were drilled to a depth of 30 mbgl (representing the depth of the backfilled pit/disturbed area) with solid steel casing installed from surface to 6 mbgl, and perforated steel casing from 6 mbgl to 30 mbgl. A gravel pack was installed over the perforation, with a cement sanitary seal over the solid steel casing. A concrete collar were installed and the boreholes were sanitised, capped and marked (Refer to Appendix B2).

BHT06: Pyroxenite was intersected for the entire length of the borehole with highly weathered pyroxenite topsoil from 0 – 3 m, slightly weathered pyroxenite from 3 m to 19 m and fresh pyroxenite from 19 m to EOH. Water strikes were encountered at 15 m, 17 m and 19 m with a final blow yield of 1.3 ℓ/s (112 m^3/d) measured (Figure 7-6).

BHT07: Five meters of highly weathered pyroxenite topsoil overlie slightly weathered pyroxenite from 5 m to 19 m and fresh pyroxenite from 19 m to 30 m. Water strikes were encountered at 14 m, 15 m, 17 m and 22 m. The cumulative blow yield was measured at 3.1 ℓ/s (268 m^3/d) (Figure 7-7).

3.5.3.4 Aquifer testing

Boreholes were pump tested after the completion of drilling. Stepped drawdown tests were performed to determine the optimal pumping yield for the constant discharge tests. Constant discharge tests were conducted 500 minutes per test and were followed by recovery tests. Refer to Appendix B3 for a summary of pump tests conducted.

BHT06: During the stepped drawdown test the borehole was pump tested for five consecutive steppes with yields ranging from 26 m^3/d to 147 m^3/d. The first four steps lasted 30 minutes each and the fifth step 20 minutes. The constant discharge test was performed at 95 m^3/d utilising only 8.5 m (85%) of the available 10 m drawdown. The water level recovered to 93% of the original within 40% of the pumping time. The early transmissivity (T) is calculated to be 18 m^2/d the late T is 3.89 m^2/d and the recovery T is 51.3 m^2/d, indicating a minor aquifer (Table 3-4).

BHT07: A stepped drawdown test consisting of four consecutive steps of 30 minutes each with pumping yields ranging from 112 m^3/d to 432 m^3/d was conducted to determine the optimum yield for the constant discharge tests. The constant discharge test was pumped at a constant yield of 363 m^3/d and a drawdown of 15.43 m was reached after 500 minutes of pumping. The water level in the borehole recovered to 96% of the original water level in 600 minutes, which is 120% of the pumping time. The aquifer parameters were calculated using analytical methods as indicated and summarised in Table 3-4. The transmissivity values were calculated at 29.2 m^2/d for early T, 3.18 m^2/d late T and 40.7 m^2/d for recovery T, indicative of a minor aquifer.

Table 3-4 Aquifer test summary table.

	No	BHT06	BHT07
General Information	Latitude	24.95888	24.95754
	Longitude	30.12501	30.12505
	Borehole Depth (m)	30.1	29.8
	Pump Depth (m)	29	28
	Water Level (m)	7.17	8.7
	Main Water Strikes (m)	15; 17; 19	14; 15; 17; 22
	Available Drawdown (m)	10	6
Stepped Drawdown Test	Step 1: 30 min (m^3/d)	25.92	112.32
	Step 2: 30 min (m^3/d)	60.48	233.28
	Step 3: 30 min (m^3/d)	86.40	345.60
	Step 4: 30 min (m^3/d)	112.32	432.00
	Step 5: 20 min (m^3/d)	146.88	NA
Constant Discharge Test	Average Pump Rate (m^3/d)	95.04	362.88
	Duration (min)	500	500
	Maximum Drawdown (m)	8.5	15.43
	Early T (m^2/d)	3.89	29.2
	Late T (m^2/d)	3.18	18
Recovery Test	Recovery Time (min)	200	600
	Recovery Reached (m)	0.6	0.65
	Recovery Reached %	93	95.8
	% Time	40	120
	Recovery T (m^2/d)	51.3	40.7

Line.Stat	Lo Y	Lo X
1.000	88542	2761523
1.030	88540	2761553
1.060	88539	2761583
1.090	88537	2761613
1.120	88535	2761643
1.150	88533	2761673
1.180	88531	2761703
1.210	88532	2761734
1.240	88533	2761763
1.270	88534	2761792
1.300	88535	2761821
1.330	88535	2761853
1.360	88534	2761884
1.390	88533	2761916
1.420	88535	2761944
1.430	88534	2761956
2.000	88373	2761520
2.030	88372	2761550
2.060	88369	2761580
2.090	88363	2761609
2.120	88357	2761639
2.150	88351	2761668
2.180	88346	2761699
2.210	88338	2761727
2.240	88332	2761756
2.270	88322	2761785
2.300	88314	2761814
2.330	88306	2761842
2.355	88299	2761866

Line.Stat	Lo Y	Lo X
3.000	88359	2761672
3.030	88387	2761678
3.060	88416	2761684
3.090	88447	2761691
3.120	88474	2761698
3.150	88503	2761705
3.185	88531	2761711
4.000	88322	2761795
4.030	88351	2761796
4.060	88383	2761796
4.090	88414	2761796
4.120	88441	2761794
4.150	88471	2761793
4.180	88500	2761787
4.210	88531	2761782
5.000	88287	2761855
5.030	88318	2761857
5.060	88347	2761860
5.090	88377	2761862
5.120	88407	2761865
5.150	88436	2761862
5.180	88466	2761863
5.210	88496	2761862
5.235	88521	2761863

WGS84 Lo 31

Thorncliffe Tailings Facility

Geophysical traverse lines

Prepared for AGES (Pty) Ltd by E&EGS cc June 2008

Figure 3-8 Configuration of geophysical traverses.

Figure 3-9 **Site characterisation borehole localities.**

3.5.4 Water quality

Newly drilled monitoring sites were selected for chemical analyses and the development of a water quality baseline database. The two sampling localities were selected to represent the spatial extent of the site in terms of disturbed and undisturbed areas and were compared accordingly. Samples were submitted and analysed at a SANAS (South African National Accreditation System) accredited laboratory for macro- and micro chemical analysis (refer to Table 7-2 and Table 7-3 in Appendix C).

3.5.4.1 Piper diagram

Water quality data was plotted on a Piper diagram and analysed accordingly. A Piper diagram is a tri-linear plot and represents the relative concentrations of major ions in solution. For each constituent, the concentration (mg/l) is converted to chemical equivalents (meq/l) based on the valence and atomic weight. The percentages of each ion relative to the total are calculated, and plotted on the Piper diagram (Figure 3-10).The nature of the sampled groundwater is characteristic of a shallow, weathered aquifer within the Bushveld Complex as described by Witthuser *et al.* (2009).

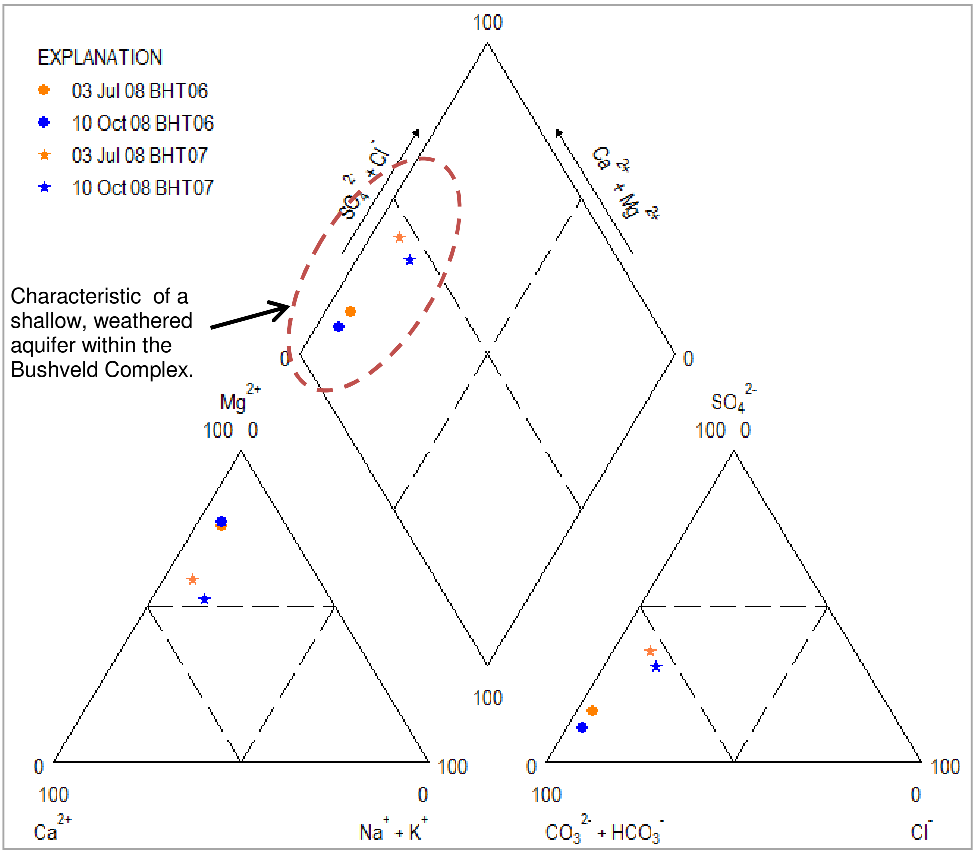

Figure 3-10 Piper diagram indicating the chemical nature of sampled boreholes.

3.5.5 Recharge

Site characterisation boreholes were drilled in an undisturbed, natural aquifer (BHT06) as well as a disturbed, rehabilitated area *i.e.* aquifer (BHT07). Recharge calculations were conducted by means of the chloride mass balance (CMB) method as described by Beekman *et al.* (1999) (refer to Equation 2-11) and compared accordingly. The recharge for BHT06 was calculated at 28 mm/a, which accounts to ~4% of the MAP, while the recharge for BHT07 was calculated at 70 mm/a which is equal to ~11% of the MAP (Refer to Figure 3-11 and Figure 3-12).

3.5.6 Modified hydrological system

A site assessment was conducted on the study area in terms of modified zones (Figure 3-14) which can also act as modified hydrological units influencing the overall mine water balance. Figure 3-15 clearly indicates modified hydrological units within the mining area as potential higher recharge zones (expected increase in local water table) as well as zones of over-abstraction (expected lowering of local water table, *i.e.* formation of a cone of depression). Estimated recharge, runoff and evaporation coefficients were assigned to each zone and calculations were made according to Equation 2-3, Equation 2-4, Equation 2-5 and Equation 2-12. The coefficients shown in Table 3-6 to Table 3-8 are assumptions based on published literature (Coleman *et al.*, 2011; Vermeulen and Usher, 2006; Hodgson *et al.*, 2006 and Middleton and Bailey, 2005) with susceptible areas delineated and calculated accordingly.

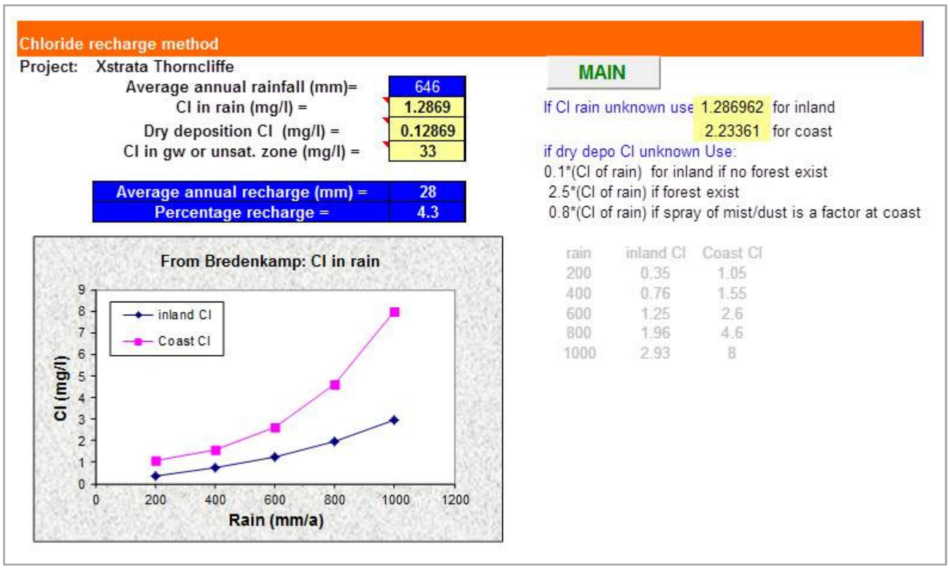

Figure 3-11 CMB recharge calculation – BHT06 (Based on van Tonder and Xu, 2000).

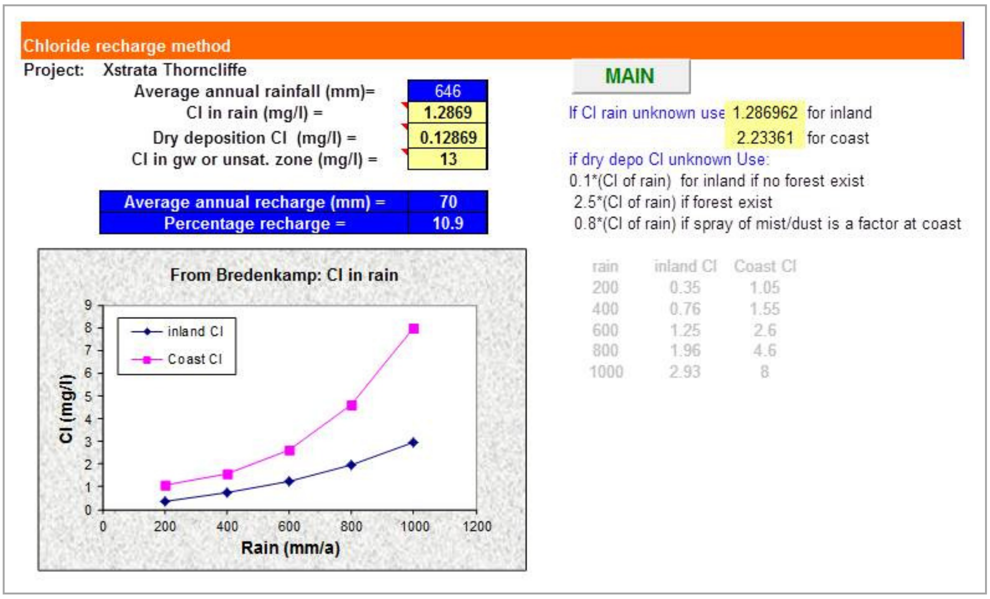

Figure 3-12 CMB recharge calculation – BHT07 (Based on van Tonder and Xu, 2000).

3.5.7 Product moisture content

Water content analyses were conducted on the chrome product leaving the beneficiation plant. Concentrated metallurgical grade product was analysed as separate batches and indicated an average moisture content of 5.93 %m. Refer to Table 3-8 for a summary of analyses of water retention tests conducted.

3.5.8 Tailings Storage Facility design criteria

The TSF is one of the main drivers of a mine water balance and water requirement is particularly sensitive to the rheological properties of discarded tailings. A water-release curve for a typical base-metal mine tailings circuit, is shown in Figure 3-13 and is unique to each tailings material, dependent on a number of factors such as particle size distribution, particle shape, the presence or absence of clay minerals and the tailings chemical conditions. Technical criteria of the TSF including beach areas and tailings post crush density are provided in Table 3-6 and Table 4-2 respectively.

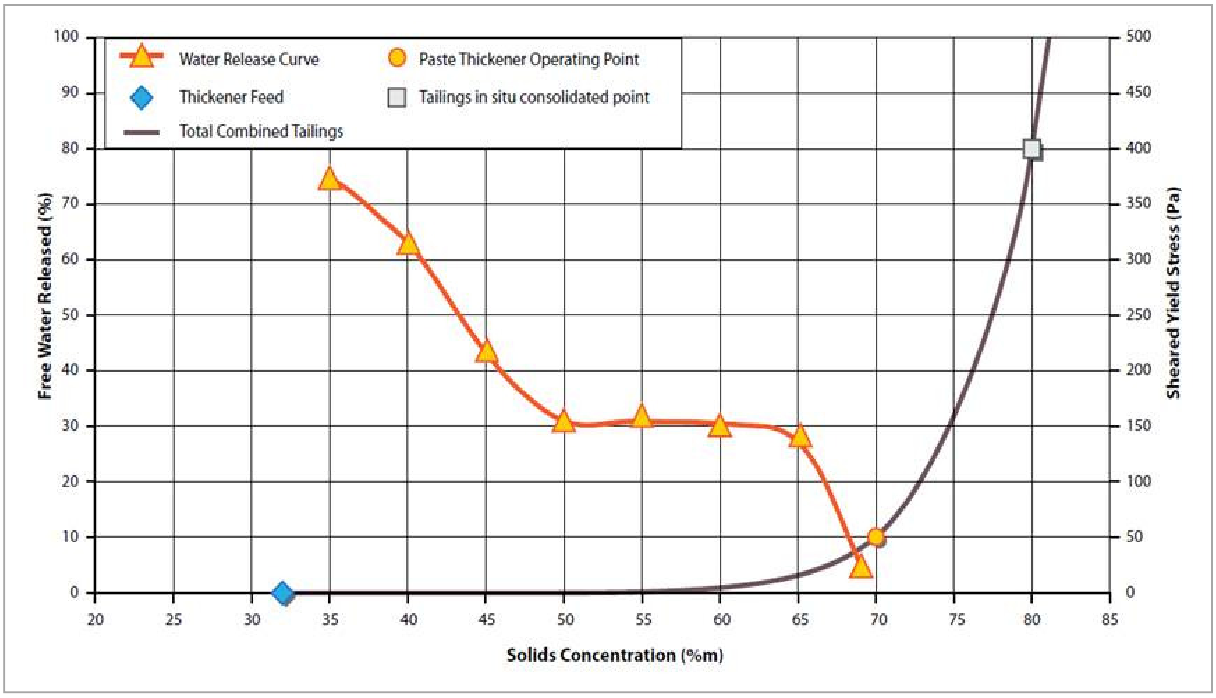

Figure 3-13 Tailings water-release curve (After Vietti *et al.,* 2010).

3.6 Mine dewatering

To ensure a safe working environment and continuation of efficient mining, underground fissure water ingress needs to be mitigated by means of having a pumping system and procedure in place. This can only be implemented once dewatering rates have been estimated and predicted. Table 3-5 summarises the aquifer parameters representative of the study area and Figure 3-16 indicates a stratigraphic column of the local geology, also depicting groundwater units. Hydraulic conductivities, derived from aquifer tests analyses, for both the local aquifer as well as the confining aquitard are stated along with respective thicknesses. Based on geological logging and subsurface exploration, it is assumed that the unit to be dewatered and exploited is ~40m in thickness and the drawdown to be reached is ~160m with a radius of influence and cone of depression of ~200m. Horizontal fissure water ingress as well as vertical aquitard leakage from the hanging wall was incorporated, and by applying Equations 2-13 to Equation 2-16 (Singh and Atkins, 1984) expected underground water inflows for a semi-confined aquifer were calculated at ~260 m^3/d for MAP conditions.

Table 3-5 Summary of dewatering parameters (Figure 3-16).

Parameters	Formulae notations	Value	Unit
Aquifer Hydraulic Conductivity	K	1.5 x $10e^{-2}$	m/d
Aquitard Hydraulic Conductivity	K'	1.0 x $10e^{-3}$	m/d
Aquifer thickness (dewatering unit)	L	40	m
Aquitard thickness	L'	120	m
Drawdown	D	160	m
Radius of draw down	r	200	m

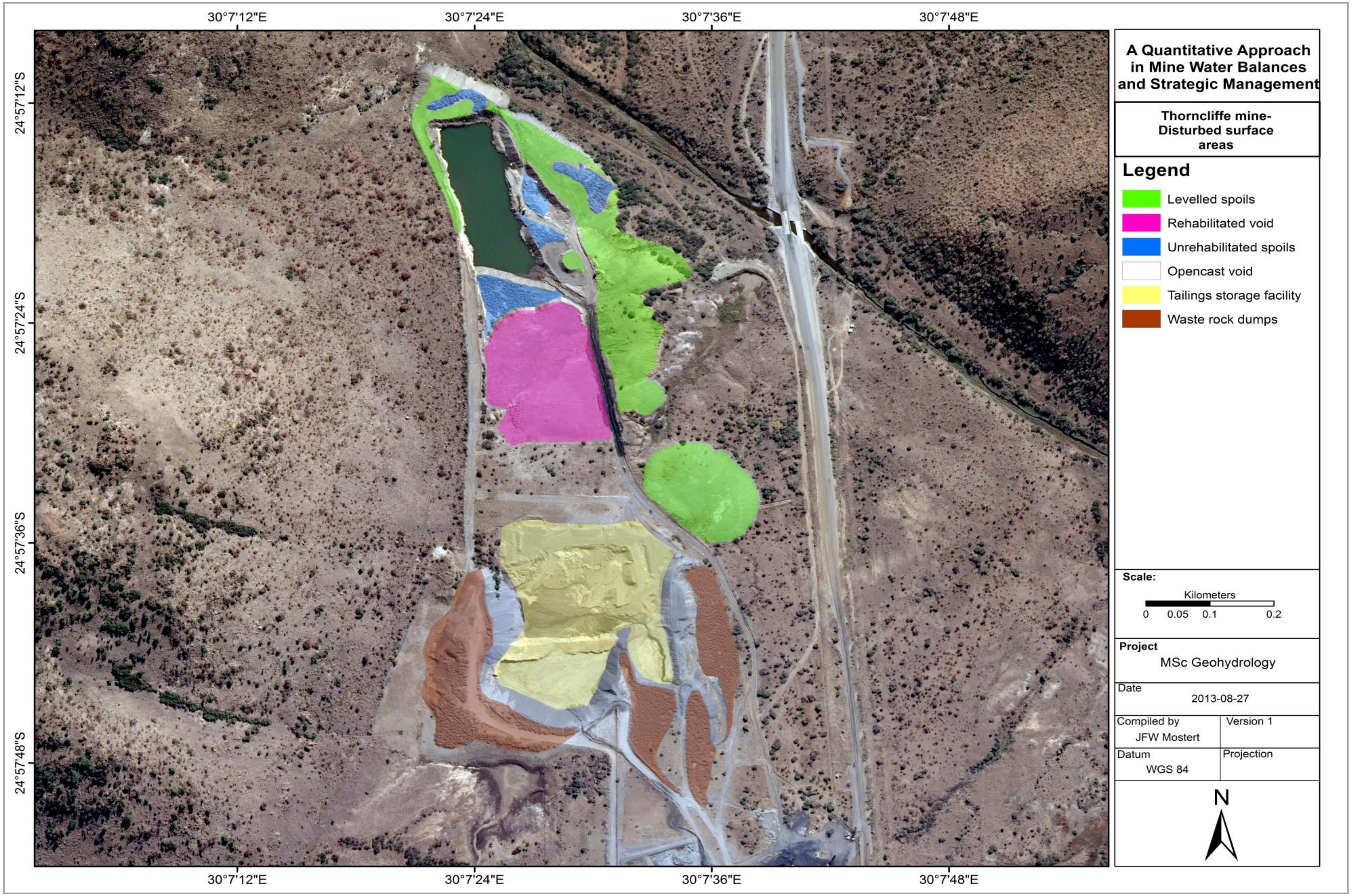

Figure 3-14 Indication of hydrogeological modified areas caused by mining operations.

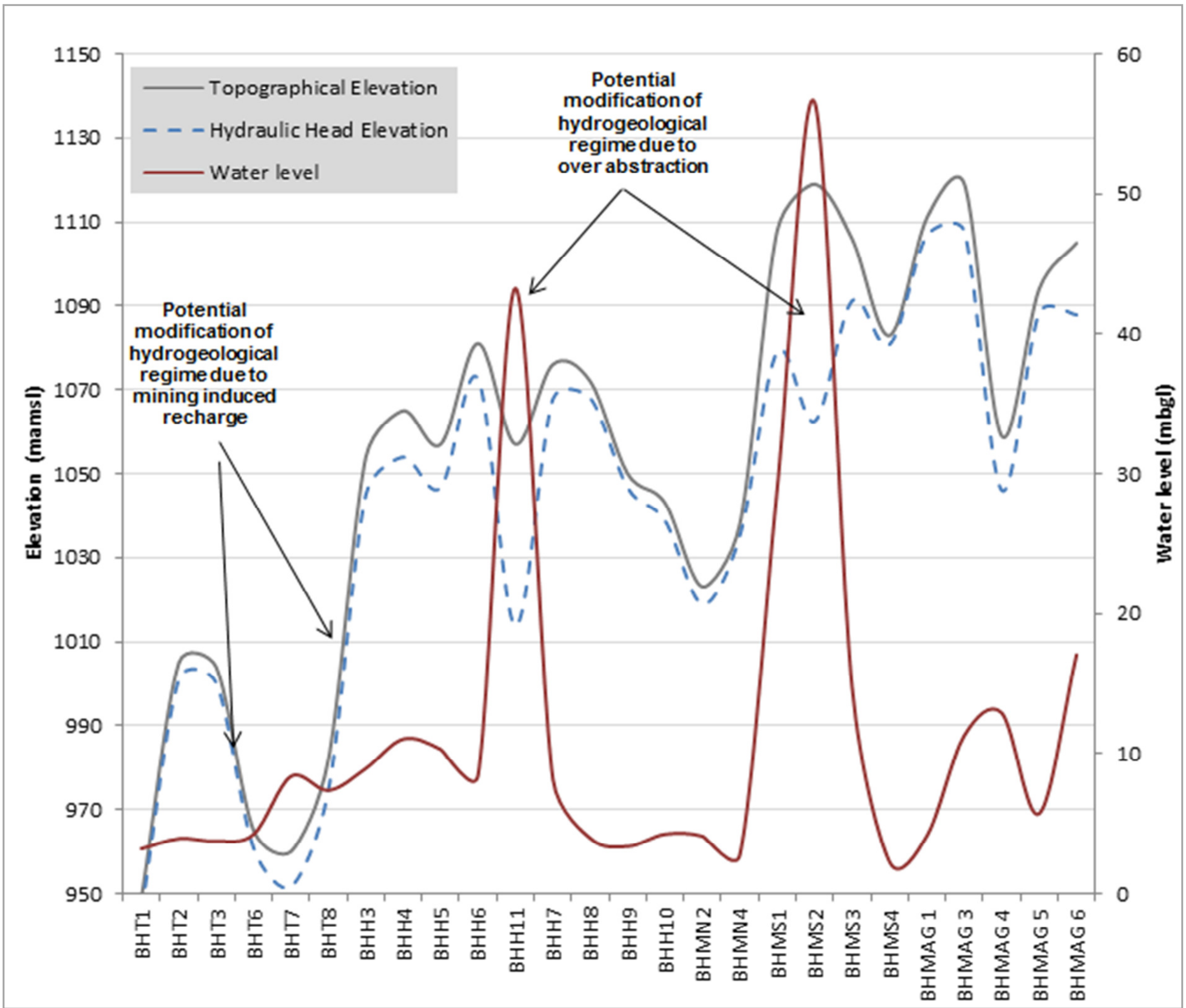

Figure 3-15 Hydraulic head elevation in comparison with topographic elevation.

Table 3-6 Environmental parameters of mining areas under MAP conditions (after Hodgson *et al*. (2006) and McPail (2005)).

Area description	Surface area (m^2)	Recharge coefficient (%)	Recharge (m^3/d) (Equation 2-12)	Runoff coefficient (%)	Runoff (m^3/d) (Equation 2-4)	Evaporation coefficient (%)	Evaporation (m^3/d) (Equation 2-5)
Undisturbed/virgin area	841253.00	0.04	64.02	0.09	126.56	0.00	0.00
Levelled spoils	62128.03	0.20	21.99	0.10	11.00	0.00	0.00
Unrehabilitated spoils	12430.21	0.60	13.20	0.15	3.30	0.00	0.00
Rehabilitated void	33255.91	0.20	11.77	0.10	5.89	0.00	0.00
Open cast void	19630.88	1.00	34.74	0.00	0.00	0.80	84.20
Waste rock dumps	51705.04	0.70	64.06	0.30	27.45	0.00	0.00
TSF supernatant pond area	3003.65	1.00	5.32	0.00	0.00	0.80	12.88
TSF wet beach area	45054.71	0.00	0.00	0.75	59.81	0.60	144.93
TSF dry beach area	12014.59	0.00	0.00	0.20	4.25	0.00	0.00
Plant area	32950.00	0.00	0.00	0.50	29.16	0.00	0.00
Upstream SWD	3040.00	1.00	5.38	0.00	0.00	0.80	13.04
Downstream SWD	2650.00	1.00	4.69	0.00	0.00	0.80	11.37
Process water dam	725.00	1.00	1.28	0.00	0.00	0.80	3.11
Settlers	2035.00	1.00	3.60	0.00	0.00	0.80	8.73
Pollution control dam	650.00	1.00	1.15	0.00	0.00	0.80	2.79
Maximum	**841253.00**	**1.00**	**64.06**	**0.75**	**126.56**	**0.80**	**144.93**
Minimum	**650.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Average	**74835.07**	**0.58**	**15.41**	**0.15**	**17.83**	**0.41**	**18.74**
Standard deviation	**213000.97**	**0.45**	**21.94**	**0.22**	**34.45**	**0.40**	**40.87**

Table 3-7 Environmental parameters of mining areas under dry conditions (5th Percentile data limits).

Area description	Surface area (m^2)	Recharge coefficient (%)	Recharge (m^3/d) (Equation 2-12)	Runoff coefficient (%)	Runoff (m^3/d) (Equation 2-4)	Evaporation coefficient (%)	Evaporation (m^3/d) (Equation 2-5)
Undisturbed/virgin area	841 253.00	0.04	37.93	0.09	74.98	0.00	0.00
Levelled spoils	62 128.03	0.20	13.03	0.10	6.51	0.00	0.00
Unrehabilitated spoils	12 430.21	0.60	7.82	0.15	1.96	0.00	0.00
Rehabilitated void	33 255.91	0.20	6.97	0.10	3.49	0.00	0.00
Opencast void	19 630.88	0.70	14.41	0.00	0.00	0.80	84.20
Waste rock dumps	51 705.04	0.70	37.95	0.30	16.27	0.00	0.00
TSF supernatant pond area	3 003.65	0.80	2.52	0.00	0.00	0.80	12.88
TSF wet beach	32 950.00	0.00	0.00	0.75	25.91	0.60	105.99
TSF dry beach	12 014.59	0.00	0.00	0.20	2.52	0.00	0.00
Plant area	32 950.00	0.00	0.00	0.50	17.28	0.00	0.00
Upstream SWD	3 040.00	0.80	2.55	0.00	0.00	0.80	13.04
Downstream SWD	2 650.00	0.80	2.22	0.00	0.00	0.80	11.37
Process water dam	725.00	0.80	0.61	0.00	0.00	0.80	3.11
Settlers	2 035.00	0.80	1.71	0.00	0.00	0.80	8.73
Pollution control dam	650.00	0.80	0.55	0.00	0.00	0.80	2.79
Maximum	**841253.00**	**0.80**	**37.95**	**0.75**	**74.98**	**0.80**	**105.99**
Minimum	**650.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Average	**74028.09**	**0.48**	**8.55**	**0.15**	**9.93**	**0.41**	**16.14**
Standard deviation	**213144.74**	**0.36**	**12.79**	**0.22**	**19.72**	**0.40**	**32.71**

Table 3-8 Environmental parameters of mining areas under wet conditions (95th Percentile data limits).

Area description	Surface area (m²)	Recharge coefficient (%)	Recharge (m³/d) (Equation 2-12)	Runoff coefficient (%)	Runoff (m³/d) (Equation 2-4)	Evaporation coefficient (%)	Evaporation (m³/d) (Equation 2-5)
Undisturbed/virgin area	841 253.00	0.04	90.26	0.09	178.42	0.00	0.00
Levelled spoils	62 128.03	0.20	31.00	0.10	15.50	0.00	0.00
Unrehabilitated spoils	12 430.21	0.60	18.61	0.15	4.65	0.00	0.00
Rehabilitated void	33 255.91	0.20	16.60	0.10	8.30	0.00	0.00
Opencast void	19 630.88	0.70	34.29	0.00	0.00	0.80	84.20
Waste rock dumps	51 705.04	0.70	90.31	0.30	38.70	0.00	0.00
TSF supernatant pond area	3 003.65	0.80	6.00	0.00	0.00	0.80	12.88
TSF wet beach	32 950.00	0.00	0.00	0.75	61.66	0.60	105.99
TSF dry beach	12 014.59	0.00	0.00	0.20	6.00	0.00	0.00
Plant area	32 950.00	0.00	0.00	0.50	41.11	0.00	0.00
Upstream SWD	3 040.00	0.80	6.07	0.00	0.00	0.80	13.04
Downstream SWD	2 650.00	0.80	5.29	0.00	0.00	0.80	11.37
Process water dam	725.00	0.80	1.45	0.00	0.00	0.80	3.11
Settlers	2 035.00	0.80	4.06	0.00	0.00	0.80	8.73
Pollution control dam	650.00	0.80	1.30	0.00	0.00	0.80	2.79
Maximum	**841253.00**	**0.80**	**90.31**	**0.75**	**178.42**	**0.80**	**105.99**
Minimum	**650.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Average	**74028.09**	**0.48**	**20.35**	**0.15**	**23.62**	**0.41**	**16.14**
Standard deviation	**213144.74**	**0.36**	**30.44**	**0.22**	**46.92**	**0.40**	**32.71**

Table 3-9 Product moisture content.

Mine	Ore Type	Wet Weight (t)	Dry weight (t)	Dry volume (m^3)	Moisture content (t)	Moisture content (wt%)
Thorncliffe	Concentrated metallurgical grade (Batch1)	50 471.40	47 169.21	10 254.18	3 302.19	6.54
	Lumpy (Batch 1)	1 134.30	1 132.52	246.20	1.78	0.16
	Concentrated metallurgical grade (Batch 2)	6 333.26	6 075.43	1 320.75	257.83	4.07
	Lumpy (Batch 2)	2 235.94	2 227.96	484.34	7.98	0.36
	Total	**60 174.90**	**56 605.11**	**12 305.46**	**3 569.79**	**5.93**

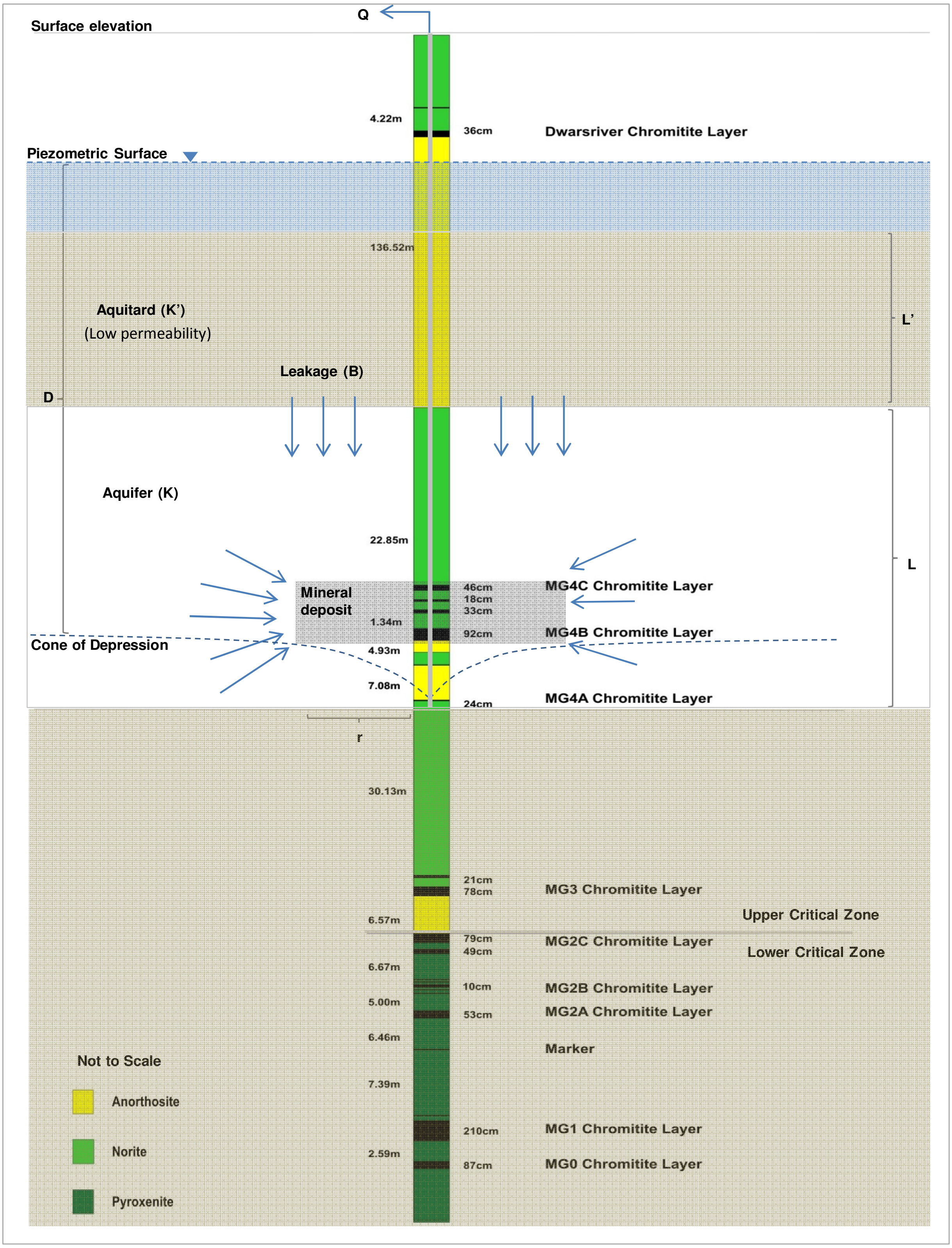

Figure 3-16 Schematic representation of stratigraphic column for the local geology and dewatering units (modified from Singh and Atkins, 1984).

3.7 Discussion: Chapter 3

A methodology for developing an adapted mine water balance, data collection techniques, data inputs as well as data sources and descriptions were covered in this chapter. The integrity and accuracy of water balances are dependent on the precision of data and, as with any data processing system, the principle of garbage in garbage out applies. In a phased-approached methodology, developing an adapted mine water balance, incorporation of water from the natural system should be highlighted. Consequently, decision making is based on evaluation of the system as a whole, hence adapted management measures. Application of statistical analysis techniques for data input *i.e.* data distribution curves and probabilities, incorporates variability and probability to the model. Climatic data, groundwater recharge parameters as well as dewatering volumes are major drivers of the natural system and inclusion of such to calculations is a necessity. The following chapter will apply assembled data to a case study to be presented for interpretation.

Chapter 4

4 ANALYSES AND INTERPRETATION

An overview of data analyses and interpretation is provided in this chapter. A case study which demonstrates practical implementation of the concepts under investigation, by applying various data sets to an adapted mine water balance model, is discussed.

4.1 Case study: Background

The Xstrata Thorncliffe mining operation was selected to be evaluated as part of a case study and falls under the Chrome Division of Xstrata Eastern Mines Limited. This mine is an existing ferrochrome producer and has been in operation since 1983. Mining involves the exploitation of chromite from the upper and lower critical zones of the Igneous Bushveld Complex and encompasses underground mine workings, a beneficiation and crusher plant, waste rock dump, tailings storage facility, supporting water reticulation infrastructure, storm water management facilities as well as associated groundwork.

4.1.1 Mining infrastructure

The mining infrastructure consists of the following facilities:

- Underground mine workings (~170 mbgl);
- A rehabilitated open cast mine void, backfilled with tailings material;
- Open cast pit flooded with groundwater;
- Two waste rock dumps;
- Process plant (130 ktpm)
- Tailings storage facility;
- Return water dam;
- Storm water storage facilities;
- Concrete process water dam;
- Eight water supply boreholes that are authorised to abstract on average 780 m^3/d;
- An abstraction point from the Dwars River, from which 700 m^3/d is authorised to be abstracted for make-up water requirements.

4.1.2 Plant activities

Plant activities are listed below:

- Primary Crushing (Gyratory Crusher);
- Secondary cone crusher;
- Tertiary cone crushers;
- Ball mill;
- Semi-autogenous grinding mill;
- Regrind cyclone; and
- Dewatering of product in thickener followed by a vertical plate pressure filter.

4.1.3 Administration and supporting infrastructure

Administration and supporting infrastructure include the following:

- Administration building;
- Change house complex;
- Package sewerage treatment plant;
- Reverse osmosis plant for water treatment;
- Raw water pumping station;
- Heavy and light vehicle workshops with tyre change and repair facilities; and
- Heavy vehicle wash-down bays;

4.2 Site assessment

4.2.1 Locality

The study area is located in the Eastern Limb of the Bushveld Complex between Roossenekal (28 km) and Steelpoort (23 km), and is situated approximately 50 km northwest of Lydenburg (greater Mashishing), Limpopo Province, South Africa (Figure 4-1 and Figure 4-2). Table 4-1 summarises the general coordinates of the mining site.

Table 4-1 General site coordinates (Reference datum: WGS84).

Latitude	-24.96
Longitude	30.13

4.2.2 Climatology

The climate of the Olifants Water Management Area (WMA) is largely controlled by movement of air-masses associated with the Inter-Tropical Convergence Zone (ITCZ). Summer months are characterised by high land temperatures and produce low pressures and moisture is brought to the catchment through the inflow of maritime air masses from the Indian Ocean. During the winter, the sun moves further north and the land cools, causing the development of a continental high pressure system. The regional dry season is therefore caused by descending and outflowing air. For this reason, rainfall is seasonal and largely occurs during the summer months, October to April. The catchment MAP is 630 mm, but the rainfall pattern is irregular with coefficients of variation greater than 0.25 across most of the catchment (DWAF, 2004).

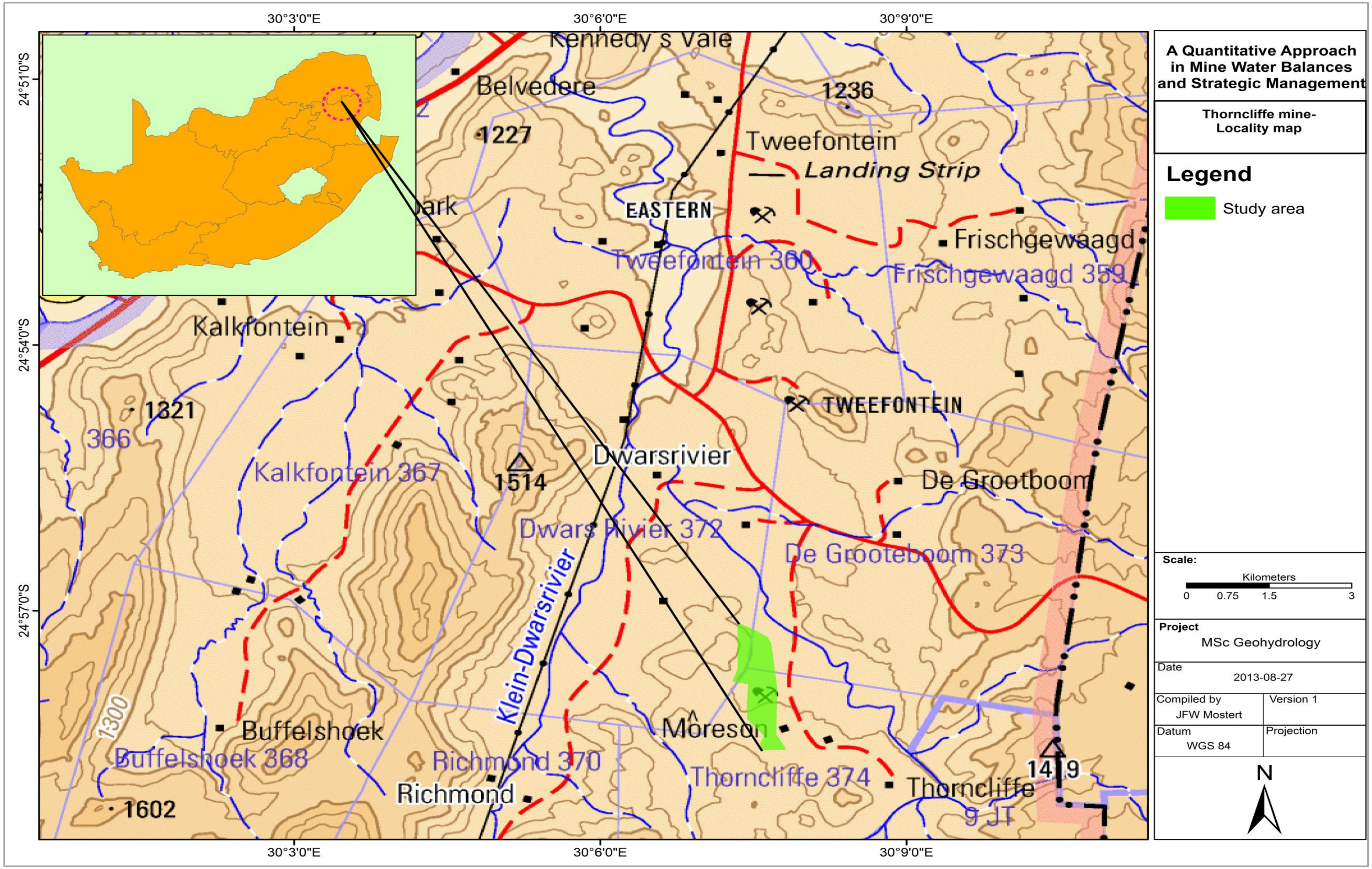

Figure 4-1 **Regional locality map of the study area.**

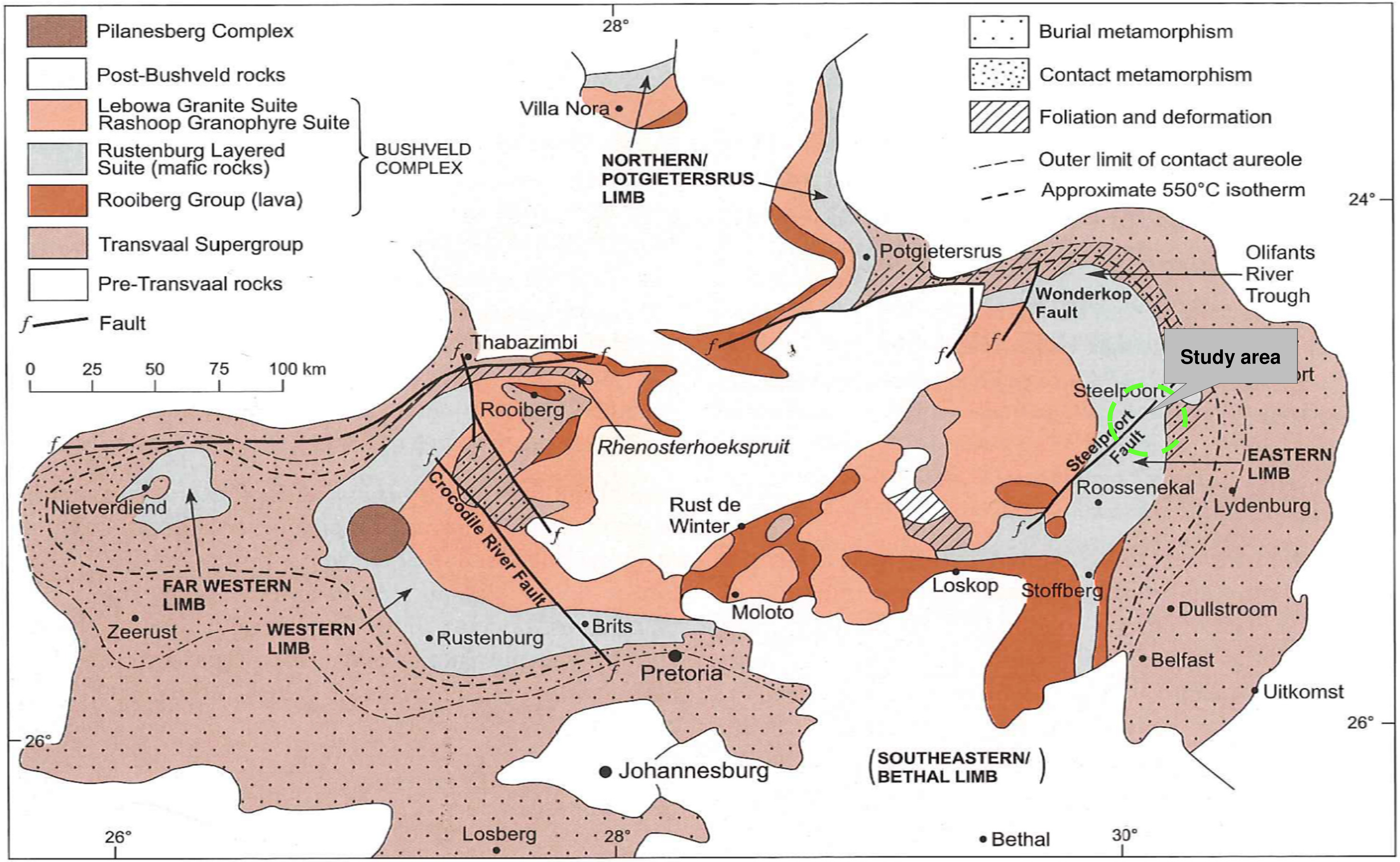

Figure 4-2 Locality of study area in relation with the Bushveld Complex (Based on Cawthorn *et al.* 2006).

4.2.3 Topography and drainage

The regional topography is rugged with steep slopes and incised valleys that strike east to west and north-east to south-west with a topographical profile depicted in Figure 4-3 and Figure 4-4. The highest elevation is at 1500 mamsl in the south of the study area and the lowest at 850 mamsl in the north-eastern and north-western boundaries of the study area. This is along the Klein- and Groot Dwars Rivers. The topographic gradient at the Thorncliffe site is steep and ranges between 1.7% and 5.3 % (Figure 4-5) which can have a major influence on the runoff volumes calculated. In order to manage existing water resources, the country's hydrological basins have been divided into 19 WMA's (Adewumi *et al.*, 2010). The greater study area is situated in the primary catchment of the Olifants River and falls under quaternary catchment B41G (Figure 4-6). The latter can proof valuable for water management purposes as specific catchments should comply with specific water quality and strategic objectives in terms of regulatory frameworks as promulgated by the DWA (Pulles and van Rensburg, 2006b).

Figure 4-3 Northeast-southwest slice through the study area indicating the average hill slope (Courtesy of Google Earth TM, 2013).

Figure 4-4 Topographical elevation and drainage of study area.

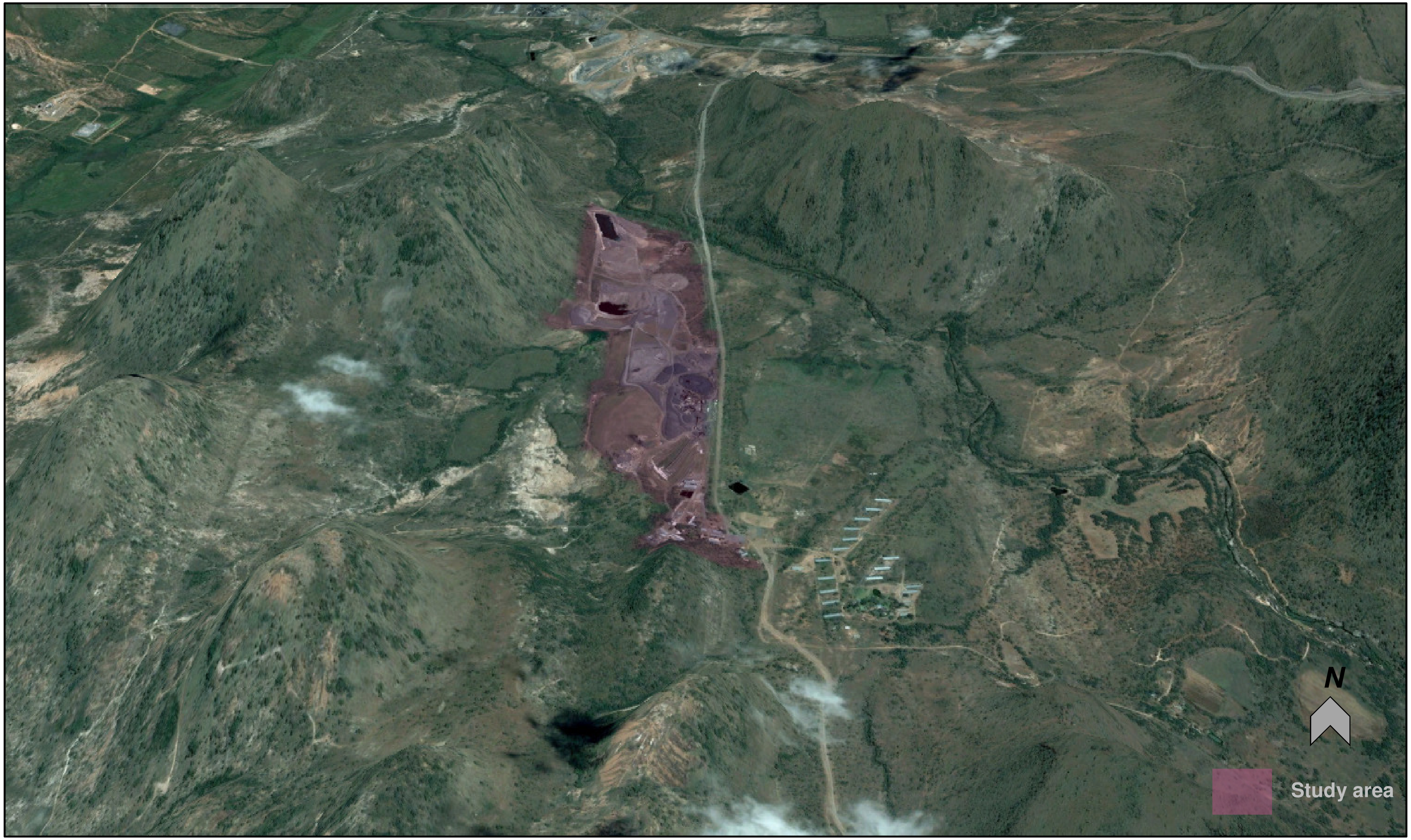

Figure 4-5 Aerial extend of mining boundary and surface water catchment (Courtesy of Google Earth TM, 2013).

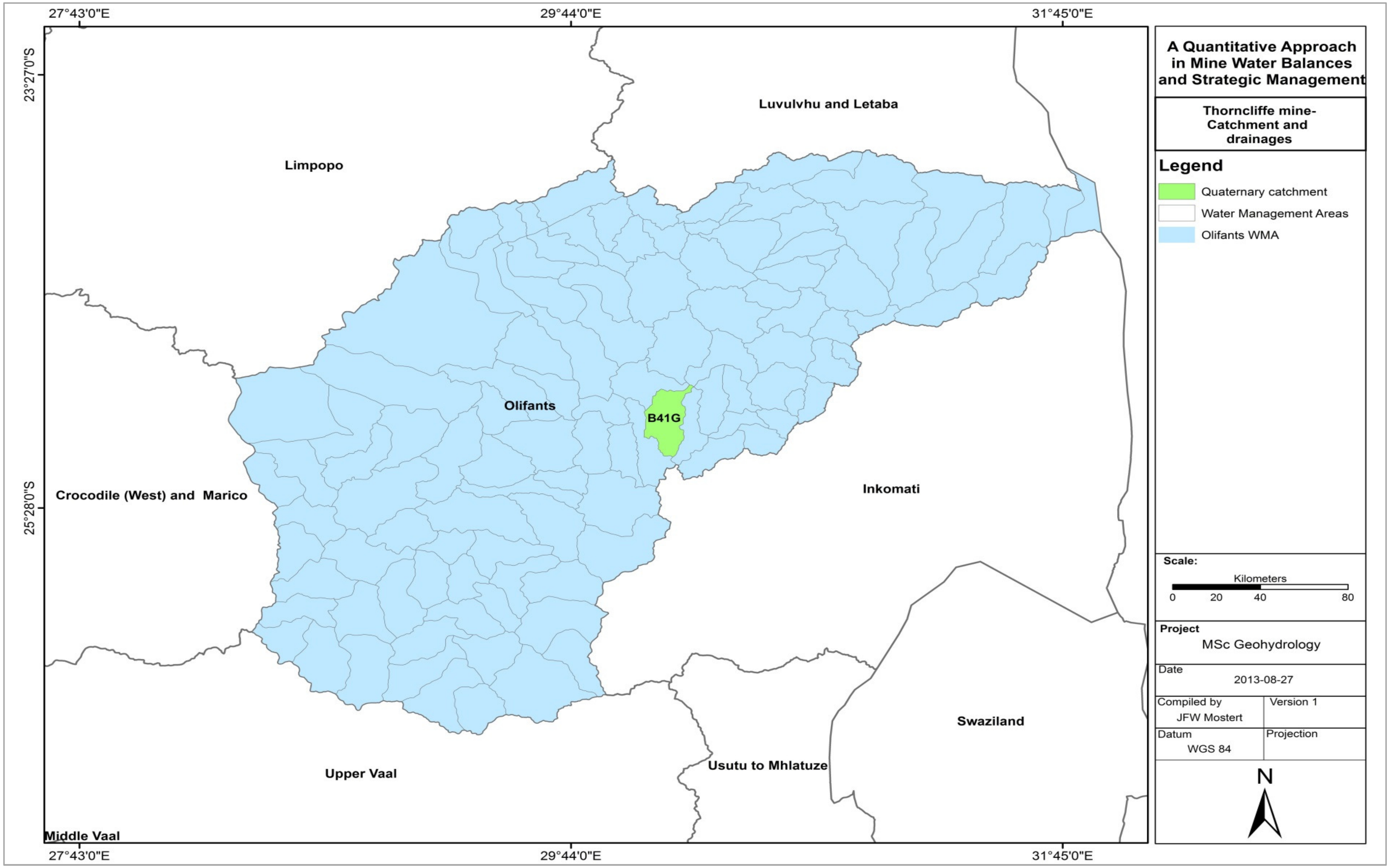

Figure 4-6 Quaternary catchment B41G in relation to the Olifants WMA.

4.2.4 Geologic and hydrogeological setting

4.2.4.1 Regional geology and stratigraphy

The project area is located in the regional Rustenburg Layered Suite (RLS) with quaternary deposits along the river and stream canals. Thorncliffe is situated on the Critical and Main Zones of the Bushveld Complex. The main economic layers in this part of the Bushveld are the Merensky Reef, the UG2 Chromite Layer and the MG1 Chromite Layer, which are uniform in the project areas. The reefs outcrop along the Groot Dwars River and dip to the west at 9 to 10 degrees. The regional strike of the layering is north-south parallel to the long axis of the valley. The PGM Merensky Reef occurs 165m above the UG2 Chromite Layer that is developed 350 m above the MG1 Chromite Layer. The quaternary deposits consist of sand, clay, silt and pedocrete material. The concave hill slopes exhibit prominent calcrete pedocrete material, which may reach depths of 3-6 m. Alluvial deposits next to the Dwars River consist of coarse sand with lenses of boulders, clay and silt.

4.2.4.2 Local geology

The Thorncliffe mining section is located in the Dsjate Subsuite (Vdj) of the RLS that consists of coarse grained norite, anorhosite in the upper zones and medium to coarse grained pyroxenite in the lower zones (Figure 4-7). These mines exploit the chrome layers in the UG1, UG2, Dwars River Chromite layer, MG4, MG3, MG2, MG1 and LG7, LG6, LG5, LG3 and LG1.

4.2.4.3 Structural geology

Large scale fault zones occur in the project areas, with horizontal displacements. Magnetic anomalies were identified that are interpreted as dunite pipes. Regional dolerite dykes that strike north-northeast, were determined from surface mapping and exploration boreholes. The most dominant structural fracture zone in the area is a zone with a north-south trend underlying the Groot Dwarsriver. This zone appears to be narrowing towards the south. The fracture zone is associated with dyke swarms.

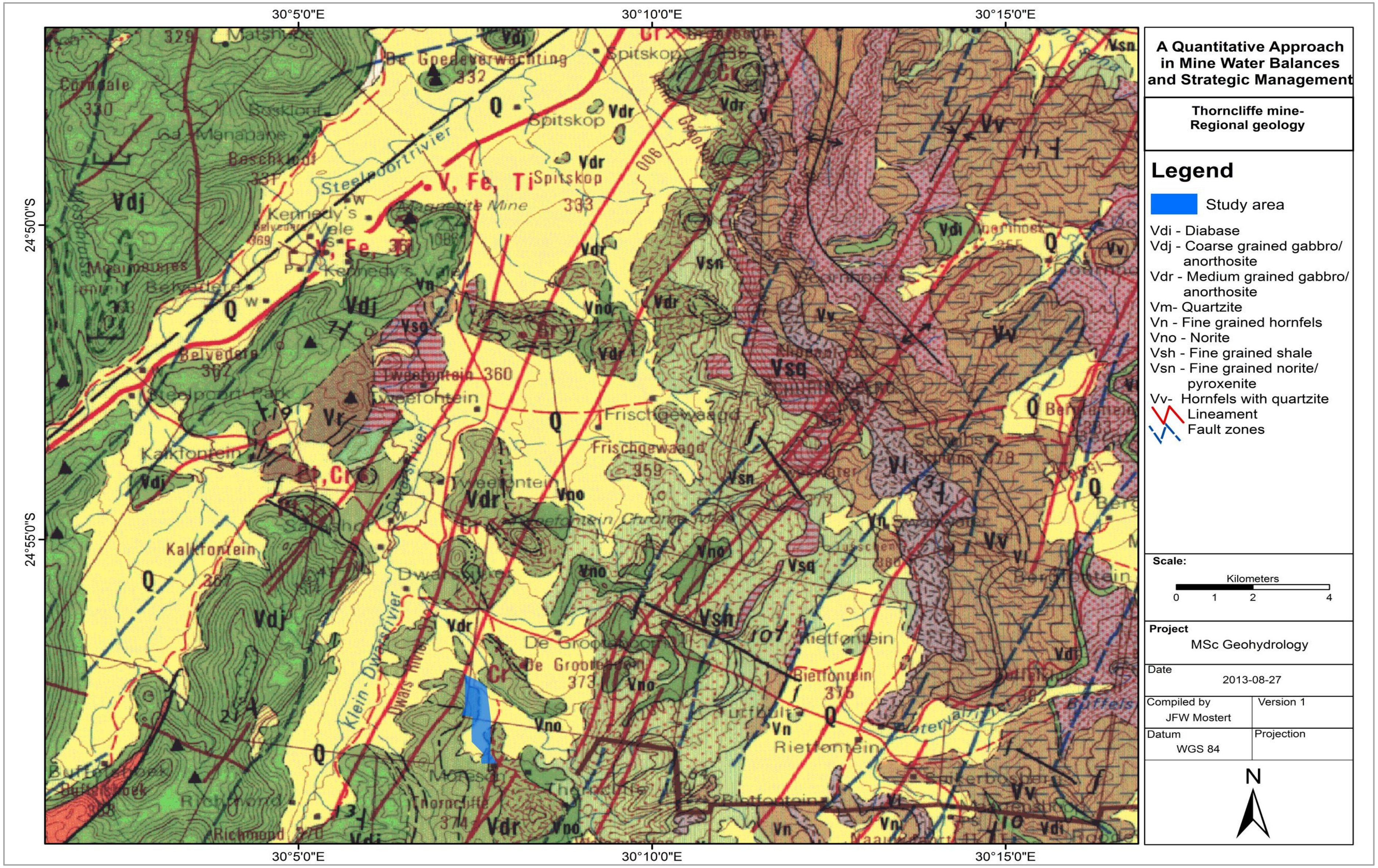

Figure 4-7 Regional geology of the study area (Council for GeoScience, 1999).

4.3 Hydrogeology and conceptual model

At the heart of every model is a conceptual model (Nordstrom, 2012) and accordingly, the development of such a model is central to the understanding of surface and groundwater dynamics (Idrysy and Connelly, 2012). A conceptual model begins by defining the area of interest and is constructed in conjunction with field data, desk-based analyses and hydrogeological principles. It provides a tool for identifying and interpreting any questions to analyse by using an analytical model.

The geology of the area forms a number of hydraulic zones that are controlled by the lithological units, structural geology, surface water features as well as hydrogeological units due to modification caused by mining activities. Figure 4-8 illustrates the conceptual understanding of the study area and potential hydrogeological units and aquifers in relation to mine infrastructure. The Bushveld Complex is characterised by a shallow, weathered aquifer underlain by a fractured bedrock aquifer with inflows along distinct fracture systems, also referred to as secondary porosity rock matrix (Witthüser *et al.,* 2009). The following hydrogeological units can be distinguished:

- The Dwars River Aquifer, which is a primary alluvial and weathered aquifer that occurs along a zone of 20-100 m from the river;
- The areas of elevated topography are formed by solid, dense bedrock and are therefore expected to have a low permeability;
- The topographic low-lying valley areas are weathered and fractured to depths of 40-60 m and form the main aquifer zones in the study area;
- Fault structures that strike north-north-east form important aquifer zones, especially where they are hydraulically linked to the Dwars River Aquifer;
- Dyke structures and dyke contact zones occur and they strike north-north-east and east-west. The dyke structures are fractured and permeable in the upper, weathered zone, and are expected to become solid and less permeable with depth. The dyke-contact zones extend for 2-10 m around the dyke and are fractured and permeable in the uppermost weathered zone;
- The weathered, layered norite/anorthosite is present at a vertical depth of 5-10 m and is more pronounced in the topographic low-lying areas. The weathered norite/ anorthosite is expected to be fractured with micro to meso-scale fracturing on the layered surfaces;
- An aquitard (very low hydraulic conductivity characteristics) forms the divide between the shallow and deep aquifers;

- The fractured/solid bedrock aquifer that underlies the weathered zone is formed by the basal pyroxenite, norite and anorthosite at depths of >18 mbgl. The fractured/solid pyroxenite, norite, anorthosite is also expected to be fractured with micro- scale fracturing on the layered surfaces; and
- Backfilled open pits, rehabilitated areas as well as mining spoils, create zones of high recharge.

4.4 Water reticulation system

A simplified mine reticulation system is indicated in Figure 4-10. Mining operations source water from existing groundwater and surface water allocations as well as water pumped from mine dewatering. Raw water is pumped and stored in a site reservoir and gravitates to various operating units. Potable water for domestic purposes is reticulated to the administration block and change house/work shop and a sewage treatment plant treats grey water and sewage of which the effluent gets recycled back to the process water dam. The latter serves as a buffer dam for different operating units and receives a mixture of raw water as well as worked water from different components. Services water is pumped underground and contained in an underground reservoir. Dewatered fissure water and recirculated underground water are pumped to settling ponds (settlers) where solids settle out and clear water is pumped to the plant process water dam. Dust suppression is conducted with process water sourced from this facility. This facility also receives water in the wet season from a storm water dam situated in the site footprint capturing rainfall runoff, a pollution control dam located at the waste rock dump as well as worked water from the return water dam. From here water is reticulated to the plant for beneficiation purposes and for mixture of slurry to be transported to the tailings storage facility. The tailings facility consist of a conventional tailings dam with supernatant water cumulating in the centre of the dam basin equipped with a penstock to recirculate clear water to the return water dam and back to the process water dam. The mining operation also comprises a plant for water treatment, preventing salt build-up in the system.

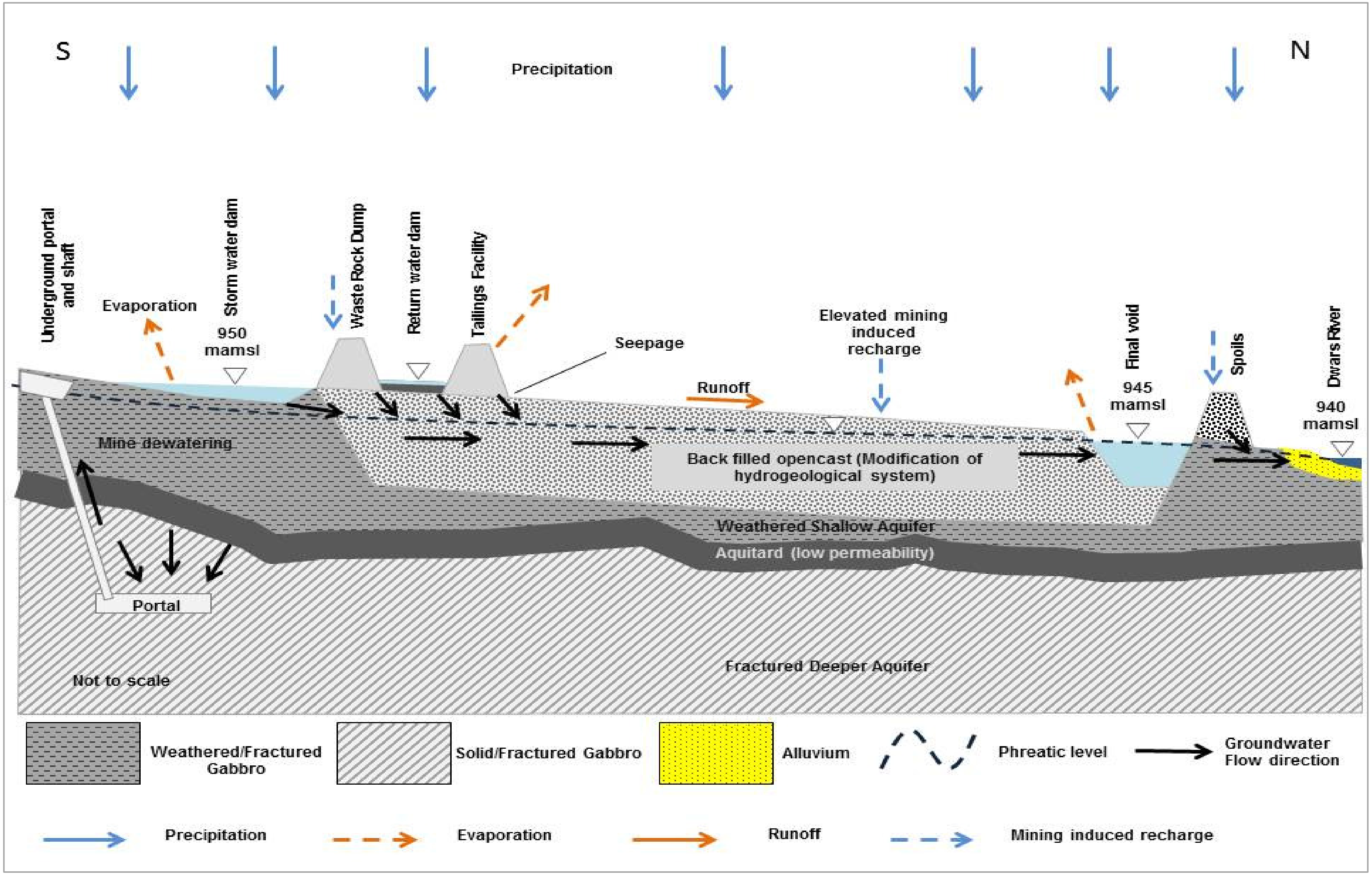

Figure 4-8 Conceptual model reflecting the groundwater system of the study area (Modified from AGES, 2008).

4.5 Water balance assumptions and notations

Limited data holds challenges when developing a mine water balance. Accordingly, the implementation of conservative assumptions is imperative if the system behaviour and extend need to be understood for quantification. The following assumptions were made:

- The water balance is considered conservative for pre-feasibility study purposes, and can therefore be used to validate the viability of a project with an accuracy level of approximately 10% - 15% (Pulles and van Rensburg, 2006b). However, it is not suitable for detailed planning and specialised models should be investigated for further detail;
- Sources are positive (inflow) and sinks are negative (outflow);
- Runoff coefficients for each surface area were fixed and not influenced by antecedent climatic conditions;
- Storm water containment facilities are designed to store storm water runoff from the project meso-catchment with storm water runoff outside of this catchment diverted around the disturbed areas according to GN 704;
- Evaporation from land was not dependent on availability of water and evaporation would occur regardless of the antecedent climatic conditions (evaporation coefficients were used to correct the evaporation rate to the relevant surface coverage);
- All rain falling on the top surface of the WRD would either runoff or infiltrate into the WRD;
- Any rainfall infiltrating through the WRD would flow into the perimeter drainage channels and are captured in the pollution control dam;
- It was assumed that seepage losses are only applicable for earth dams and calculated accordingly. Unlined facilities prone to seepage include the tailings storage facility, return water dam as well as waste rock dump;
- Seepage would only occur from the WRD during rainfall events;
- Open circuit facilities susceptible to evaporation are indicated in Figure 4-10 and include the TSF supernatant pond, TSF beaches, return water dam, storm water facilities, process water dam, pollution control dam as well as settling ponds;
- The tailings dam was assumed to be a conventional tailings dam;
- Any rainfall infiltrating through the surface of the TSF would either be lost to rewetting, seepage or would go into pore-water storage and would be released from storage into the solution trench at the maximum flow rate of the toe drains;

- The supernatant pond, wet beach and dry beach areas were constant in area, equating to 5%, 25% and 70% of the top surface of the TSF respectively; and
- It is assumed that storm water contained from rain events will be of a suitable quality or will be treated to a suitable quality to allow re-use in the operations.

4.6 Application: Mine water balance scenarios

The following section provides a summary of the quantification of mine water consumption (make-up water requirements) for different scenarios based on assumptions and equations investigated. As part of this investigation, different scenarios were evaluated using site specific data to cater for a combination of management options. Scenarios assessed include: A conventional, base case scenario (Table 4-2), demonstrating the quantification of mine make-up water requirements without incorporating the influence of the natural system, MAP scenario with incorporation of the natural system, where the mean annual rainfall figures were used as input, representing average conditions (Table 4-3), draught scenario (1:20 years) with incorporation of the natural system and rainfall data lower limit inputs (5th percentile) as well as a flooding scenario (1:20 years) with incorporation of the natural system and rainfall data upper limit inputs (95th percentile) (Table 4-5).

4.6.1 Conventional base case scenario

Table 4-2 provides a summary of the quantification of mine make-up water requirement for different components of a conventional mine water balance. The latter is estimated without incorporating any influences and contributions from surface and groundwater components. Assumptions and equations from the literature review are applied as indicated.

Table 4-2 Mine water balance – Conventional base case scenario with calculations.

Component	Description	Quantity	Notations
Summary	**Make up water requirement (m^3/ton milled)**	**0.72**	
	Make up water requirement (m^3/d)	**3079.99**	Water consumed = **(Mining process + Process plant + TSF + Domestic purposes + Dust suppression)**
	Water consumed in mining process (m^3/d)	433.33	Refer to mining component calculation
	Water consumption in process plant (m^3/d)	128.18	Refer to beneficiation plant component calculation
	Water consumption in tailings facility circuit (m^3/d)	2090.01	Refer to tailings storage facility component calculation
	Water consumption for domestic purposes (m^3/d)	28.46	Refer to domestic component
	Water consumption for dust suppression (m^3/d)	400.00	Refer to dust suppression component

Component	Description	Quantity	Notations
Mining	Total RoM (t/month)	130000.00	Mine production schedule
	Mine ore : waste ratio	0.60	Resources development plan
	Mine production - ore (t/month)	78000.00	Calculated = **(RoM x Ore:Waste Ratio)**
	Mine production - waste (t/month)	52000.00	Calculated = **(RoM – Ore production)**
	Mine make-up water use (m^3/ton)	0.10	Assumption based on Section 2.2
	Mine make-up water use (m^3/d)	433.33	
Beneficiation Plant	ROM plant feed (t/month)	78000.00	Mine production – ore
	Water in ore (m^3/d)	52.00	Assumption based on Gunson et al. (2010), **Equation 2-2**
	Losses as product moisture (m^3/d)	154.18	Moisture retention tests = **~6% (Table 3-9)**
	Process water consumption (m^3/ton)	0.01	Assumption based on Section 2.2.1.2
	Process make-up water consumption (m^3/d)	128.18	
Tailings Storage Facility	Tailings production rate (ton/m^3)	52000.00	Mine production - waste
	Percentage solids by mass (%)	0.50	Design criteria – technical specifications
	Mass of slurry (t/month)	104000.00	Calculated = **(Mine waste production/mass of slurry)**
	Tailings post crush density (ton/m^3)	2.40	Design criteria – technical specifications
	Slurry density (ton/m^3)	1.41	Calculated = **((Mass of slurry/(Tailings production/post crush density)+(Mass of slurry – Tailings production rate))** after GJ Wiid (2013)
	Slurry water use (total water m^3/ton)	1.70	Calculated = **Post crush density/Slurry density**
	Evaporation losses (m^3/d)	442.44	Calculated = **Slurry water use x 15%** after McPhail (2005)
	Interstitial water lock-up (m^3/d)	1559.08	Calculated = **Slurry water use x 53%** after McPhail (2005)
	Beach rewetting (m^3/d)	88.49	Calculated = **Slurry water use x 3%** Wels & Robertson (2003)
	Water loss in tailings circuit %	70.93	Calculated = **Sum (Evaporation+Interstitial lock-up+Rewetting losses)/Water in slurry) x 100**
	Water in slurry from plant to tailings dam (m^3/d)	2946.67	Calculated = (**Slurry water use x waste production)/30**
	Return water to plant (m^3/d)	856.65	Calculated = **Water in slurry – (Evaporation+Interstitial lock-up+Rewetting losses)**
	Tailings circuit water consumption (m^3/ton)	0.48	Section 2.2.1.3. Calculated = **Tailings water consumptions/(RoM/30)**
	Tailings circuit water consumption (m^3/d)	2090.01	Calculated = **(Evaporation+Interstitial lock-up+Rewetting losses)**
Domestic	Employees	1157.00	Mine Social and Labour Plan
	Water use L/person/day	120.00	Destatis (2009)
	Mine potable/drinking water requirement (L/person/day)	3.00	Assumption based
	Total drinking water use (m^3/d)	3.47	Calculated = **Employees x drinking water requirement/1000**
	Change house potable water component (m^3/d)	138.84	Calculated = **Employees x Water use per person/1000**
	Total potable water use (m^3/d)	142.31	Calculated = **Total drinking water + Change house requirement**

Component	Description	Quantity	Notations
	Sewage water discharge (m³/d)	113.85	Calculated = **Total potable water use x 80%** D.Mara (2003)
	Sewerage water returned to circuit (m³/d)	85.39	Calculated = **Sewage water discharge – sewage water loss**
	Sewerage water loss in sludge (m³/d)	28.46	Section 2.2.1.5, Calculated = **Total potable water use x 20%** D.Mara (2003)
Other	Water used for dust suppression (m³/d)	400.00	Qualified report review

Note that water consumption equals the make-up component and is less than the total water use. Make-up water components are highlighted in grey.

Contributing water sinks for a conventional mine water balance are depicted in Figure 4-9. High water losses from the tailings circuit are evident with the major drivers of the mine water balance being losses to the TSF, mining activities as well as dust suppression. Also refer to Figure 2-5 for a comparison with water sinks derived from similar qualified studies. Note that the calculated make-up water requirement of 0.72 m^3 per tonne of ore milled corresponds to volumes as estimated by Brown (2003). The make-up water requirement can also be indicative of water use efficiency and should be evaluated accordingly.

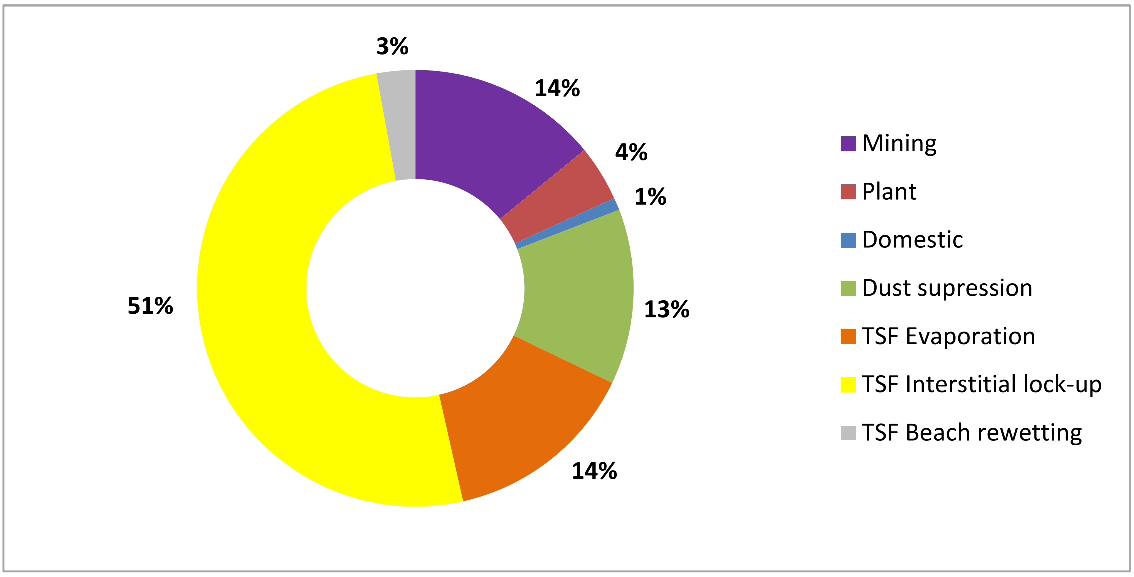

Figure 4-9 Representation of contributing water losses - conventional mine water balance.

4.6.2 Scenarios incorporating the natural system

For a more accurate and representative mine water balance, reflecting site specific conditions, scenarios incorporating climatic conditions and groundwater influences, *i.e.* the natural system, were also evaluated.

4.6.2.1 MAP scenario

In this scenario, a probability distribution of mean annual rainfall data was used as input, representing average conditions (Table 4-3). Figure 4-10 provides an indication of an adapted mine water balance flow diagram, with simulated daily flow volumes shown between facilities. Areas of data uncertainty are mitigated by proposing calibrated flow meters for accurate measurements and validation for model updates. Figure 4-11 provides an indication of a mine salt balance flow diagram, depicting simulated TDS contribution per facility, where net flow volumes and salt loads to facilities were assessed and calculated. Once more, areas where quality analyses are absent or need to be validated are mitigated by proposed monitoring localities.

Table 4-3 Adapted mine water balance – MAP scenario.

Component	Description	Quantity	Notations
Summary	**Make up water requirement (m^3/ton milled)**	**0.66**	
	Make up water requirement (m^3/d)	**2831.01**	
	Mean Annual Precipitation (MAP) (mm/a)	645.97	Rainfall Station no. 0554786
	Mean Annual Evaporation (MAE) (mm/a)	1956.90	WRC (2005)
	Water consumed in mining process (m^3/d)	178.46	
	Water consumption in process plant (m^3/d)	130.01	
	Water consumption in tailings facility circuit (m^3/d)	2070.09	
	Water make from waste rock dump (m^3/d)	23.99	
	Water consumption for domestic purposes (m^3/d)	28.46	
	Water consumption for dust suppression (m^3/d)	400.00	
Mining	Total RoM (t/month)	130000.00	Mine production schedule
	Mine ore : waste ratio	0.60	Resources development plan
	Mine production - ore (t/month)	78000.00	
	Mine production - waste (t/month)	52000.00	
	Precipitation on settlers (m^3/d)	3.60	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses settlers (m^3/d)	8.73	**Equation 2-5**, Kampf and Burges (2009)
	Dewatering of underground mine workings (m^3/d)	260.00	**Equation 2-11, Equation 2-12 and Equation 2-13** after Singh and Atkins (1984).
	Mine make-up water use (m^3/ton)	0.10	Assumption, Section 2.2.1.1
	Mine make-up water use (m^3/d)	178.46	
Beneficiation Plant	ROM plant feed (t/month)	78000.00	Mine production schedule
	Water in ore (m^3/d)	52.00	**Equation 2-2** after Gunson (2010)

Component	Description	Quantity	Notations
	Losses as product moisture (m^3/d)	154.18	Moisture retention tests = ~6% (Table 3-9)
	Precipitation on PWD (m^3/d)	1.28	**Equation 2-3,** Cote *et al.* (2010)
	Evaporation losses PWD (m^3/d)	3.11	**Equation 2-5**, Kampf and Burges (2009)
	Process water consumption (m^3/ton)	0.01	Assumption, Section 2.2.1.2
	Process make-up water consumption (m^3/d)	130.01	
Tailings Storage Facility	Tailings production rate (ton/m^3)	52000.00	Mine production schedule
	Percentage solids by mass (%)	0.50	Design criteria
	Mass of slurry (t/month)	104000.00	Calculated
	Tailings post crush density (ton/m^3)	2.40	Design criteria
	Slurry density (ton/m^3)	1.41	Calculated after GJ Wiid (2013)
	Slurry water use (total water m^3/ton)	1.70	Calculated
	Evaporation losses (% of tailings loss)	442.44	McPhail (2005)
	Interstitial water lock-up (% of tailings loss)	1559.08	McPhail (2005)
	Beach rewetting (% of tailings losses)	88.49	Wels & Robertson (2003)
	Foundation seepage to groundwater (% of tailings losses)	47.97	Equation 2-7 after Darcy (1856)
	Water loss in tailings circuit %	70.93	Calculated
	Water in slurry from plant to tailings dam (m^3/d)	2946.67	Calculated
	Return water to plant (m^3/d)	856.65	Calculated
	Precipitation on TSF (m^3/d)	69.37	**Equation 2-3**, Cote *et al.* (2010)
	Precipitation on RWD (m^3/d)	34.74	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses RWD (m^3/d)	84.20	**Equation 2-5**, Kampf and Burges (2009)
	Seepage losses RWD (m^3/d)	98.15	50% assumption after Madramootoo (1997)
	Tailings circuit water consumption (m^3/ton)	0.48	Calculated
	Tailings circuit water consumption (m^3/d)	2070.09	
Waste Rock Dump	Waste rock dump drainage (m^3/d)	25.62	Ogola *et al.*(2011)
	Precipitation on pollution control dam (m^3/d)	1.15	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses from pollution control dam (m^3/d)	2.79	**Equation 2-5**, Kampf and Burges (2009)
	Seepage to groundwater (m^3/d)	5.12	Assumption based
Domestic	Employees	1157.00	Mine Social and Labour Plan
	Water use L/person/day	120.00	Destatis (2009)
	Mine potable/drinking water requirement (L/person/day)	3.00	Assumption based
	Total drinking water use (m^3/d)	3.47	Calculated
	Change house potable water component (m^3/d)	138.84	Calculated
	Total potable water use (m^3/d)	142.31	Calculated
	Sewage water discharge (m^3/d)	113.85	D.Mara (2003)
	Sewerage water returned to circuit (m^3/d)	85.39	Calculated
	Sewerage water loss in sludge (m^3/d)	28.46	Assumption, Section 2.2.1.4

Component	Description	Quantity	Notations
Other	Water used for dust suppression (m^3/d)	400.00	Assumption based - Qualified report review
Groundwater system	Total basin inflow (m^3/d)	262.23	**Table 3-5** after Singh and Atkins (1984)
	Total basin outflow (m^3/d)	360.00	**Equation 2-6** after de Ridder and Boonstra
	Change in storage (m^3/d)	-97.77	Indicating unsustainable scenario
Surface water system	Total precipitation runoff from meso-catchment (m^3/d)	323.57	**Equation 2-4**
	Total evaporation losses from meso-catchment (m^3/d)	723.49	**Equation 2-5**, Kampf and Burges (2009)
	Net inflow/outflow (m^3/d)	-399.91	**Equation 2-1**, Moran (2006)

Make-up water components are highlighted in grey. Water gains or losses from the surface water system are highlighted in green with water gains or losses to the groundwater system highlighted in blue.

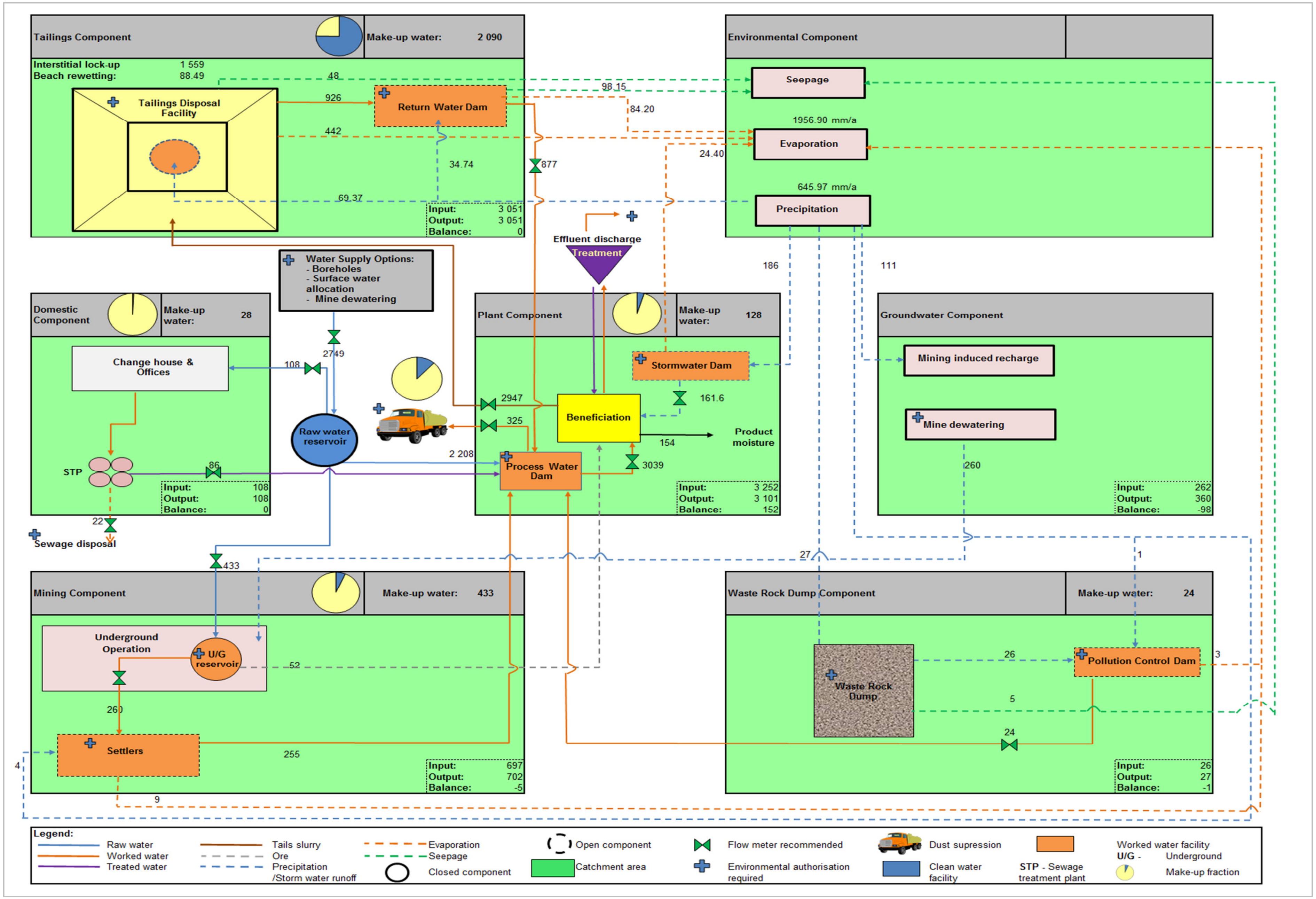

Figure 4-10 Adapted mine water balance flow diagram for MAP conditions indicating make-up fraction per component (m^3/d).

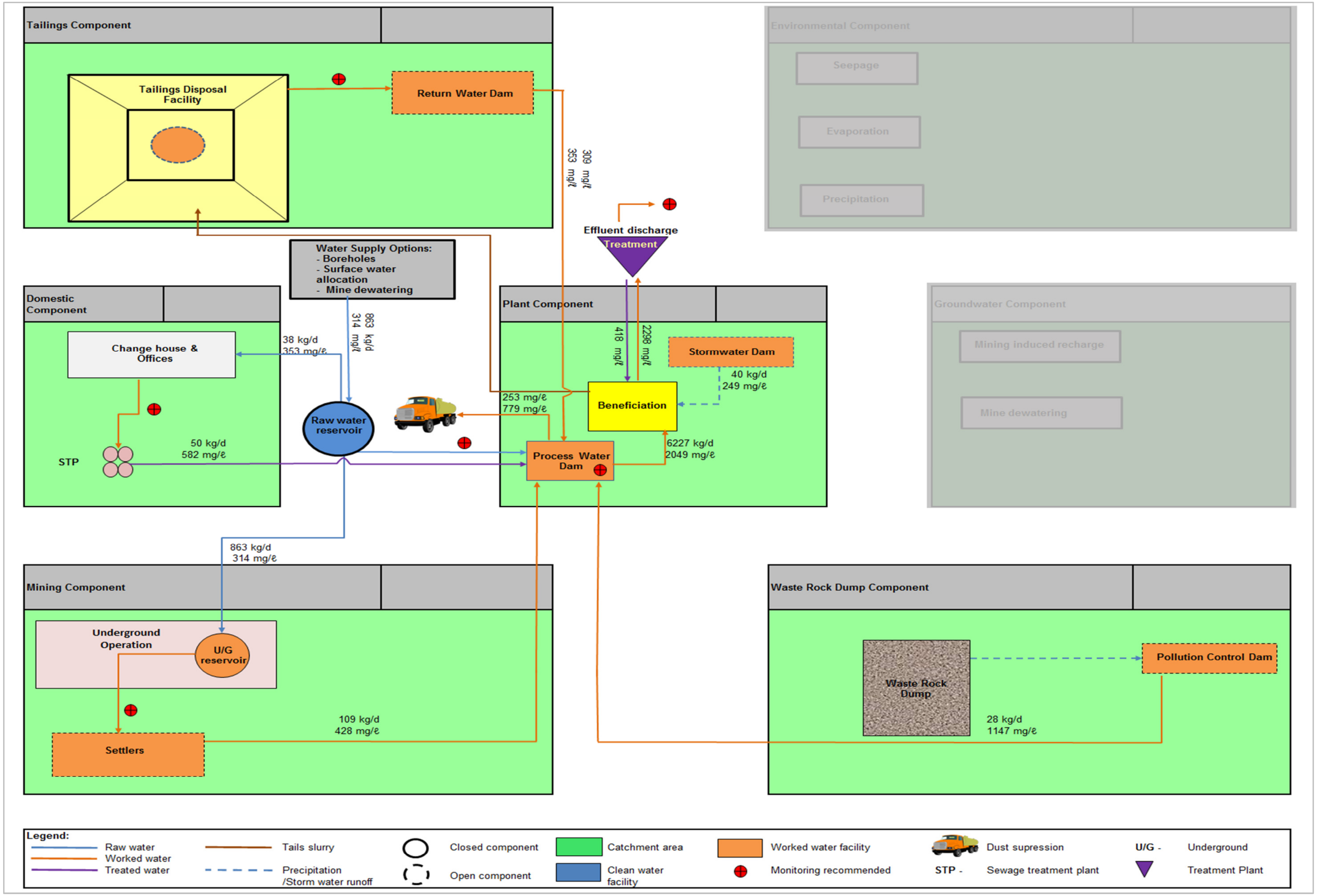

Figure 4-11 Salt balance flow diagram for MAP conditions.

4.6.2.2 Impacts of surface and groundwater interaction on make-up water

A comparison in make-up water requirements, per component, for a conventional mine water balance (not incorporating surface and groundwater interaction) and an adapted mine water balance (incorporating surface and groundwater interaction) is depicted in Figure 4-12. The impact of the latter is significant and incorporating the natural system decreased make-up water requirements by approximately 10% for MAP conditions. As expected, climatic conditions did not have a significant effect on the plant and domestic components of the water balance. It is evident that beneficiation and ore processing are not dependant on climatic conditions and, except for evaporation losses, will not be influenced significantly. This confirms the statement of Gunson *et al.* (2012) noting that ore processing requires a constant supply of water. Because the domestic component's contribution is a small fraction of the total make-up water requirement, any change in water consumption has a minor effect on the overall water requirement of the operation, as indicated and is not sensitive to changes to this component. Contrary to this, climatic conditions and groundwater interaction has a significant effect on the water consumption of the mining, tailings and dust suppression components, which represents a decrease in make-up requirements. The latter can be due to dust suppression decreasing in summer months with frequent rainstorm events wetting the access and haul roads, and the effect of precipitation on the tailings facility, contributing to rainwater reuse and less water being lost to this sink. Mine dewatering also significantly decrease the make-up water requirement for the mining component.

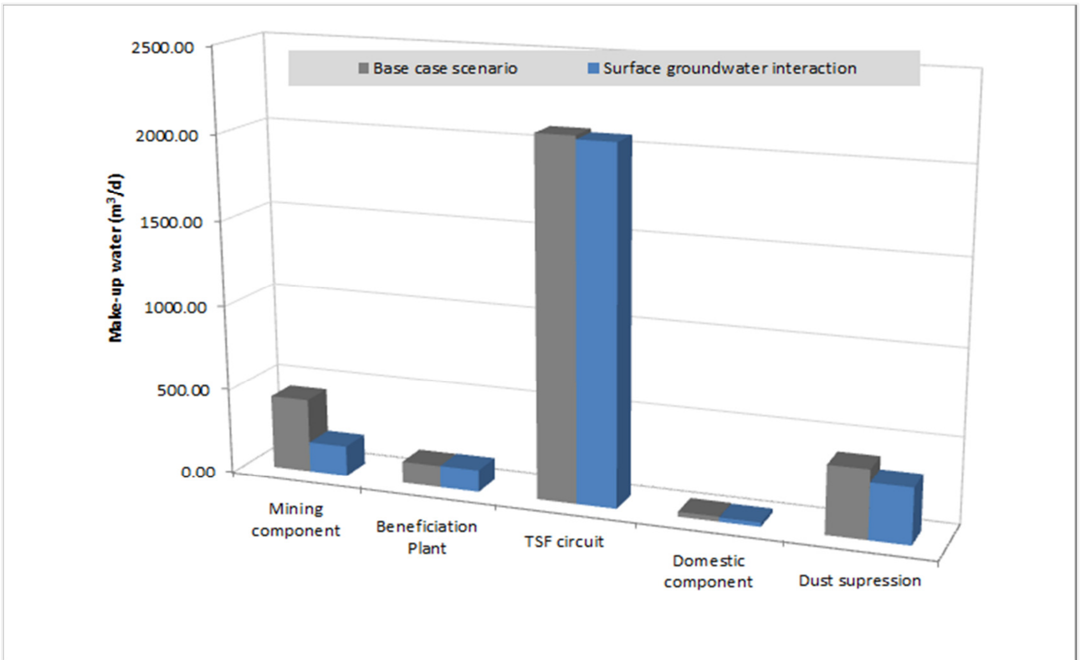

Figure 4-12 Mine make-up water requirement – conventional vs. adapted methodology.

4.6.2.3 Comparison between precipitation and evaporation volumes

Figure 4-13 indicates a comparison between precipitation runoff volumes and evaporation volumes for the project's meso-catchment. It is evident that evaporation losses equate to much higher water losses than gains from precipitation and it is therefore necessary to implement evaporation reduction measures as this is one of the most uncertain and main sinks of the natural system of mine water balances.

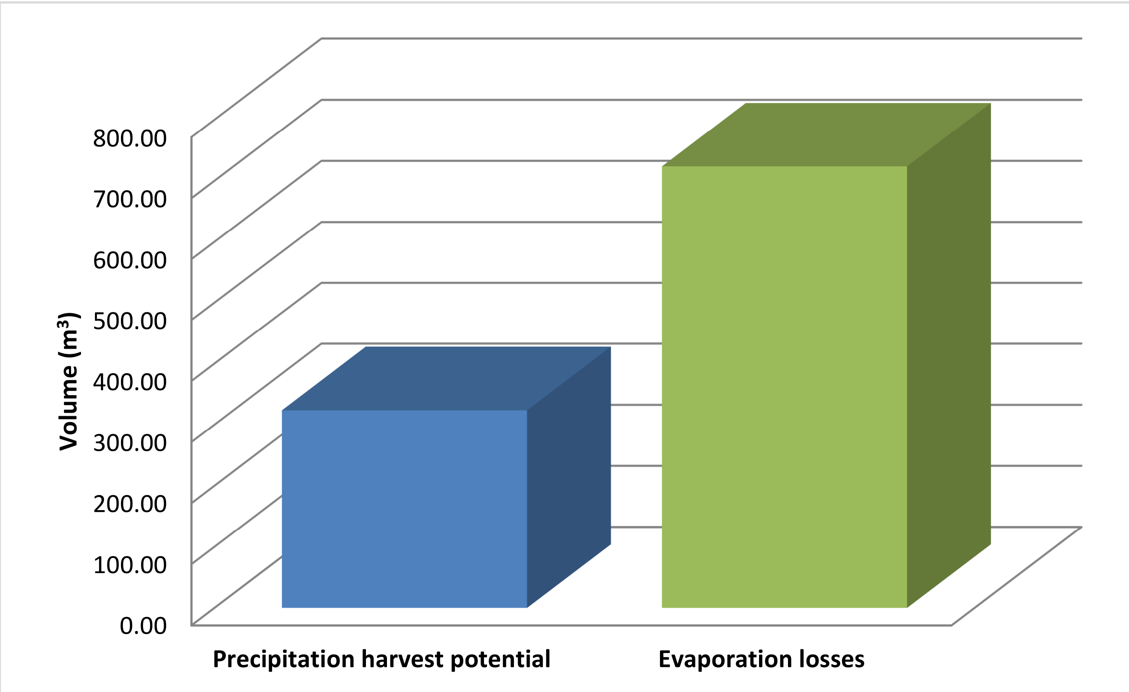

Figure 4-13 Comparison of precipitation and evaporation losses for a mine water balance.

A catchment management approach should be considered and storm water containment facilities should be designed to cater for flood events, capturing and re-using runoff. This approach is also referred to as rainwater harvesting, which is the process of maximising and capturing rainfall runoff for re-use in mining processes. Containment facilities should at all times hold a minimum freeboard and should not be used for process water reticulation purposes as is often the case in mining operations. Figure 4-14 and Figure 4-15 provide a comparison between the potential for rainfall harvesting considering both dry (5^{th} percentile data limits) and flood (95^{th} percentile data limits) events. There is a distinct difference in volumes available for reuse due to the difference in precipitation volumes recorded for draught and flood events. It must be kept in mind that rainwater and storm water are non-billable water sources and should be regarded as the best economical option available compared to groundwater and surface water allocations. Therefore water consumption after rain events should be prioritised in order to first use captured and contained storm water before it is lost to high rates of evaporation and seepage. The use of a control logic function as part of the water balance can manage the offset between water sourced from existing allocations and storm water in storage. Figure 4-15 validates the statement of Pulles *et al.* (2001) suggesting that rainwater-harvesting can account for up to 3% of input water sourcing, and illustrates that rainwater harvesting account for 6% (Figure 4-14) of the total make-up requirement for dry cycles (lower data limits) and up to 15% for wet cycles (upper data limits).

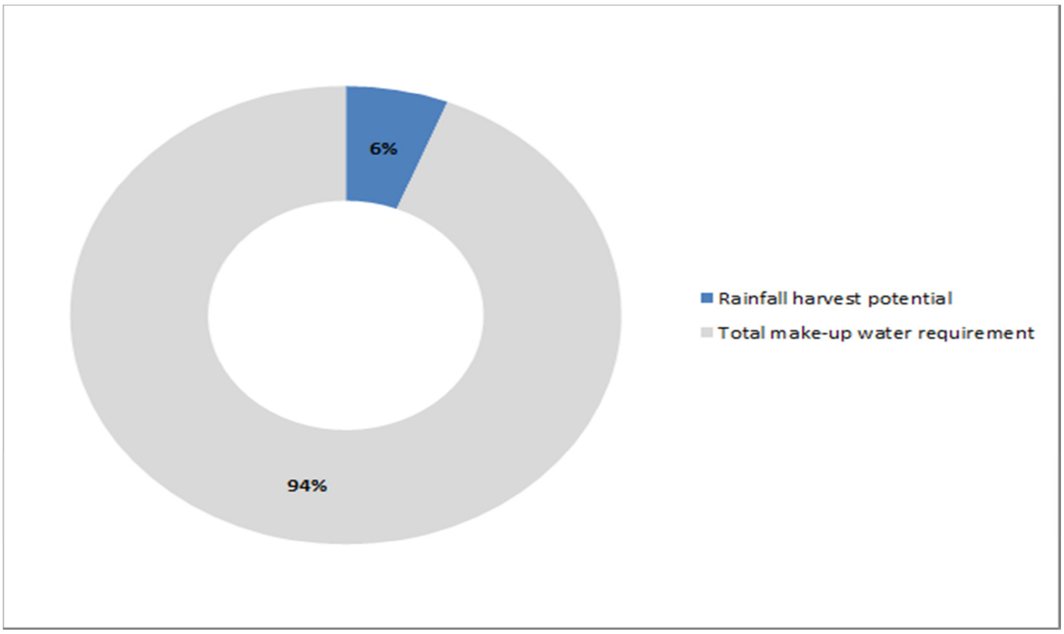

Figure 4-14 Potential for rainfall harvesting (5th percentile).

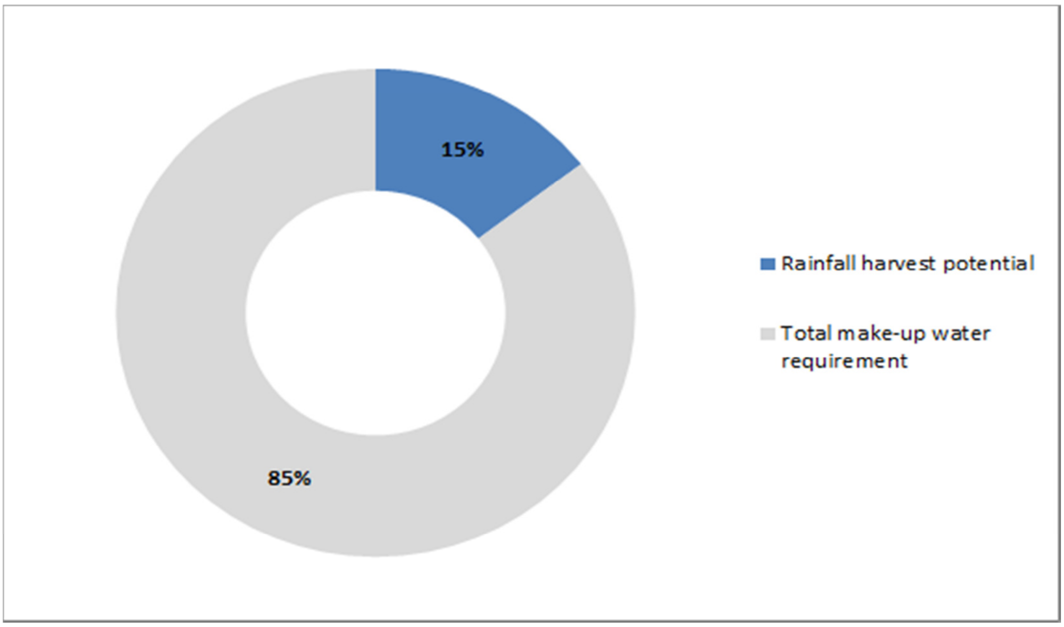

Figure 4-15 Potential for rainfall harvesting (95th percentile).

4.6.2.4 Incorporating mine dewatering

A significant contribution can be obtained from mine dewatered water and it is imperative to integrate dewatering predictions into the mine water balance. By doing so, accurate forecasts in terms of water requirements and sources can be made for management and planning purposes. Figure 4-16 indicates mine dewatering volumes as a function of time (5 year intervals) and can be included in forecasts, as discussed. Dewatering volumes are expected to increase with time and this can be incorporated in the management and strategic approach. Dewatering rates are validated by Witthuser *et al.* (2009) who state that relatively little groundwater is found in the deeper, un-weathered aquifers of the Bushveld Complex rocks.

4.6.2.5 Model calibration

It is important to verify values by regular updates as part of a dynamic calibration process. Figure 4-17 indicates a comparison between calculated and recorded flows at existing flow meters, with a good correlation between data sets. Measured flow volumes are higher than expected, especially water consumption for dust suppression, mining activities as well as domestic water use. This can probably be ascribed to the inefficient use of water and should be addressed as part of the updated water management plan. Dust suppression should be monitored and planned according to rain occurrences and Cote *et al.* (2010) reported that mine sites should not water roads if the rainfall exceeds 10mm over a period of 24 hours and can be implemented as part of the strategic management process. Considering an organic binder to be used in the suppression process can also be an alternative to water savings. As mentioned by GE (2006), dust suppression water savings of between 67% - 90% can be reached when making use of organic binders, while Kissel (2003) found that dust suppression by foam and fogging systems can dramatically lower water consumption. Underground service water use should be optimised and reused where possible. Further investigation and research should also be conducted on underground mining water usage for representative forecasts aiding in planning purposes. Domestic water usage can be optimised by implementation of water saving practices such as water low-consumption showers, reuse of grey water as part of the flushing system and awareness of water saving practices amongst employees.

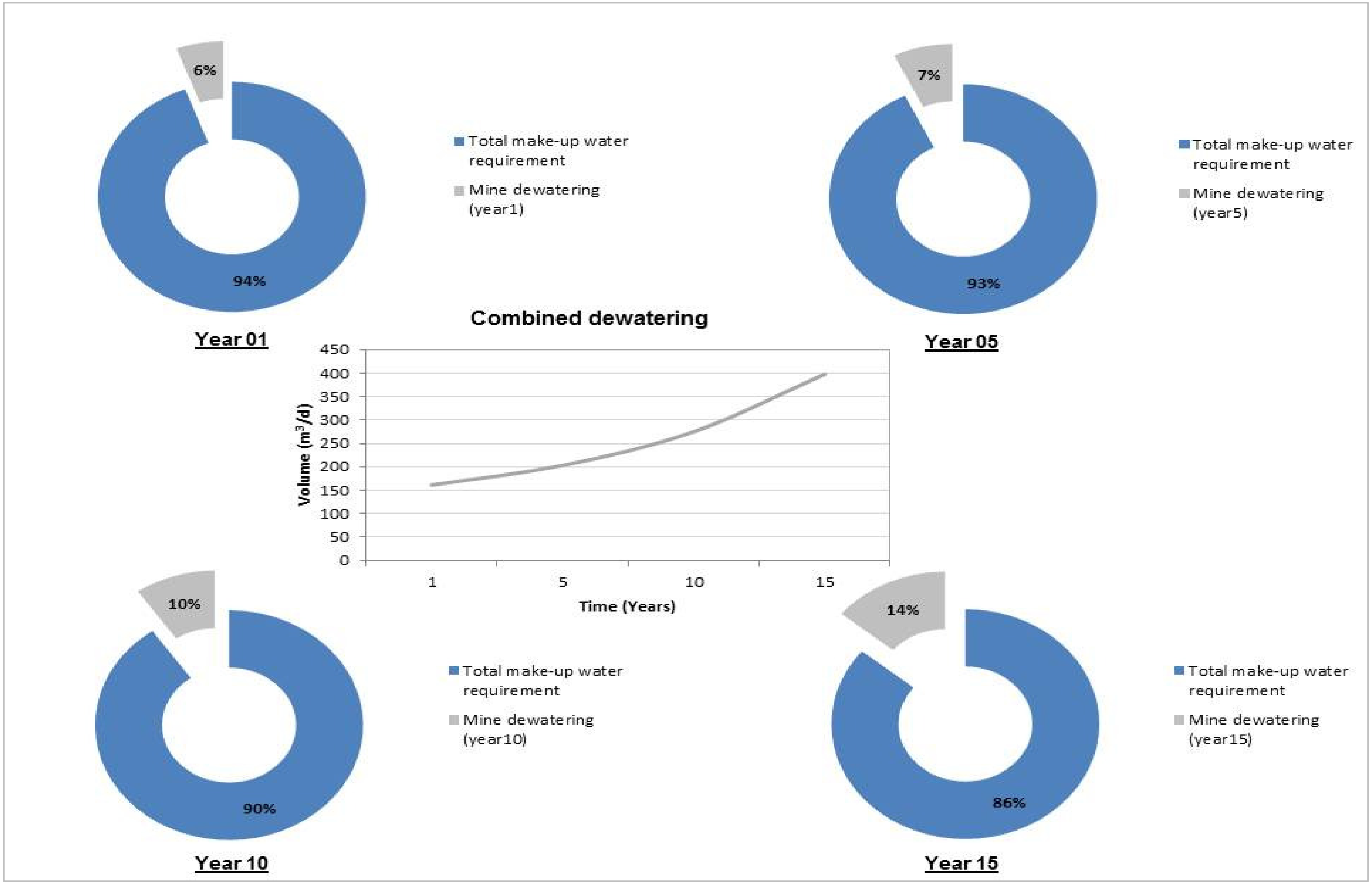

Figure 4-16 LOM dewatering ramp-up volumes relative to total make-up water requirement as a function of time.

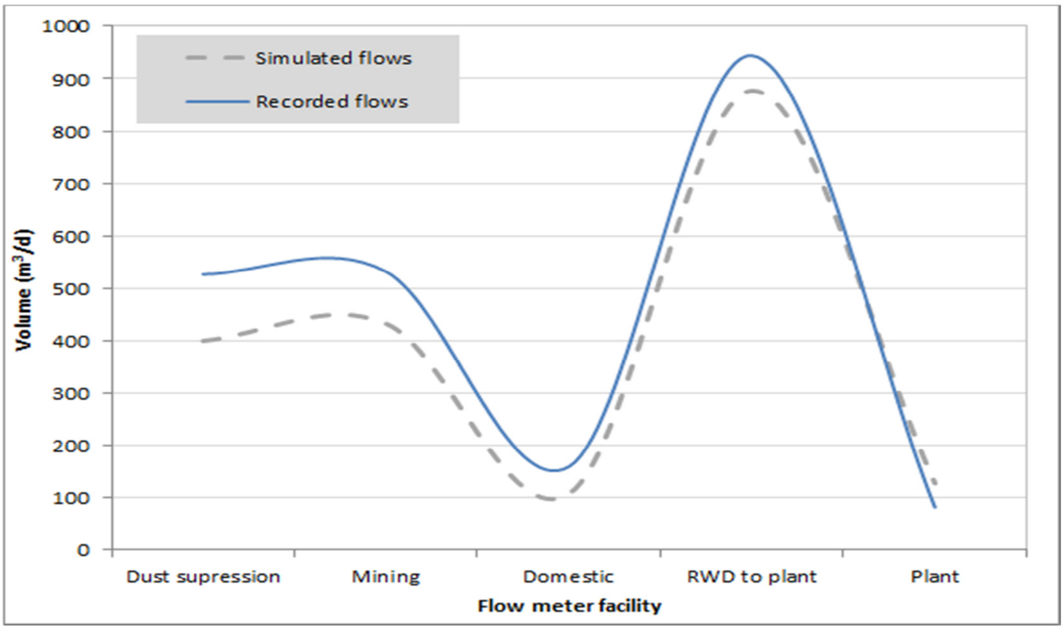

Figure 4-17 Simulated flows in relation to recorded flows as part of a calibration process.

4.6.2.6 Drought scenario

In this scenario, the lower 5th percentile of rainfall data was used as input, representing drought conditions (Table 4-4). This scenario should be evaluated as part of the worst case scenario from a water supply perspective (*i.e.* water deficit).

Table 4-4 Adapted mine water balance – dry conditions (5th percentile).

Component	Description	Quantity	Notations
Summary	**Make up water requirement (m³/ton milled)**	**0.67**	
	Make up water requirement (m³/d)	**2881.28**	
	Mean Annual Precipitation (MAP) (mm/a)	382.74	Rainfall Station no. 0554786
	Mean Annual Evaporation (MAE) (mm/a)	1956.90	WRC (2005)
	Water consumed in mining process (m³/d)	180.35	
	Water consumption in process plant (m³/d)	130.68	
	Water consumption in tailings facility circuit (m³/d)	2128.85	
	Water make from waste rock dump (m³/d)	12.94	
	Water consumption for domestic purposes (m³/d)	28.46	
	Water consumption for dust suppression (m³/d)	400.00	
Mining	Total RoM (t/month)	130000.00	Mine production schedule
	Mine ore : waste ratio	0.60	Resources development plan
	Mine production - ore (t/month)	78000.00	
	Mine production - waste (t/month)	52000.00	
	Precipitation on settlers (m³/d)	1.71	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses settlers (m³/d)	8.73	**Equation 2-5**, Kampf and Burges (2009)

Component	Description	Quantity	Notations
	Dewatering of underground mine workings (m^3/d)	260.00	**Equation 2-11** to Equation 2-13 after Singh and Atkins (1984).
	Mine make-up water use (m^3/ton)	0.10	Assumption, Section 2.2.1.1
	Mine make-up water use (m^3/d)	180.35	
Beneficiation Plant	ROM plant feed (t/month)	78000.00	Mine production schedule
	Water in ore (m^3/d)	52.00	**Equation 2-2** after Gunson (2010)
	Losses as product moisture (m^3/d)	154.18	Moisture retention tests = ~6% (Table 3-9)
	Precipitation on PWD (m^3/d)	0.61	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses PWD (m^3/d)	3.11	**Equation 2-5**, Kampf and Burges (2009)
	Process water consumption (m^3/ton)	0.01	Assumption, Section 2.2.1.2
	Process make-up water consumption (m^3/d)	130.68	
Tailings Storage Facility	Tailings production rate (ton/m^3)	52000.00	Mine production schedule
	Percentage solids by mass (%)	0.50	Design criteria
	Mass of slurry (t/month)	104000.00	Calculated
	Tailings post crush density (ton/m^3)	2.40	Design criteria
	Slurry density (ton/m^3)	1.41	Calculated after GJ Wiid (2013)
	Slurry water use (total water m^3/ton)	1.70	Calculated
	Evaporation losses (% of tailings loss)	442.44	McPhail (2005)
	Interstitial water lock-up (% of tailings loss)	1559.08	McPhail (2005)
	Beach rewetting (% of tailings losses)	88.49	Wels & Robertson (2003)
	Foundation seepage to groundwater (% of tailings losses)	47.97	**Equation 2-7** after Darcy (1856)
	Water loss in tailings circuit %	70.93	Calculated
	Water in slurry from plant to tailings dam (m^3/d)	2946.67	Calculated
	Return water to plant (m^3/d)	856.65	Calculated
	Precipitation on TSF (m^3/d)	30.95	**Equation 2-3**, Cote *et al.* (2010)
	Precipitation on RWD (m^3/d)	14.41	**Equation 2-9** after Beekman (1999)
	Evaporation losses RWD (m^3/d)	84.20	**Equation 2-5**, Kampf and Burges (2009)
	Seepage losses RWD (m^3/d)	98.15	50% assumption after Madramootoo (1997)
	Tailings circuit water consumption (m^3/ton)	0.49	Calculated
	Tailings circuit water consumption (m^3/d)	2128.85	
Waste Rock Dump	Waste rock dump drainage (m^3/d)	15.18	Ogola *et al.*(2011)
	Precipitation on pollution control dam (m^3/d)	0.55	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses from pollution control dam (m^3/d)	2.79	**Equation 2-5**, Kampf and Burges (2009)
	Seepage to groundwater (m^3/d)	3.04	Assumption based
Domestic	Employees	1157.00	Mine Social and Labour Plan
	Water use L/person/day	120.00	Destatis (2009)
	Mine potable/drinking water requirement (L/person/day)	3.00	Assumption based
	Total drinking water use (m^3/d)	3.47	Calculated
	Change house potable water component (m^3/d)	138.84	Calculated
	Total potable water use (m^3/d)	142.31	Calculated

Component	Description	Quantity	Notations
	Sewage water discharge (m^3/d)	113.85	D.Mara (2003)
	Sewerage water returned to circuit (m^3/d)	85.39	Calculated
	Sewerage water loss in sludge (m^3/d)	28.46	Assumption, Section 2.2.1.4
Other	Water used for dust suppression (m^3/d)	400.00	Assumption based - Qualified report review
Groundwater system	Total basin inflow (m^3/d)	214.91	**Table 3-5** after Singh and Atkins (1984)
	Total basin outflow (m^3/d)	360.00	**Equation 2-6** after de Ridder and Boonstra
	Change in storage (m^3/d)	-145.09	Indicating unsustainable scenario
Surface water system	Total precipitation runoff from meso-catchment (m^3/d)	173.48	**Equation 2-4**
	Total evaporation losses from meso-catchment (m^3/d)	684.55	**Equation 2-5**, Kampf and Burges (2009)
	Net inflow/outflow (m^3/d)	-511.07	**Equation 2-1**, Moran (2006)

4.6.2.7 Flooding scenario

In this scenario, the lower 95th percentile of rainfall data were used as input, representing wet conditions (Table 4-5). This scenario should be evaluated as part of the worst case scenario from a storm water management perspective (*i.e.* water surplus). As expected, the make-up water requirement for wet conditions (2837 m^3/d) differ from the make-up water requirement for dry conditions (2881 m^3/d) which can be ascribed to cycles occurring within the natural system.

Table 4-5 Adapted mine water balance – wet conditions (95th percentile).

Component	Description	Quantity	Notations
Summary	**Make up water requirement (m^3/ton milled)**	**0.66**	
	Make up water requirement (m^3/d)	**2837.21**	
	Mean Annual Precipitation (MAP) (mm/a)	910.72	Rainfall Station no. 0554786
	Mean Annual Evaporation (MAE) (mm/a)	1956.90	WRC (2005).
	Water consumed in mining process (m^3/d)	178.00	
	Water consumption in process plant (m^3/d)	129.84	
	Water consumption in tailings facility circuit (m^3/d)	2066.27	
	Water make from waste rock dump (m^3/d)	34.63	
	Water consumption for domestic purposes (m^3/d)	28.46	
	Water consumption for dust suppression (m^3/d)	400.00	
Mining	Total RoM (t/month)	130000.00	Mine production schedule
	Mine ore : waste ratio	0.60	Resources development plan
	Mine production - ore (t/month)	78000.00	
	Mine production - waste (t/month)	52000.00	

Component	Description	Quantity	Notations
	Precipitation on settlers (m^3/d)	4.06	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses settlers (m^3/d)	8.73	**Equation 2-5**, Kampf and Burges (2009)
	Dewatering of underground mine workings (m^3/d)	260.00	**Equation 2-11** to Equation 2-13 after Singh and Atkins (1984).
	Mine make-up water use (m^3/ton)	0.10	Assumption, Section 2.2.1.1
	Mine make-up water use (m^3/d)	178.00	
Beneficiation Plant	ROM plant feed (t/month)	78000.00	Mine production schedule
	Water in ore (m^3/d)	52.00	**Equation 2-2** after Gunson (2010)
	Losses as product moisture (m^3/d)	154.18	Moisture retention tests = ~6% (Table 3-9)
	Precipitation on PWD (m^3/d)	1.45	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses PWD (m^3/d)	3.11	**Equation 2-5**, Kampf and Burges (2009)
	Process water consumption (m^3/ton)	0.01	Assumption, Section 2.2.1.2
	Process make-up water consumption (m^3/d)	129.84	
Tailings Storage Facility	Tailings production rate (ton/m^3)	52000.00	Mine production schedule
	Percentage solids by mass (%)	0.50	Design criteria
	Mass of slurry (t/month)	104000.00	Calculated
	Tailings post crush density (ton/m^3)	2.40	Design criteria
	Slurry density (ton/m^3)	1.41	Calculated after GJ Wiid (2013)
	Slurry water use (total water m^3/ton)	1.70	Calculated
	Evaporation losses (% of tailings loss)	442.44	McPhail (2005)
	Interstitial water lock-up (% of tailings loss)	1559.08	McPhail (2005)
	Beach rewetting (% of tailings losses)	88.49	Wels & Robertson (2003)
	Foundation seepage to groundwater (% of tailings losses)	47.97	**Equation 2-7** after Darcy (1856)
	Water loss in tailings circuit %	70.93	Calculated
	Water in slurry from plant to tailings dam (m^3/d)	2946.67	Calculated
	Return water to plant (m^3/d)	856.65	Calculated
	Precipitation on TSF (m^3/d)	73.65	**Equation 2-3**, Cote *et al.* (2010)
	Precipitation on RWD (m^3/d)	34.29	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses RWD (m^3/d)	84.20	**Equation 2-5**, Kampf and Burges (2009)
	Seepage losses RWD (m^3/d)	98.15	50% assumption after Madramootoo (1997)
	Tailings circuit water consumption (m^3/ton)	0.48	Calculated
	Tailings circuit water consumption (m^3/d)	2066.27	
Waste Rock Dump	Waste rock dump drainage (m^3/d)	36.12	Ogola *et al.*(2011)
	Precipitation on pollution control dam (m^3/d)	1.30	**Equation 2-3**, Cote *et al.* (2010)
	Evaporation losses from pollution control dam (m^3/d)	2.79	**Equation 2-5**, Kampf and Burges (2009)
	Seepage to groundwater (m^3/d)	7.22	Assumption based
Domestic	Employees	1157.00	Mine Social and Labour Plan

Component	Description	Quantity	Notations
	Water use L/person/day	120.00	Destatis (2009)
	Mine potable/drinking water requirement (L/person/day)	3.00	Assumption based
	Total drinking water use (m^3/d)	3.47	Calculated
	Change house potable water component (m^3/d)	138.84	Calculated
	Total potable water use (m^3/d)	142.31	Calculated
	Sewage water discharge (m^3/d)	113.85	D.Mara (2003)
	Sewerage water returned to circuit (m^3/d)	85.39	Calculated
	Sewerage water loss in sludge (m^3/d)	28.46	Assumption, Section 2.2.1.4
Other	Water used for dust suppression (m^3/d)	400.00	Assumption based - Qualified report review
Groundwater system	Total basin inflow (m^3/d)	309.81	**Table 3-5** after Singh and Atkins (1984)
	Total basin outflow (m^3/d)	360.00	**Equation 2-6** after de Ridder and Boonstra
	Change in storage (m^3/d)	-50.19	Indicating unsustainable scenario
Surface water system	Total precipitation runoff from meso-catchment (m^3/d)	412.78	**Equation 2-4**
	Total evaporation losses from meso-catchment (m^3/d)	684.55	**Equation 2-5**, Kampf and Burges (2009)
	Net inflow/outflow (m^3/d)	-271.77	**Equation 2-1**, Moran (2006)

4.6.3 Seasonal fluctuations

Ward and Loftis (1986) state that commonly assumed parameters, which do not apply for hydrological models, include the absence of incorporating the effect of seasonal fluctuations. Accordingly, a monthly evaluation of mine make-up water requirements (Table 4-6) highlights months of expected water deficit as well as surplus stages when compared to the MAP scenario. Ore processing usually requires a constant supply of water while water consumption for the remaining components in the circuit will vary seasonably (Gunson *et al.*, 2012). As indicated in Figure 4-18, these climatic fluctuations have a major effect on dust suppression as well as evaporation losses. This iterates the importance of a monthly water balance break-down and indicates that planning cannot be based solely on an annual MAP scenario. However, in order to forecast periods of increased water usage and periods of a decrease in make-up requirements accurately, interval periods have to be kept to a minimum. The dynamic calculation of a mine water balance is associated with varying seasonal water demands, and is often poorly understood by plant managers. Accordingly, excessive costs can result from both poor understanding of water resource availability, incomplete information relating to water consumption and resulting water management decisions (Griffiths *et al.*, 2009).

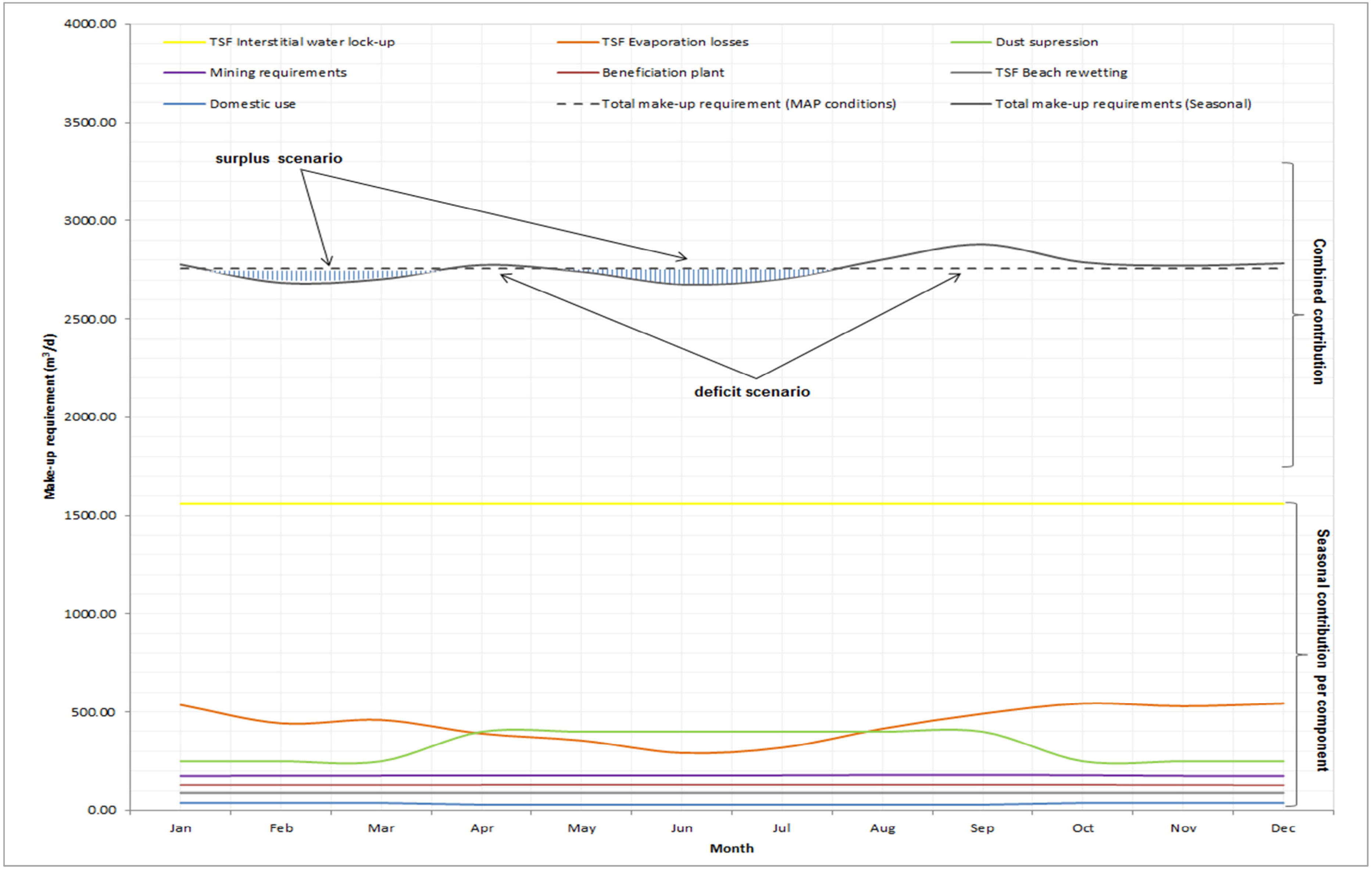

Figure 4-18 **Effect of seasonal fluctuations on mine make-up water requirements.**

Table 4-6 Mine water balance – Monthly evaluation.

Component	Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Summary	**Make up water requirement (m³/ton milled)**	**0.63**	**0.62**	**0.63**	**0.65**	**0.65**	**0.64**	**0.64**	**0.67**	**0.69**	**0.65**	**0.63**	**0.63**	**0.65**
	Make up water requirement (m³/d)	**2711.4**	**2646.2**	**2688.7**	**2784.5**	**2783.7**	**2726.6**	**2753.8**	**2872.3**	**2953.0**	**2796.6**	**2713.4**	**2713.9**	**2762.0**
	Mean Annual Precipitation (MAP) (mm/a)	111.8	87.1	66.4	43.2	14.4	5.3	6.0	5.8	21.3	62.1	107.8	114.8	53.8
	Mean Annual Evaporation (MAE) (mm/a)	197.4	162.9	169.1	143.6	130.6	107.4	117.5	152.8	180.8	199.9	195.0	199.9	163.1
	Water consumed in mining process (m³/d)	176.1	176.9	177.7	178.2	179.2	178.8	179.1	181.0	181.7	179.6	176.6	176.0	178.4
	Water consumption in process plant (m³/d)	129.2	129.4	129.7	129.9	130.3	130.1	130.2	130.1	131.2	130.4	129.3	128.2	129.8
	Water consumption in tailings facility circuit (m³/d)	2065.3	2011.2	2062.9	2028.7	2040.6	1988.4	2014.9	2132.4	2204.0	2170.9	2068.8	2067.5	2071.3
	Water make from waste rock dump (m³/d)	53.1	40.9	30.7	19.3	5.1	0.8	1.1	0.4	7.6	27.9	51.0	54.5	24.4
	Water consumption for domestic purposes (m³/d)	37.7	37.7	37.7	28.5	28.5	28.5	28.5	28.5	28.5	37.7	37.7	37.7	33.1
	Water consumption for dust suppression (m³/d)	250.0	250.0	250.0	400.0	400.0	400.0	400.0	400.0	400.0	250.0	250.0	250.0	325.0
Mining	Total RoM (t/month)	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0	130000.0
	Mine ore : waste ratio	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Mine production - ore (t/month)	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0
	Mine production - waste (t/month)	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0
	Precipitation on settlers (m³/d)	7.6	5.9	4.5	2.9	1.0	0.4	0.4	0.4	1.4	4.2	7.3	7.8	3.7
	Evaporation losses settlers (m³/d)	10.4	9.5	8.9	7.8	6.9	5.8	6.2	8.0	9.8	10.5	10.6	10.5	8.7
	Dewatering of underground mine workings (m³/d)	260.0	260.0	260.0	260.0	260.0	260.0	260.0	260.0	260.0	260.0	260.0	260.0	260.0
	Mine make-up water use (m³/ton)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Compo-nent	Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
	Mine make-up water use (m³/d)	176.1	176.9	177.7	178.2	179.2	178.8	179.1	181.0	181.7	179.6	176.6	176.0	**178.4**
Beneficiation Plant	ROM plant feed (t/month)	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0	78000.0
	Water in ore (m³/d)	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0
	Losses as product moisture (m³/d)	154.2	154.2	154.2	154.2	154.2	154.2	154.2	154.2	154.2	154.2	154.2	154.2	154.2
	Precipitation on PWD (m³/d)	2.7	2.1	1.6	1.0	0.3	0.1	0.1	0.1	0.5	1.5	2.6	3.7	1.4
	Evaporation losses PWD (m³/d)	3.7	3.4	3.2	2.8	2.4	2.1	2.2	2.9	3.5	3.7	3.8	3.7	3.1
	Process water consumption (m³/ton)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Process make-up water consumption (m³/d)	129.2	129.4	129.7	129.9	130.3	130.1	130.2	130.1	131.2	130.4	129.3	128.2	**129.8**
Tailings Storage Facility	Tailings production rate (ton/m³)	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0	52000.0
	Percentage solids by mass (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Mass of slurry (t/month)	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0	104000.0
	Tailings post crush density (ton/m³)	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	Slurry density (ton/m³)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	Slurry water use (total water m³/ton)	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Evaporation losses (% of tailings loss)	536.9	443.1	460.0	390.6	355.2	292.1	319.6	415.6	491.8	543.7	530.4	543.7	443.6
	Interstitial water lock-up (% of tailings loss)	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1	1559.1
	Beach rewetting (% of tailings losses)	88.5	88.5	88.5	88.5	88.5	88.5	88.5	88.5	88.5	88.5	88.5	88.5	88.5
	Foundation seepage to groundwater (% of tailings losses)	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0
	Water loss in tailings circuit %	74.1	70.9	71.5	69.2	68.0	65.8	66.8	70.0	72.6	74.4	73.9	74.4	71.0
	Water in slurry from plant to tailings dam (m³/d)	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7	2946.7
	Return water to plant (m³/d)	762.2	856.0	839.1	908.5	943.9	1007.0	979.5	883.5	807.3	755.4	768.7	755.4	855.5

Component	Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
	Precipitation on TSF (m^3/d)	146.1	113.8	86.8	56.4	18.9	7.0	7.9	7.6	27.8	81.1	140.8	150.0	70.3
	Precipitation on RWD (m^3/d)	73.2	57.0	43.5	28.2	9.5	0.5	3.9	0.6	2.1	40.6	70.5	75.1	33.7
	Evaporation losses RWD (m^3/d)	100.0	91.4	85.7	75.2	66.2	56.2	59.5	77.4	94.6	101.3	102.1	101.3	84.2
	Seepage losses RWD (m^3/d)	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2
	Tailings circuit water consumption (m^3/ton)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Tailings circuit water consumption (m^3/d)	2065.3	2011.2	2062.9	2028.7	2040.6	1988.4	2014.9	2132.4	2204.0	2170.9	2068.8	2067.5	**2071.3**
Waste Rock Dump	Waste rock dump drainage (m^3/d)	53.9	42.0	32.1	20.8	7.0	2.6	2.9	2.8	10.3	29.9	52.0	55.4	26.0
	Precipitation on pollution control dam (m^3/d)	2.4	1.9	1.4	0.9	0.3	0.1	0.1	0.1	0.5	1.3	2.3	2.5	1.2
	Evaporation losses from pollution control dam (m^3/d)	3.3	3.0	2.8	2.5	2.2	1.9	2.0	2.6	3.1	3.4	3.4	3.4	2.8
	Seepage to groundwater (m^3/d)	10.8	8.4	6.4	4.2	1.4	0.5	0.6	0.6	2.1	6.0	10.4	11.1	5.2
Domestic	Employees	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0	1157.0
	Water use L/person/day	160.0	160.0	160.0	120.0	120.0	120.0	120.0	120.0	120.0	160.0	160.0	160.0	140.0
	Mine potable/drinking water requirement (L/person/day)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	Total drinking water use (m^3/d)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	Change house potable water component (m^3/d)	185.1	185.1	185.1	138.8	138.8	138.8	138.8	138.8	138.8	185.1	185.1	185.1	162.0
	Total potable water use (m^3/d)	188.6	188.6	188.6	142.3	142.3	142.3	142.3	142.3	142.3	188.6	188.6	188.6	165.5
	Sewage water discharge (m^3/d)	150.9	150.9	150.9	113.8	113.8	113.8	113.8	113.8	113.8	150.9	150.9	150.9	132.4
	Sewerage water returned to circuit (m^3/d)	113.2	113.2	113.2	85.4	85.4	85.4	85.4	85.4	85.4	113.2	113.2	113.2	99.3
	Sewerage water loss in sludge (m^3/d)	37.7	37.7	37.7	28.5	28.5	28.5	28.5	28.5	28.5	37.7	37.7	37.7	**33.1**
Other	Water used for dust suppression (m^3/d)	250.0	250.0	250.0	400.0	400.0	400.0	400.0	400.0	400.0	250.0	250.0	250.0	**325.0**
Groundwater system	Total basin inflow (m^3/d)	390.7	336.7	291.5	240.5	177.7	157.8	159.3	158.8	192.7	281.9	381.8	397.2	263.9
	Total basin outflow (m^3/d)	360.0	360.0	360.0	360.0	360.0	360.0	360.0	360.0	360.0	360.0	360.0	360.0	360.0
	Change in storage (m^3/d)	30.7	-23.3	-68.5	-119.5	-182.3	-202.2	-200.7	-201.2	-167.3	-78.1	21.8	37.2	-96.1

Compo-nent	Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Surface water system	Total precipitation runoff from meso-catchment (m³/d)	681.3	530.9	404.9	263.0	88.0	32.4	36.6	35.4	129.8	378.2	656.7	699.5	328.1
	Total evaporation losses from meso-catchment (m³/d)	870.7	748.1	745.9	676.5	576.1	479.8	518.3	674.0	807.7	881.8	871.1	881.8	727.6
	Net inflow/outflow (m³/d)	-189.5	-217.2	-341.0	-413.5	-488.0	-447.4	-481.7	-638.6	-677.9	-503.6	-214.5	-182.2	-399.6

4.7 Discussion: Chapter 4

This chapter focussed on applying acquired data for the development of different mine water balance scenarios and applicable interpretations. Any system operating within specified boundaries should be subjected to certain assumptions in order to understand its behaviour.

The first scenario applied the methodology to a conventional mine water balance, thus not incorporating any influences from the natural water system. Total make-up water requirements calculated corresponds well to published literature for base-metal operations. The following scenarios focussed on applying the adapted methodology, accounting for influences from natural system. For mean annual precipitation conditions, make-up water requirements decreased by approximately 10% compared to the conventional approach, implying that the adapted methodology does have a significant effect on calculations and estimations. This supports the argument that natural system water is often disregarded and underestimated during calculations and estimations, which can significantly impact on mine water usage and losses. Climatic conditions and groundwater interaction has a significant effect on the water consumption of the mining, tailings and dust suppression components as is indicated.

Additional scenarios, evaluating mine make-up water requirements for different data percentile distributions *i.e.* drought and flooding events, highlights the importance of integrating hydrological cycles, occurring within the natural system, into the water management strategy. Seasonal fluctuations and the effect thereof should also be considered as wet and dry month's water consumptions can differ dramatically. It is evident that a mine water balance will be just as dynamic as climatic conditions when developed in parallel with each other and influences of such should be incorporated for effective mine water management. The following chapter will conclude this investigation and will include a discussion on objectives reached.

Chapter 5

5 CONCLUSIONS AND OUTLOOK

From the present study it is evident that the mining sector can expect to be increasingly required to demonstrate leadership through water use management. As water scarcity will continue to be one of the greatest challenges facing mine water management, regulations by environmental authorities along with past polluting practices, are forcing mining operations to improve and prioritise their water consumption. Accordingly, an accurate mine water balance is proposed aiding in strategic water management and is considered to be one of the most important management tools available for mining operations.

This investigation summarises general water balance principles, based on the fundamentals of mass conservation, in which the inflows to a system are balanced by the sum of outflows or a change in storage under natural conditions. This basic water accounting principle can be applied to any operating unit within specified boundaries. An appropriate balance should exist between the required level of complexity in a model and the purpose of the model, and can be achieved by applying a systems model approach focussing on the system as a whole. It has also been concluded that water management on mining operations is intrinsically associated with uncertain and indefinable parameters of the larger hydrological cycle such as evaporation, precipitation, seepage, infiltration, recharge and groundwater ingress into mine workings, which can have a significant influence on the overall mine water balance. Through the literature review it has become apparent that assumptions form the basis for these uncertain parameters which can be incorporated by a selection of appropriate statistical analysis techniques.

Mining operations can evolve into large, complex reticulation systems and it is important to identify the main drivers of water usage to focus and improve management within these areas. Main components or operating units of a mine water balance include the mining component, open pit and/or underground, beneficiation plant component, tailings component, waste rock dump component, domestic component as well as an environmental component. An overall mine water balance superimposes two water systems and can be categorised as water consumed in the process system and water forming part of the natural system, encompassing the intrinsic hydrological cycle. The latter component represents the most variability and uncertainty within a mine water balance and is therefore often neglected from water balance calculations. This component can however have a significant effect on mine water losses and usage and accordingly should be incorporated into an adapted mine water balance in order to provide a better and more representative output.

A comparison between conventional mine water balances, with emphasis on process system water, and an adapted mine water balance incorporating natural systems water, is presented and compared. The latter system includes a surface water environmental circuit as well as a groundwater environmental circuit. Consequently, components of hydrology as well as hydrogeology must not be viewed in isolation from each other, but interaction between process system and the natural system is required to facilitate resource management. Research also revealed mining activities to have a significant impact on the hydrological regime and mining induced recharge should be evaluated and included in the water balance as the groundwater component. Furthermore, underground mine dewatering was evaluated as a scenario and shown to have a definite impact and contribution to the total make-up water requirement, which can serve as an economical alternative source for water supply.

More than ever, special measures are needed to identify options for life-of-mine strategies and initiatives for water conservation. As part of a strategic approach, a waste management hierarchy must be developed, establishing a clear priority order in which applicable management options must be considered. The key principle of effective and efficient mine water management is the requirement that all water conservation as well as pollution prevention options should initially be considered and exhausted. This should be carried out before a shift is made to impact minimisation measures, water reuse and reclamation and ultimately, treatment and discharge as last option. Continuing, the investigation indicated that water management principles must direct the development of a management strategy and mining operations should optically match their water uses with the required water quantity and quality. Novel water use efficiency techniques covered include the use of high density thickened tailings, the implementation of a water reduction model focussing on available off-the-shelf mining technology options as well as considering artificial recharge to bring groundwater into mining as a sustainable partner. These techniques should be used to simulate strategies and implement such to improve management.

An overview of existing literature established that there is a lack in detail contained in evaluated mine water balances. It was found that due to the incompleteness of water balances, reflected by large percentages of water losses to unspecified sinks, meaningful conclusions about water usage patterns on mining operations cannot be made. Accordingly the absence of appropriate mine water balances is believed to be a serious hindrance to effective mine water management and needs to be addressed as a matter of priority.

Primary problems include an inadequate consideration of the effects of evaporation and seepage losses as well as the effect of rainwater as an input, *i.e.* the natural system, to the water balance model. Additional findings revealed that water balances are not being updated regularly and as an operational concern. Reluctance from mining operations to provide data result in repeated requests for information. Existing methodologies place the focus on developing a mine water balance solely on a process systems water approach while it should be considered to incorporate both the process water system as well as the natural water system. Decision making and management options should be based on the evaluation of the system as a whole, with the inclusion of the natural system as a component of the mine water balance imperative for accurate quantification and prediction of site conditions.

Consequently, an adapted mine water balance was developed and it is believed that mining operations will benefit greatly from such a simplistic, computerised water balance model. This model allows the easy updating of data to reflect a change in reticulation patterns. The preparation of a mine water balance requires close collaboration between plant, mining and tailings engineers, hydrologists, hydrogeologists and environmentalists. A mine water balance should be updated during the mine development and operational phase to be calibrated more accurately and used as a management tool in order to support aftercare strategies. Figure 5-1 summarises the mine water balance approach adapted from the DWA BPG's (Pulles and van Rensburg, 2006b), incorporating the natural system by integrating groundwater and surface water interaction and aiding in strategic mine water management, as follows:

- Define mine water balance objectives and re-define objectives for refinement as part of a feedback process;
- Define system boundaries and identify operating units by implementing a systems approach;
- Identify water circuits and develop a schematic flow diagram for a conceptual representation of the site reticulation;
- Data collection and monitoring for model input;
- Accounting for data uncertainty by statistical analyses and probability distributions;
- Assigning collected data and solving of balances per operating unit;
- Integrate flow volumes with water qualities for development of a salt balance;
- Incorporate both natural and process system water as part of an integrated approach by implementing water balance assumptions and quantification formulations;
- Evaluate operational efficiency by application of Equation 2-18 and Equation 2-19;

- Putting the newly developed mine water balance into a contextual perspective by integrating the geographical terrain, catchment details, climatic conditions, assumptions and water policies;
- Record real-time flow volumes and compare volumes to calculated and predicted flows as part of an on-going calibration process; and
- Integrate strategic management principles and implement the mine water balance model as a management tool.

In conclusion, this mine water balance was developed as a guidance tool to support operations in improving water management. The implementation of a systems and holistic water balance approach was successful due to its simplicity and adaptability as a management tool. Future focus should be to continue investigation and implementation of the water use strategies in order to improve performance across operations and encourage engagement with other water users. Moreover to share experiences, learn from others and contribute to water discussions and debate at local, national and international levels.

"We do not want certainty (from models) we will be satisfied with engineering confidence."

De Marsily, 1992.

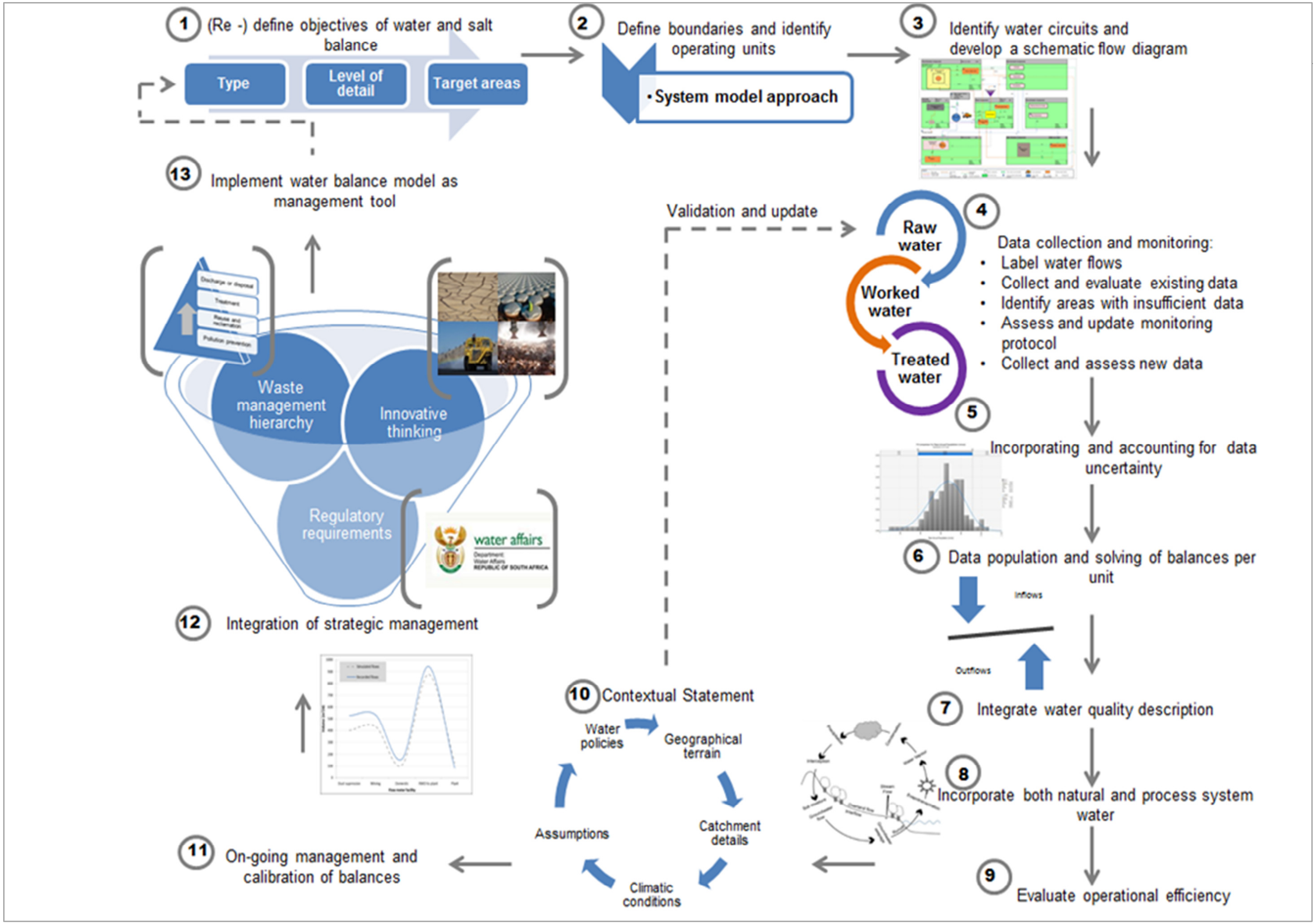

Figure 5-1 Adapted mine water balance approach accounting for uncertainties and incorporating the natural cycle as a component.

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7 APPENDICES

7.1 Appendix A: Rainfall data

Table 7-1 Historical rainfall data (1904 – 2012).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1904	38.40	111.70	113.20	19.10	7.90	0.00	0.00	0.00	4.60	35.10	159.60	71.40	561.00
1905	199.40	66.80	36.80	34.50	6.60	0.00	0.00	1.80	0.00	6.30	44.20	172.20	568.60
1906	95.30	181.80	72.00	0.00	0.00	0.00	0.00	0.00	22.30	94.80	101.10	126.40	693.70
1907	157.00	149.50	39.60	48.70	0.00	0.00	0.00	0.00	18.80	57.50	75.90	101.30	648.30
1908	122.50	82.30	19.80	27.50	6.50	0.00	0.00	0.00	4.80	52.20	112.60	85.80	514.00
1909	144.40	109.80	34.10	43.40	7.50	0.00	0.00	18.20	69.70	14.70	89.80	124.40	656.00
1910	97.80	136.70	26.70	43.00	0.00	0.00	0.00	0.00	0.00	111.00	103.10	103.70	622.00
1911	110.70	53.60	52.70	71.70	52.10	0.00	20.90	0.00	7.00	94.70	92.40	56.90	612.70
1912	96.90	17.00	106.40	94.50	9.70	0.00	0.00	0.00	0.00	23.50	42.80	107.90	498.70
1913	145.90	157.10	28.30	54.60	11.40	0.00	7.40	0.00	11.00	74.20	71.80	82.80	644.50
1914	46.70	109.20	112.10	33.30	30.70	0.90	0.00	2.00	0.00	32.40	132.60	202.70	702.60
1915	310.40	124.50	58.70	9.90	6.40	0.00	29.30	0.00	13.70	54.30	64.50	97.90	769.60
1916	56.80	43.00	42.40	21.10	5.40	0.00	0.00	0.00	0.00	14.70	152.60	127.00	463.00
1917	99.40	43.10	26.20	23.40	49.80	30.10	3.30	100.60	26.00	72.40	167.10	173.20	814.60
1918	237.20	129.50	101.40	13.40	0.00	17.60	1.40	12.20	3.10	40.60	45.80	135.40	737.60
1919	122.40	79.50	33.00	12.10	1.20	1.20	5.50	8.10	20.00	29.20	105.30	52.30	469.80
1920	224.60	76.20	114.30	5.10	68.50	0.00	0.00	0.00	0.00	111.50	173.50	74.40	848.10
1921	63.40	67.60	76.30	13.20	6.40	0.00	0.00	0.00	2.50	72.40	159.60	186.20	647.60
1922	75.10	66.80	90.00	24.20	29.50	6.10	0.00	73.20	5.60	163.10	156.80	112.80	803.20
1923	155.20	60.00	31.70	1.00	8.90	1.50	0.00	0.00	2.30	19.60	120.80	95.10	496.10
1924	74.10	76.00	82.50	8.40	53.70	0.00	0.00	1.00	14.40	54.90	163.00	95.10	623.10
1925	93.50	36.50	81.60	54.60	40.90	0.00	2.50	0.00	78.90	72.90	112.30	18.80	592.50
1926	59.00	70.10	23.50	0.00	10.70	0.00	5.80	0.00	11.50	8.60	48.00	87.00	324.20
1927	67.40	166.20	60.60	34.20	6.60	0.00	52.80	10.40	14.20	69.20	56.20	51.00	588.80
1928	136.10	142.60	15.10	34.60	0.00	0.00	0.00	5.10	2.30	43.60	32.00	102.80	514.20
1929	104.50	84.60	105.40	42.20	11.70	0.00	0.00	0.00	53.60	170.40	117.00	100.00	789.40

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1930	187.00	148.40	83.10	48.40	6.10	5.10	7.10	0.00	1.50	13.70	72.90	72.30	645.60
1931	83.00	69.10	69.20	29.90	0.00	3.00	31.40	0.00	7.10	32.50	67.10	71.30	463.60
1932	113.80	94.40	42.70	33.30	14.00	4.10	0.00	0.00	5.30	20.60	73.10	83.10	484.40
1933	187.00	27.70	83.40	19.10	0.00	4.30	5.30	0.00	17.30	41.10	127.20	96.00	608.40
1934	168.20	78.90	98.00	23.40	3.00	13.20	0.00	0.00	23.30	89.20	87.20	123.80	708.20
1935	65.10	62.90	35.30	17.80	0.00	3.30	0.00	0.00	24.20	27.90	31.30	105.70	373.50
1936	160.50	44.80	46.40	47.10	36.70	0.00	0.80	0.00	5.90	118.60	125.30	98.30	684.40
1937	229.70	69.60	67.60	20.20	0.00	0.00	0.00	0.00	20.40	19.10	84.90	247.60	759.10
1938	88.10	103.00	68.90	96.40	2.50	8.70	7.60	4.10	37.60	33.30	69.40	294.10	813.70
1939	173.10	225.40	87.70	5.80	17.50	0.00	48.70	0.00	98.10	44.50	223.00	152.00	1075.80
1940	44.80	106.40	40.00	59.70	35.10	42.90	0.00	3.30	17.80	43.40	161.60	172.00	727.00
1941	48.50	157.50	109.10	65.80	0.00	0.00	0.00	0.00	4.80	54.10	36.20	113.00	589.00
1942	47.80	12.70	193.30	0.00	36.80	20.80	0.00	4.10	41.60	32.20	201.70	67.30	658.30
1943	118.20	20.10	173.30	95.00	46.20	4.10	75.20	30.00	29.00	85.00	69.30	73.70	819.10
1944	119.70	148.60	22.80	14.00	0.00	29.50	0.00	0.00	4.60	103.30	42.00	26.20	510.70
1945	140.40	57.40	95.60	44.80	0.00	0.00	0.00	0.00	5.10	79.30	67.30	29.90	519.80
1946	120.20	121.10	47.70	118.10	8.40	0.00	0.00	0.00	16.50	3.60	142.50	128.70	706.80
1947	123.20	73.60	63.50	56.40	0.00	25.30	2.50	0.00	40.20	103.00	116.40	155.00	759.10
1948	109.40	37.30	114.10	45.00	3.80	0.00	0.00	0.00	17.30	94.70	81.10	55.60	558.30
1949	128.60	92.70	75.50	26.90	11.20	0.00	1.00	0.00	27.70	23.60	129.50	158.80	675.50
1950	77.50	0.00	51.00	79.80	27.00	0.00	5.30	0.00	81.80	45.20	129.50	135.10	632.20
1951	76.00	34.60	95.80	134.30	58.10	5.80	0.00	47.00	29.20	74.90	59.70	240.50	855.90
1952	18.60	65.60	99.50	40.90	6.10	4.30	7.10	0.00	0.00	10.40	111.20	164.60	528.30
1953	80.20	104.10	67.80	66.00	8.80	3.50	0.00	1.80	18.50	78.30	172.70	94.50	696.20
1954	110.10	92.60	19.60	53.50	15.70	0.00	0.00	0.70	7.00	38.00	127.60	66.60	531.40
1955	166.30	118.20	80.90	108.50	12.50	0.00	0.00	0.00	0.00	93.30	112.00	125.40	817.10
1956	39.50	126.60	96.50	7.00	73.50	17.00	4.50	0.00	103.50	48.00	36.50	98.50	651.10
1957	154.00	116.00	93.00	65.00	8.50	7.30	20.50	9.00	52.50	71.00	47.00	72.50	716.30
1958	221.00	46.00	20.00	46.50	1.50	3.00	0.00	0.00	23.50	58.50	198.50	133.00	751.50
1959	173.50	35.00	51.00	26.00	14.50	0.00	13.50	3.00	33.00	86.00	88.00	165.20	688.70
1960	105.00	219.70	50.50	72.00	13.50	0.00	1.50	0.00	37.00	25.00	160.30	141.20	825.70

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1961	59.30	169.50	97.50	37.50	25.50	62.40	9.60	6.20	38.00	53.50	63.60	145.00	767.60
1962	25.00	87.00	58.00	46.40	0.00	0.00	0.00	5.00	4.00	78.20	197.30	135.50	636.40
1963	109.50	21.50	21.50	65.00	9.50	45.00	13.00	0.00	0.00	75.20	85.00	111.00	556.20
1964	98.50	69.20	16.50	68.50	5.00	5.20	0.00	3.50	0.00	109.40	85.80	120.00	581.60
1965	94.20	69.80	0.00	85.50	2.50	0.00	0.00	1.10	47.00	27.00	140.00	104.60	571.70
1966	63.50	56.70	0.00	19.50	0.00	8.00	0.00	16.70	8.20	65.00	65.50	234.40	537.50
1967	106.30	133.20	55.30	134.50	6.60	0.00	27.50	3.00	2.40	76.30	99.50	105.00	749.60
1968	72.80	88.50	59.50	44.50	6.50	14.70	6.20	8.20	0.00	24.30	101.80	110.80	537.80
1969	101.90	71.40	142.60	39.30	45.80	0.00	0.70	0.00	39.00	101.90	141.90	114.80	799.30
1970	30.90	101.50	53.10	36.20	10.40	3.10	5.00	7.00	12.40	54.50	166.20	169.50	649.80
1971	108.00	67.30	58.80	43.50	29.40	14.50	0.00	0.00	46.00	93.80	191.60	98.50	751.40
1972	150.10	98.20	117.90	79.50	45.50	0.00	0.00	0.70	22.00	103.80	151.00	44.70	813.40
1973	138.10	106.10	84.50	158.50	2.50	0.00	0.00	0.00	140.80	67.40	117.70	118.10	933.70
1974	241.40	70.80	30.00	166.80	6.10	3.90	28.60	8.10	19.60	44.50	86.90	150.40	857.10
1975	250.00	112.40	62.00	60.20	19.40	4.50	0.00	0.00	20.70	23.20	112.00	162.00	826.40
1976	58.40	86.60	186.20	18.50	17.00	0.00	0.00	0.00	22.50	35.00	169.40	79.50	673.10
1977	44.50	21.70	98.80	76.10	11.00	0.00	0.00	11.00	52.60	42.00	138.50	144.80	641.00
1978	177.70	100.70	51.80	28.70	2.70	0.30	2.10	1.30	27.00	102.40	105.80	78.60	679.10
1979	116.00	52.60	65.60	106.80	11.20	0.00	35.90	31.30	5.70	64.50	189.40	117.10	796.10
1980	183.00	197.00	56.80	16.20	0.80	0.00	0.00	1.80	94.70	51.00	153.30	152.40	907.00
1981	224.10	123.30	91.00	28.20	2.70	2.50	0.00	5.00	26.00	55.90	95.30	76.60	730.60
1982	184.40	49.00	35.30	4.50	1.50	0.00	0.00	0.00	20.30	85.50	80.00	44.50	505.00
1983	131.50	16.50	74.70	9.50	15.00	10.00	0.00	18.00	2.50	95.50	279.50	260.50	913.20
1984	142.50	22.00	82.00	115.50	11.50	11.50	59.00	0.00	56.50	106.50	80.30	76.00	763.30
1985	59.50	267.00	43.70	5.00	34.00	6.00	0.00	0.00	8.00	127.50	63.00	148.50	762.20
1986	91.00	95.50	145.40	55.00	21.50	7.50	0.00	0.00	20.50	106.00	151.50	144.00	837.90
1987	207.50	64.20	149.00	11.50	0.00	0.00	0.00	56.00	39.00	60.50	106.80	202.10	896.60
1988	114.70	127.00	89.20	37.60	0.00	5.20	10.40	5.50	38.80	88.10	19.60	102.90	639.00
1989	65.50	102.50	43.40	50.50	28.60	36.80	4.50	4.60	0.00	72.00	181.40	140.90	730.70
1990	79.80	95.90	124.10	71.10	4.80	0.00	2.50	0.00	4.70	42.50	107.70	137.30	670.40
1991	208.00	88.80	141.20	0.00	15.00	17.20	0.00	0.00	8.50	29.30	138.70	57.60	704.30

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1992	126.00	26.00	47.10	26.90	0.00	1.00	0.00	16.70	9.30	60.00	43.90	122.40	479.30
1993	143.70	81.90	64.80	38.90	5.00	0.00	0.00	4.00	12.00	112.40	83.90	146.90	693.50
1994	77.50	60.30	74.70	16.10	1.80	0.00	0.00	0.00	12.70	64.30	67.20	118.90	493.50
1995	146.50	47.20	96.90	52.70	0.50	0.00	0.00	1.80	2.80	38.50	137.10	63.30	587.30
1996	127.40	292.10	103.10	52.30	51.80	1.40	12.00	28.20	8.00	70.00	98.50	143.30	988.10
1997	112.20	68.30	73.10	24.80	49.90	0.90	0.00	0.00	57.00	59.40	113.90	73.90	633.40
1998	56.40	113.20	21.70	36.70	0.00	0.00	0.00	0.00	47.90	79.20	123.40	137.00	615.50
1999	83.40	44.80	42.20	23.50	25.60	0.90	3.00	2.30	14.40	87.40	107.10	111.00	545.60
2000	35.60	185.20	71.80	94.40	13.00	12.60	24.00	0.60	9.00	66.00	131.00	148.40	791.60
2001	111.00	90.20	17.20	20.60	11.00	1.80	0.00	0.00	0.80	120.20	199.40	182.00	754.20
2002	13.40	47.00	35.40	27.80	27.20	2.20	15.00	4.40	7.60	100.40	42.00	84.60	407.00
2003	26.30	43.60	30.00	21.35	20.85	1.65	11.60	4.60	6.45	88.75	71.85	100.30	427.30
2004	39.20	40.20	24.60	14.90	14.50	1.10	8.20	4.80	5.30	77.10	101.70	116.00	447.60
2005	52.10	36.80	19.20	8.45	8.15	0.55	4.80	5.00	4.15	65.45	131.55	131.70	467.90
2006	65.00	33.40	13.80	2.00	1.80	0.00	1.40	5.20	3.00	53.80	161.40	147.40	488.20
2007	36.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	43.20	151.40	32.20	263.20
2008	88.00	71.40	39.20	41.80	15.60	2.80	0.20	0.00	0.00	91.40	67.80	38.60	456.80
2009	131.20	0.00	0.60	0.00	22.80	13.20	0.00	20.80	0.00	0.00	0.00	208.00	396.60
2010	144.00	15.00	84.00	148.00	11.00	0.00	0.00	0.00	0.00	42.00	116.00	220.00	780.00
2011	298.00	80.00	89.50	101.00	5.00	13.00	2.00	0.00	0.00	70.00	81.00	242.00	981.50
2012	145.00	170.00	99.00	49.00	0.00	0.00	0.00	0.00	100.00	125.00	92.00	207.00	987.00
Maximum	**310.40**	**292.10**	**193.30**	**166.80**	**73.50**	**62.40**	**75.20**	**100.60**	**140.80**	**170.40**	**279.50**	**294.10**	**1075.80**
Minimum	**13.40**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**18.80**	**263.20**
Average	**113.40**	**87.43**	**66.40**	**43.00**	**14.67**	**5.29**	**6.10**	**5.92**	**21.18**	**63.44**	**109.92**	**117.92**	**654.66**
Standard deviation	**60.85**	**54.45**	**39.88**	**36.53**	**16.77**	**10.45**	**12.99**	**14.48**	**26.48**	**34.02**	**49.36**	**53.23**	**153.12**
1:20 year flood	**227.66**	**183.84**	**142.04**	**117.06**	**51.04**	**27.82**	**30.56**	**29.28**	**80.64**	**116.12**	**195.02**	**228.64**	**910.72**
1:20 year drought	**35.76**	**16.70**	**15.66**	**0.40**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**14.10**	**38.70**	**44.58**	**435.42**

7.2 Appendix B: Field data

7.2.1 Appendix B1: Geophysical survey and graphs

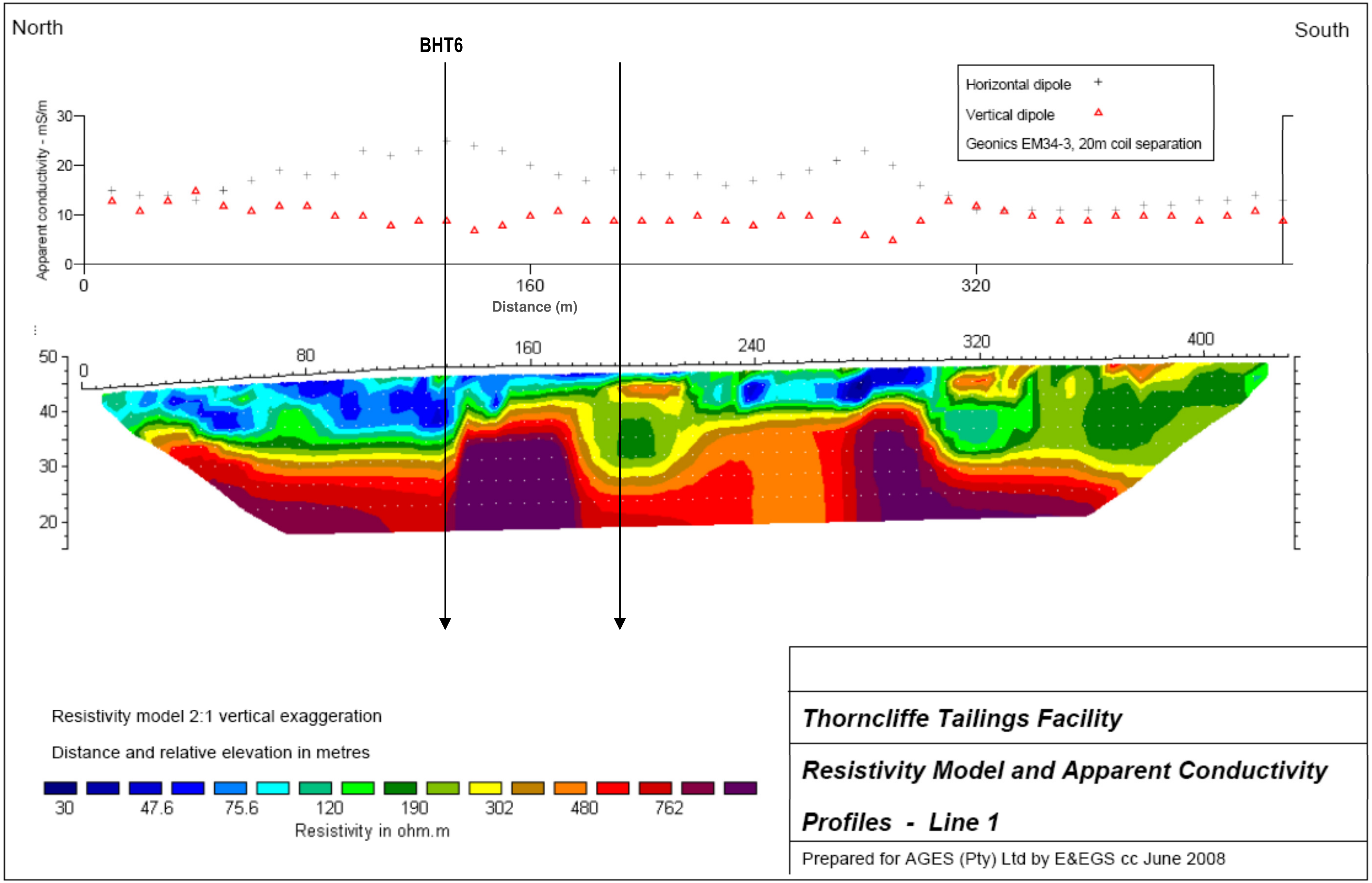

Figure 7-1 Geophysical profile – Traverse 1.

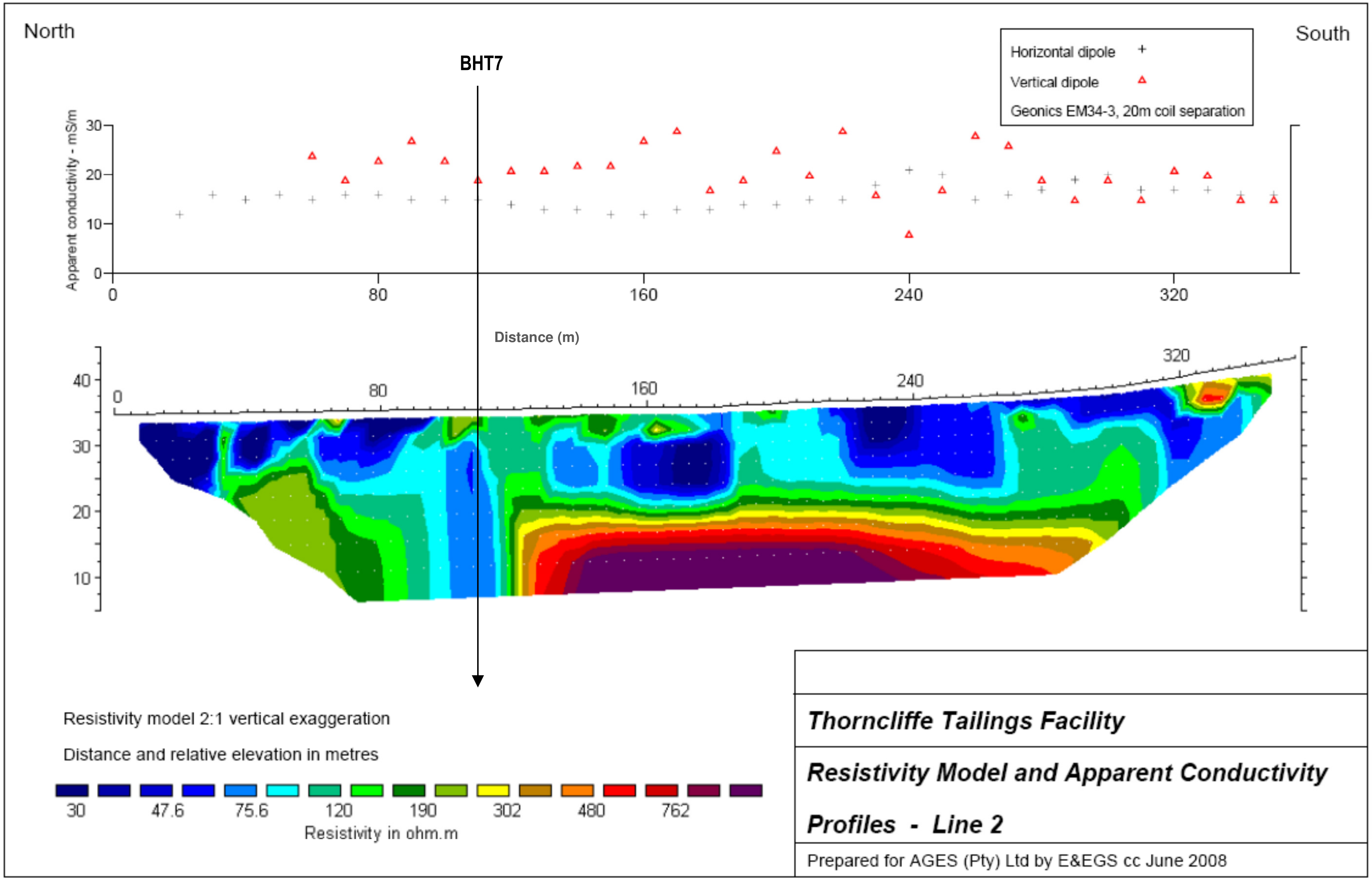

Figure 7-2 Geophysical profile – Traverse 2.

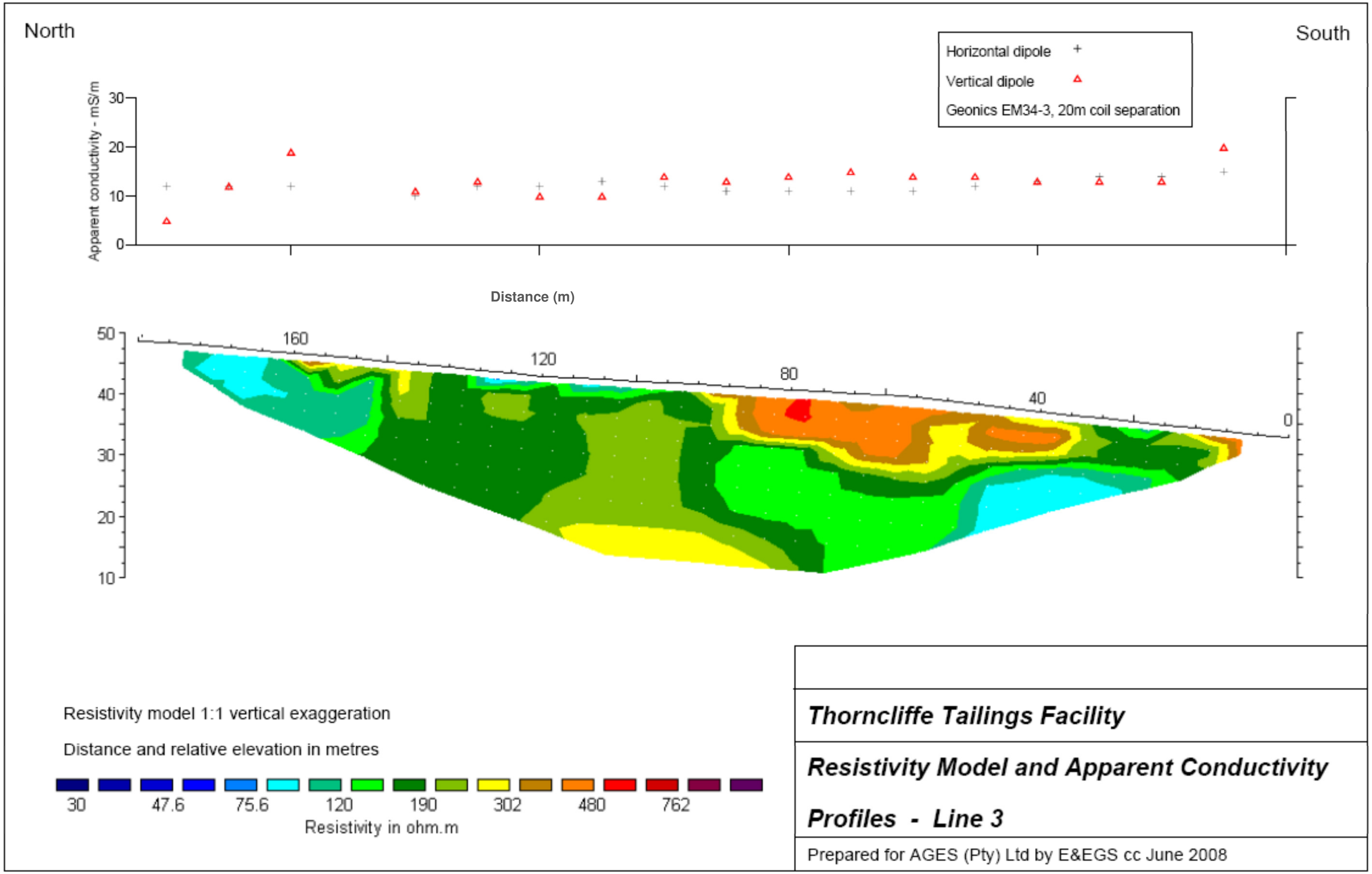

Figure 7-3 Geophysical profile – Traverse 3.

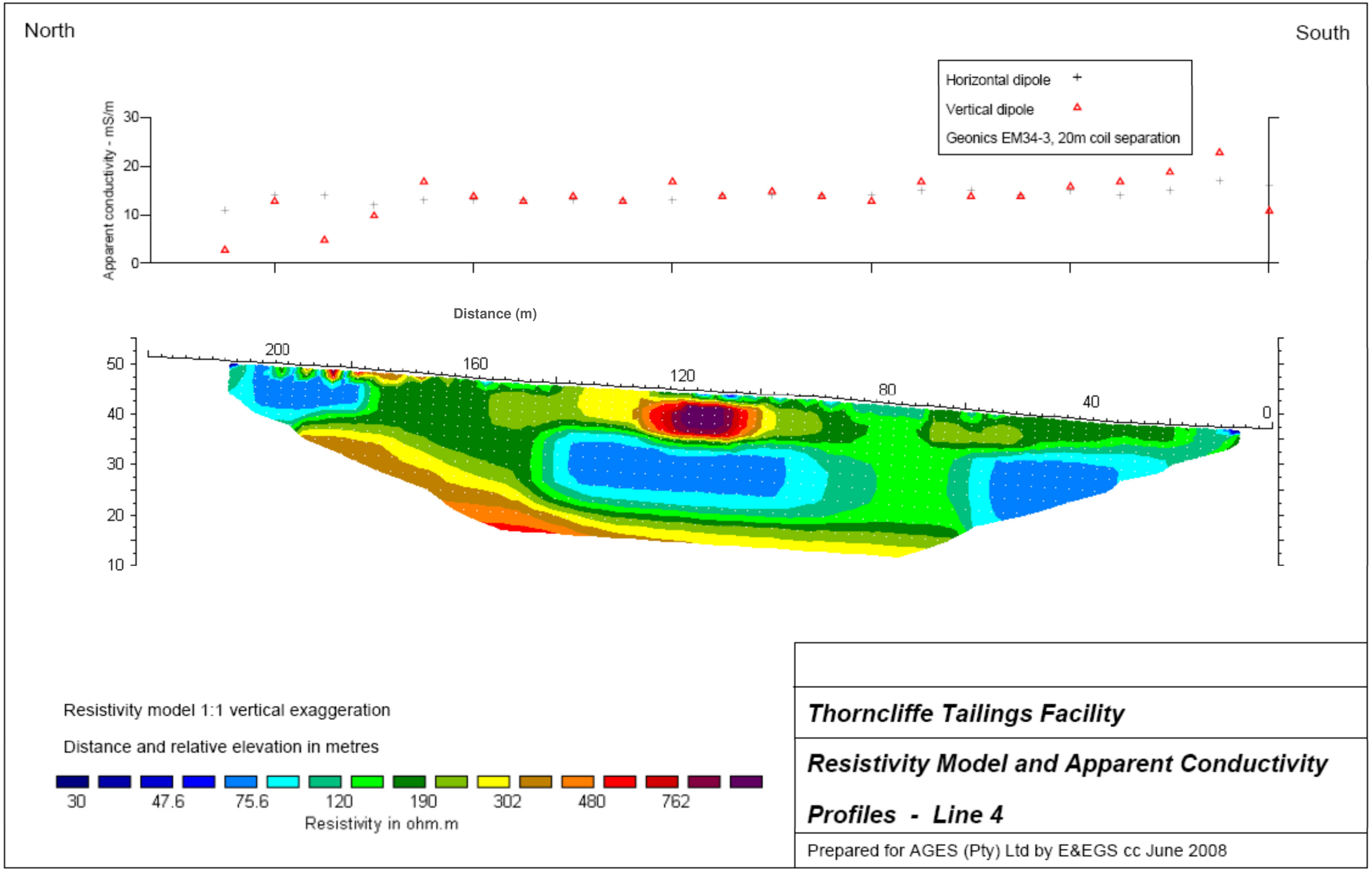

Figure 7-4 Geophysical profile – Traverse 4.

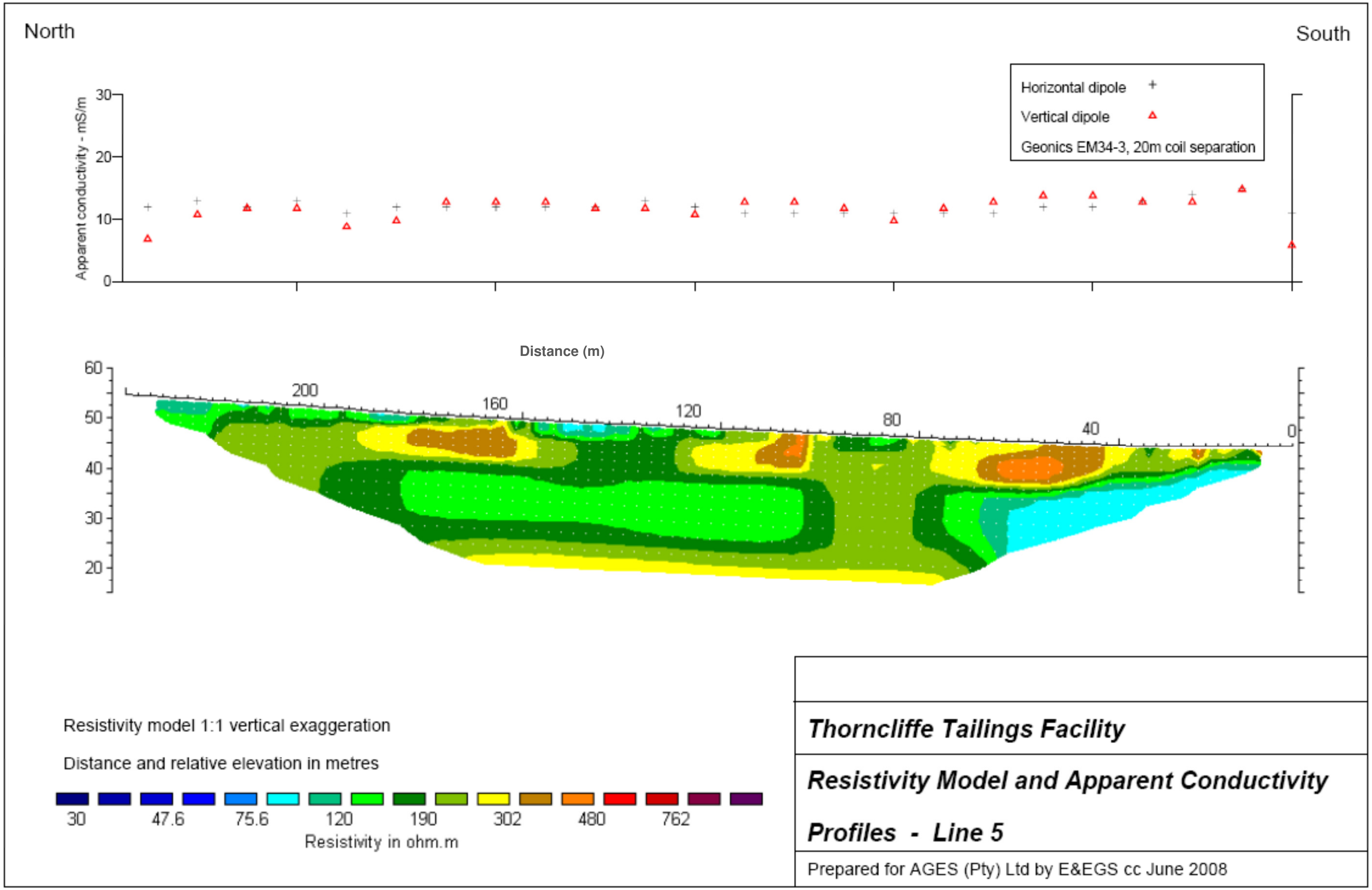

Figure 7-5 Geophysical profile – Traverse 5.

7.2.2 Appendix B2: Drilling and geotechnical logs

1. Figure 7-6 BTH06 - geological profile and borehole information.
2. Figure 7-7 BTH07 - geological profile and borehole information.

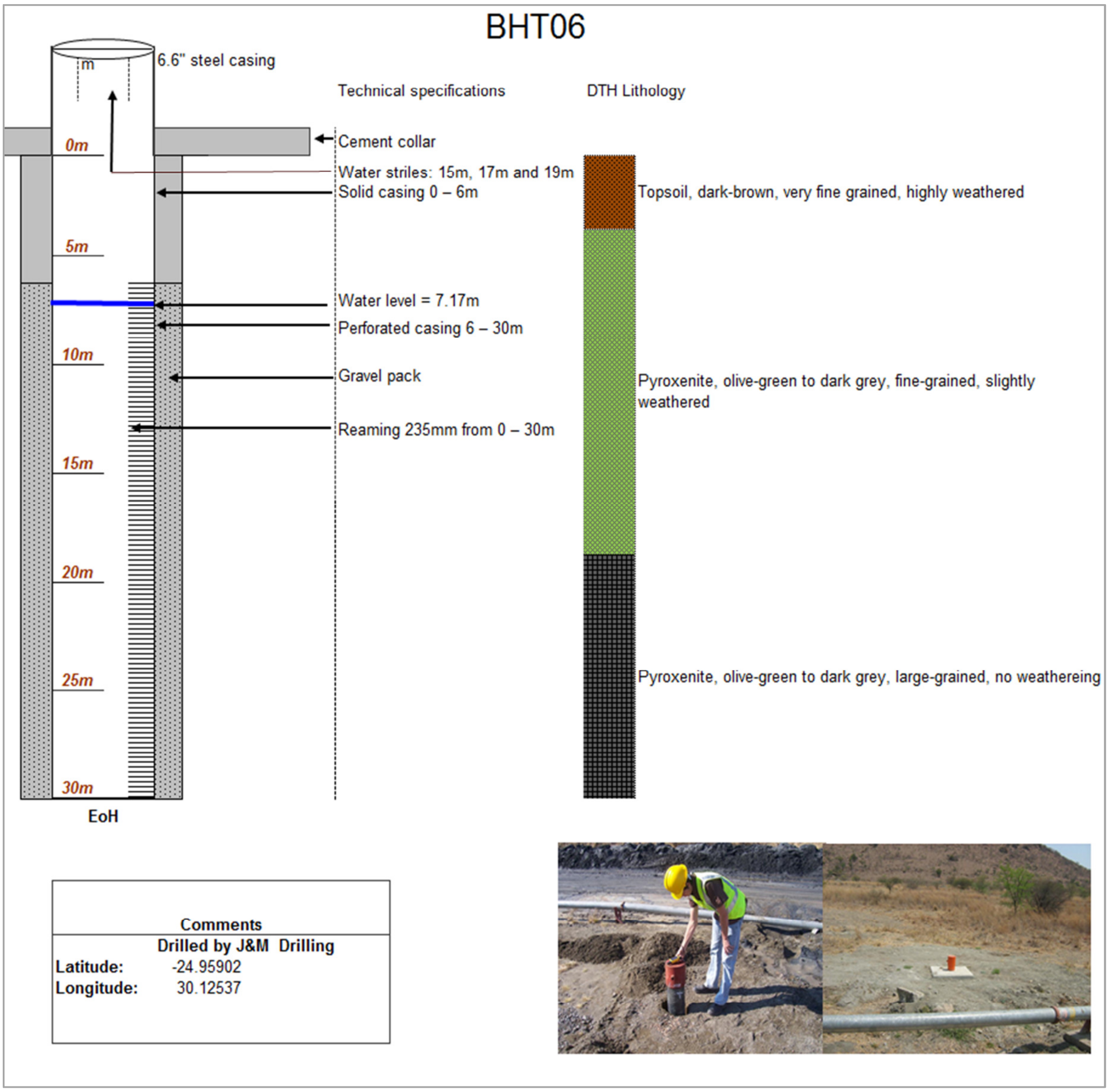

Figure 7-6 BTH06 - geological profile and borehole information.

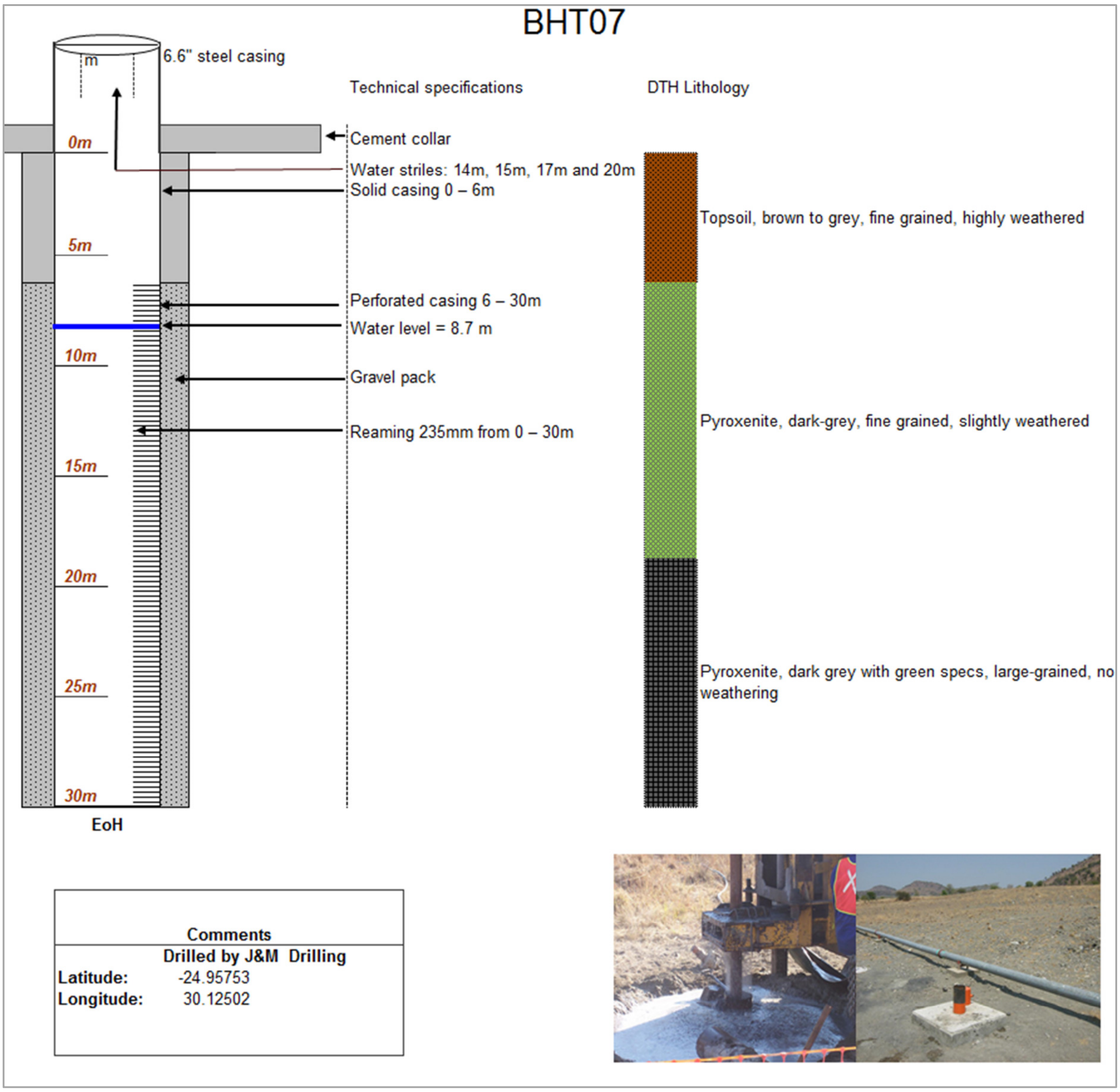

Figure 7-7 BTH07 - geological profile and borehole information.

7.2.3 Appendix B3: Aquifer test graphs

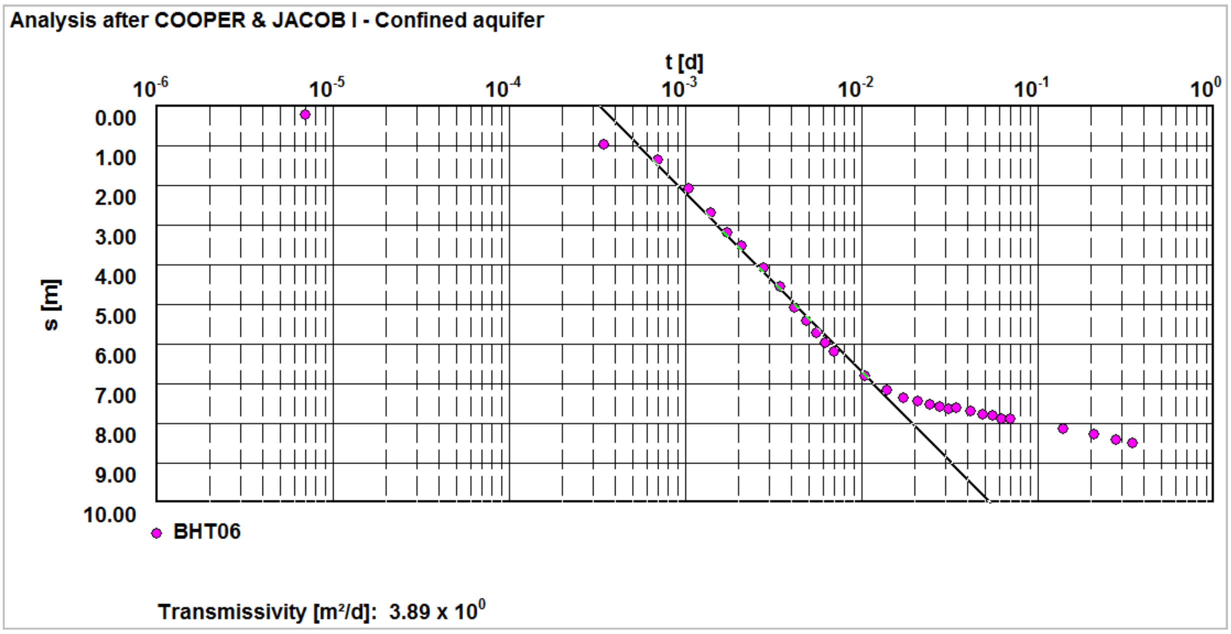

Figure 7-8 Borehole BHT06: Early Transmissivity Graph.

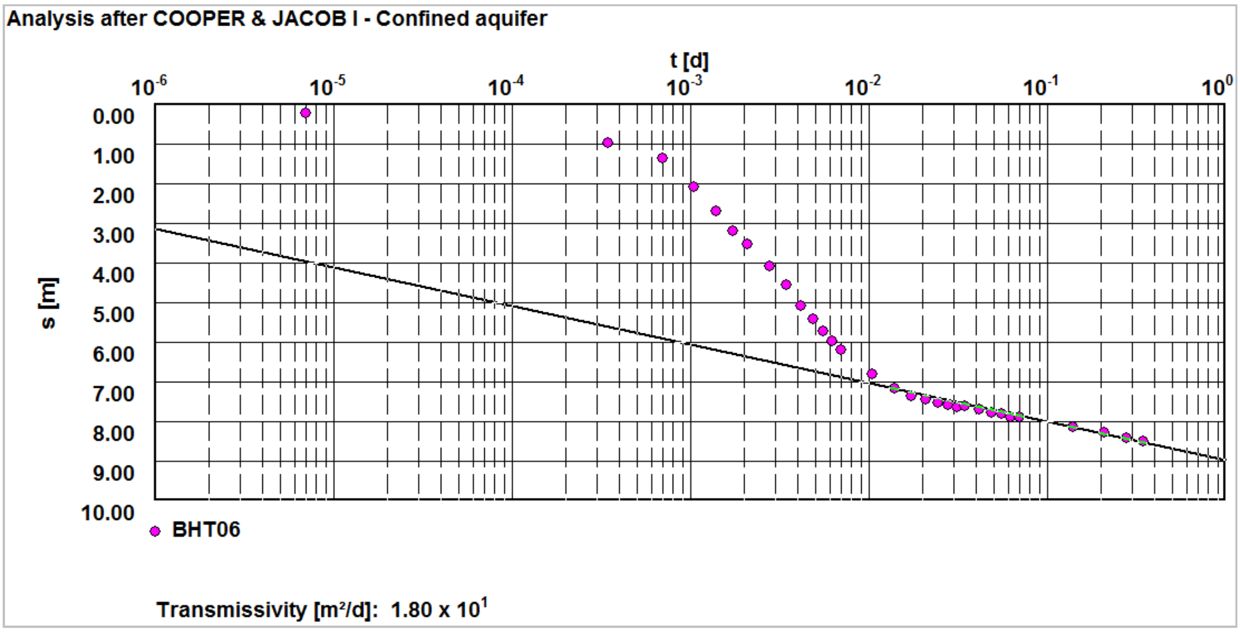

Figure 7-9 Borehole BHT06: Late Transmissivity Graph.

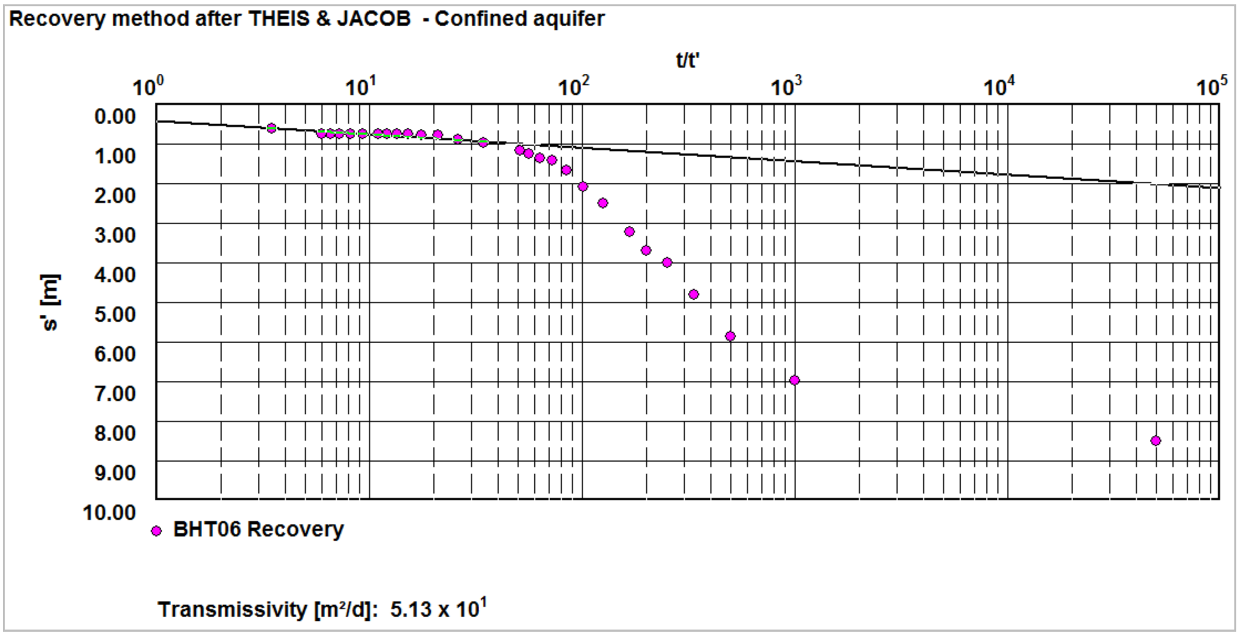

Figure 7-10 Borehole BHT06: Recovery Transmissivity Graph.

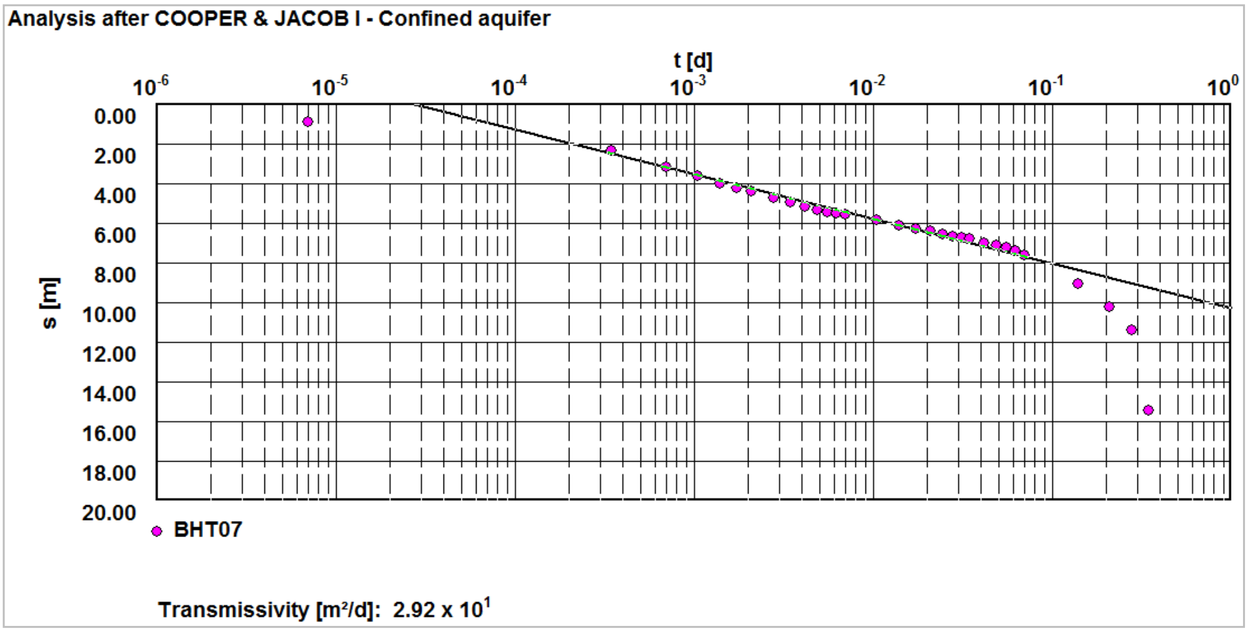

Figure 7-11 Borehole BHT07: Early Transmissivity Graph.

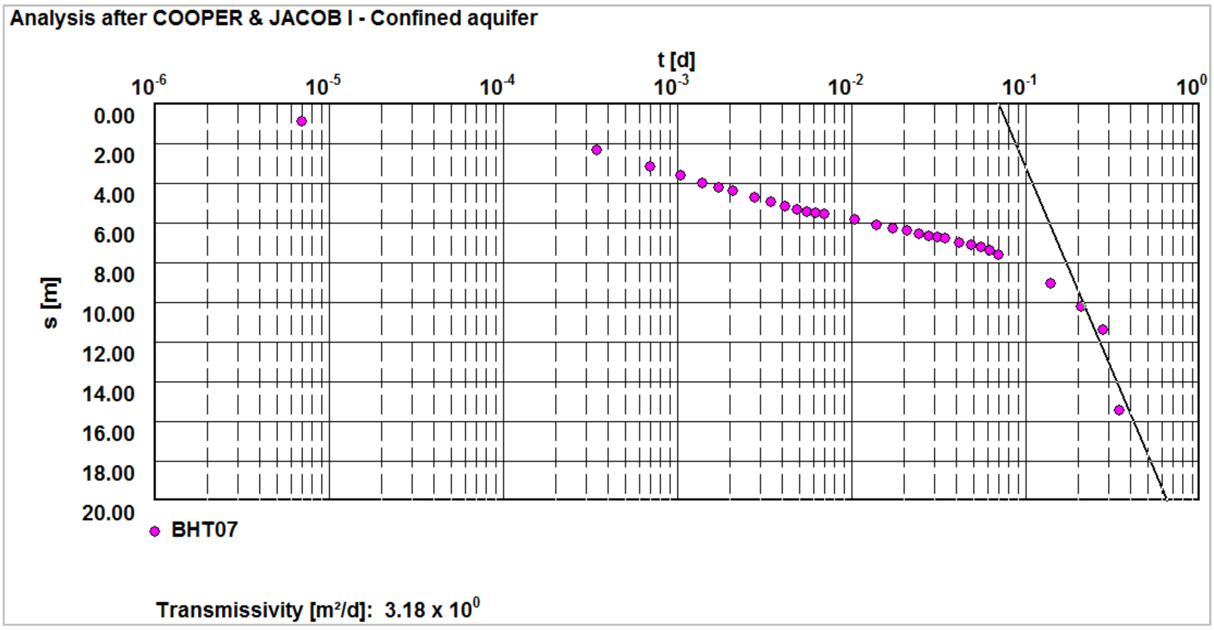

Figure 7-12 Borehole BHT07: Late Transmissivity Graph.

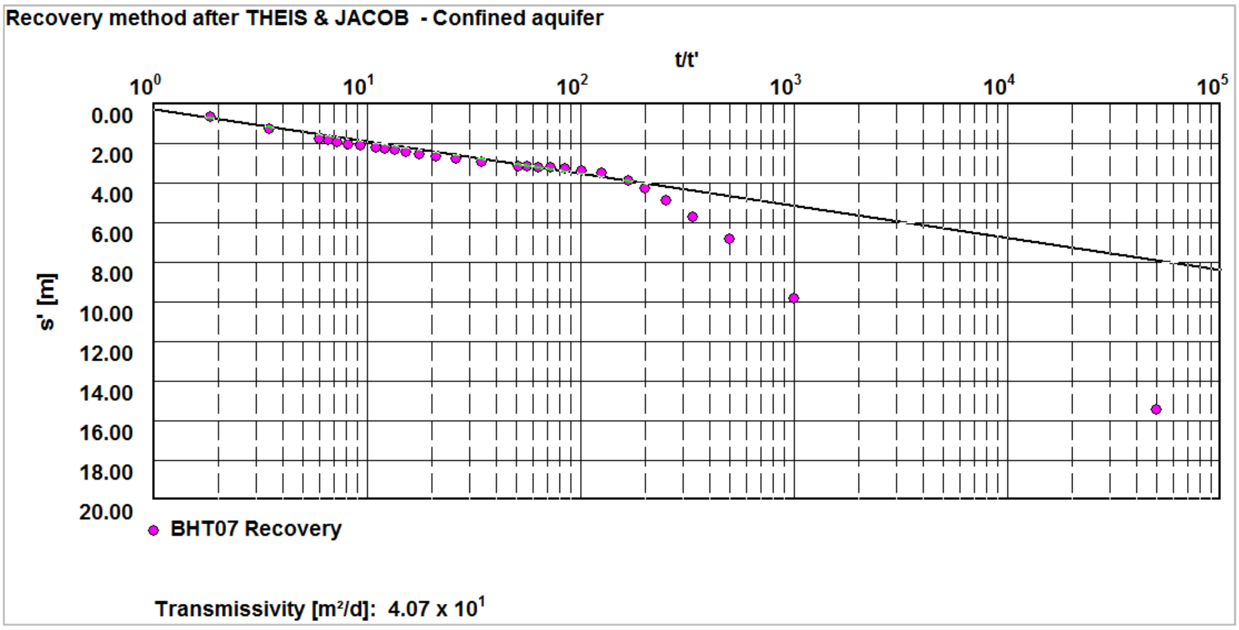

Figure 7-13 Borehole BHT07: Recovery Transmissivity Graph.

7.3 Appendix C: Water quality analyses

Table 7-2 Hydrochemistry: Micro Elements.

Sample no:	Date sampled	Al	As	B	Cd	Cr^{3+}	Cr^{6+}	Co	Cu	Fe	Pb	Mn	Hg	Ni	Se	Si
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ
BHT06	03-Jul-08	0.48	1.32	<0.06	<0.01	0.46	<0.02	-	<0.05	0.15	<0.03	<0.05	<0.001	-	<0.001	33
BHT06	10-Oct-08	<0.2	<0.005	<0.18	<0.15	<0.01		<0.05	<0.02	<0.01	<0.06	0.09	<0.001	<0.02	0.008	-
BHT07	03-Jul-08	0.34	4.18	<0.06	<0.01	0.298	<0.02	-	<0.05	0.09	<0.03	<0.05	<0.001	-	<0.001	36
BHT07	10-Oct-08	<0.2	<0.005	<0.18	<0.15	0.01	-	<0.05	<0.02	0.07	<0.06	0.04	<0.001	<0.02	0.011	-

Table 7-3 Hydrochemistry: Macro Elements.

Sample no:	Date sampled	NH4-N	HCO3	Ca	CO3	Cl	Mg	CN-	F	NO3-N	NO2-N	PO4-P	K	Na	SO4	Zn
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ
BHT06	**03-Jul-08**	-	400	50	2.1	33	133	<0.02	<0.20	44	<0.20	0.08	3	21	65	<0.06
BHT06	**10-Oct-08**	<0.02	456	35.71	8.2	33	103	-	<0.48	19	0.41	<0.04	<4	15	47	<0.1
BHT07	**03-Jul-08**	-	210	120	1	13	128	<0.02	<0.20	150	<0.20	0.03	2	32	109	<0.06
BHT07	**10-Oct-08**	<0.02	152	110.7	1.6	14.5	104	-	<0.48	141	0.39	<0.04	<4	53	68	<0.1

Table 7-4 Hydrochemistry: Physical Parameters and calculations

Sample no:	Date sampled	EC	Langelier Index	pH	T Alk	TDS	T Hard	Cations	Anions	Diff (%)
		mS/m			mg/ℓ	mg/ℓ	mg/ℓ			
BHT06	**03-Jul-08**	114	-0.11	7.74	402.14	700	672	-	-	-
BHT06	**10-Oct-08**	122	-	8.28	464	622	512	10.98	12.01	-4.51
BHT07	**03-Jul-08**	169	-0.42	7.71	211.33	1167	828	-	-	-
BHT07	**10-Oct-08**	192	-	8.05	154	1068	706	16.43	15.2	3.87

Abstract

The vital role of water within the mining industry, both as an asset which generates value as well as a shared natural resource requiring responsible stewardship, have long been recognised. Due to extreme climate changes, an increasing population density and poor water management, securing of water has become a global challenge and water scarcity will continue to be one of the greatest challenges facing mine water management. There is no simple recipe for mine water management and regulations by environmental authorities, along with past polluting practices, are forcing mining operations to improve and prioritise their water consumption. Accordingly, this sector is expected to be increasingly required to demonstrate leadership through innovative water use management.

A mine water balance is considered to be one of the most important and fundamental tools available for mining operations as management begins with a basic understanding of where water is sourced from, and where it is utilised. With this kept in mind, a mine water balance should be based on a holistic systems model approach with an appropriate relationship between the required level of complexity in the model structure and purpose. Excessive detail can cause the model to become clumsy and tend not to focus on strategic water management principles. Emphasis should be put on a system approach, taking into consideration the main interactions, feedbacks and functional relationships between the various parts of the whole system.

An overall mine water balance that superimposes different water systems can be divided into a process water system and a natural water system. The natural water system is associated with the intrinsic hydrological cycle and is often disregarded due to uncertainties. It can however significantly impact on mine water usage and losses as indicated in this case study. Consequently, decision making and management options should be based on the evaluation of the system as a whole and inclusion of the natural system as a component of the mine water balance is imperative for accurate quantification. The natural system includes a surface water environmental circuit as well as a groundwater environmental circuit. Surface and groundwater resources have historically been managed separately, but more than ever before, interaction between these two systems are required to facilitate effective resource management. Mining activities have a major effect on the modification of the hydrological regime and the influence of increased hydraulic conductivity along with mining induced recharge, should be evaluated as part of the adapted mine water balance. Furthermore, mine dewatering predictions and climatic scenarios must be incorporated to reflect site conditions more accurately.

As poor water management poses an operational risk to mining operations, this sector has developed novel ways to respond to water issues in differing circumstances and has illustrated the ability to turn risk into opportunity. Now, more than ever, special measures are needed to identify options for life-of-mine strategies and initiatives for water conservation and management. Future focus should be to continue investigation and implementation of the water use strategies in order to improve performance across operations and encourage engagement with other water users. Moreover, to share experiences, learn from others and contribute to water discussions and debate at local, national and international levels.

Opsomming

Die wesenlike rol van water in die mynbedryf, as ‘n aanwins wat waarde kan toevoeg, asook as ‘n natuurlike hulpbron wat verantwoordelike rentmeesterskap verg, word reeds jare lank erken. Ekstreme klimaatstoestande, ‘n toenemende bevolkingsdigtheid asook wanbestuur van water, is alles faktore wat water sekuriteit beïnvloed en is besig om in ‘n internasionale krisis te ontaard. Gevolglik word die beskikbaarheid van water beskou as een van die bedryf se grootste uitdagings tot op hede. Daar is nie ‘n eenvoudige oplossing vir myn-water bestuur nie en regulasies deur omgewingsdepartemente, asook historiese besoedelings praktyke forseer mynbedrywighede om water gebruik te optimiseer en te prioritiseer. Daar word voorspel dat die mynbedryf in ‘n toenemende mate geverg gaan word om leierskap te openbaar deur middel van inoverende bestuur.

‘n Waterbalans word beskou as een van die belangrikste en mees fundamentele instrumente beskikbaar vir mynbedrywighede en word geskoei op die basiese begrippe van waar water verkry word, asook waar water verbruik word. Gevolglik moet ‘n myn-waterbalans gebaseer word op ‘n holistiese, sistemiese model-benadering met ‘n toepaslike verhouding tussen die kompleksiteit van die model en die doel van die model. Oorbodige detail kan ’n oneffektiewe en lomp model tot gevolg hê wat geneig is om nie te fokus op strategiese bestuur van water nie. ‘n Sistemiese benadering moet beklemtoon word en interaksies en funksionele verwantskappe tussen eenhede van die stelsel as ‘n geheel, moet in aggeneem word.

‘n Algehele myn-waterbalans is oorliggend aan twee water sisteme naamlik, ‘n proses water sisteem, asook ‘n natuurlike water sisteem. Water van die natuurlike sisteem word geassosieër met die intrinsieke hidrologiese siklus en word dikwels afgeskeep as gevolg van onseker veranderlikes. Dit kan tog steeds ‘n noemenswaardige impak hê op water verbruik en verliese by mynbedrywighede, soos gedemonstreer in die gevalle studie. Besluitneming en bestuursopsies moet ge-evalueer word op grond van ‘n sistemiese benadering en die insluiting van die natuurlike sisteem as ‘n komponent van die myn-waterbalans is uiters noodsaaklik vir akkurate kwantifisering en voorspelling van kondisies op die myn. Water van die natuurlike sisteem kan opgedeel word in opervlak - asook grondwater siklusse. Histories is oppervlak- en grondwaterbronne afsonderlik bestuur, maar interaksie tussen die twee sisteme word benodig om effektiewe hulpbronbestuur en behoorlike besluitneming te bewerkstellig. Gevolglik moet die konvensionele waterbalans aangepas word om voorsiening te maak vir die insluiting van water van die natuurlike siteem. Myn-aktiwiteite het ‘n wesenlike effek op die modifikasie en verandering van die hidrologiese stelsel en, na aanleiding hiervan, moet die invloed van ‘n verhoogde hidrologiese kondutiwiteit, tesame

met vermeerdering in grondwater aanvulling, ondersoek word as deel van die gemodifiseerde myn-waterbalans. Verder moet voorspelling van myn-ontwaterings volumes asook verskillende klimaats-alternatiewe in die myn-waterbalans geïnkorporeer word. Sodoende sal ‘n meer verteenwoordigende weerspieëling vir terrein kondisies verkry word.

Swak bestuur van water op mynbedrywighede hou ‘n operasionele risiko in en hierdie sektor het gevolglik met innoverende oplossings vorendag gekom om sulke situasies in geleenthede te omskep. Spesiale afmetings en metodes om inisiatiewe te identifiseer vir die bewaring en strategiese bestuur van water, word al hoe meer benodig. Toekomstige fokus moet geplaas word op die bestudering en implementering van strategieë wat operasionele effektiwiteit sal verbeter, asook inskakeling met mede-water verbruikers. Ervaring ten opsigte van hierdie aspek moet gedeel word om sodoende ‘n bydrae te lewer word op ’n plaaslike, maar ook nasionale en internasionale vlak.