Water Management at a Base Metals Refinery

MSc DISSERTATION

Prepared by

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i. DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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Ayesha Osman Date

i. ABSTRACT

Most mineral processing plants have high water requirements for their operational activities. These plants often function in an environment where water is becoming increasingly scarce. An increase in population will result in an increased demand for water, potentially beyond the limits of supply, and hence increased competition for the resource. In South Africa, Gauteng and the North West Province are likely to be first to experience a shortage of potable water.

The key to a sustainable future lies in understanding and utilising resources more efficiently. This holds especially for industries who seek to minimise water usage through better management of resources. The two tools used in this study are the Water Accounting Framework (WAF) and Water Footprinting (WF) method.

This research assisted a refinery in the North West Province understand its water usage and move towards operating in a more sustainable manner. Site water management was improved and the objective of this research fulfilled by:

(i) Surveying the potable water and the storm water systems with a view to assessing the current water accountability and determining methods to improve accountability;
(ii) Determining the water balance for the site and presenting it in the form of a water balance sheet;
(iii) Reporting water usage in accordance with the Minerals Council of Australia's "Water Accounting Framework for the Minerals Industry";
(iv) Calculating the water footprints of the refinery; and
(v) Evaluating the water usage at the refinery and identifying ways in which water savings could be achieved.

It was seen that the biggest consumer of water was the boilers and utilities section and the biggest loss of water was through evaporation. The refinery potable water requirement (2 280 m^3/y) amounted to 0.16% of the daily water use for the Bojanala Platinum District. Four reports (outputs) were generated using the WAF. The four reports generated provide a

good indication of the movement of water into, out of and during a process. WFs were calculated for the process. The blue WF was calculated to be 832 363 m^3 and the green WF was calculated to be 261 970 m^3. The product WF was 43.9 m^3/t of base metal produced. There was no grey WF as the site does not discharge polluted water.

This research provided an opportunity for the refinery to improve water efficiency onsite as well as improve reporting standards. Water usage was reported using global reporting tools to set a benchmark for the base metals industry.

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- My sisters who built up my confidence from a young age and have always inspired me to better myself!

Table of Contents

iii. LIST OF TABLES

iv. LIST OF FIGURES

v. NOMENCLATURE

AMD	Acid Mine Drainage
CERES	United States Coalition for Environmentally Responsible Economics
CSIR	Council for Scientific and Industrial Research
DWA	Department of Water Affairs
E&S	Effluent and sulfate
FAO	Food and Agricultural Organisation
GDP	Gross Domestic Product
GJ	Gigajoule
GRI	Global Reporting Initiative
GSW	Gland seal water
IFC	International Financial Corporation
IPCC	Intergovernmental Panel on Climate Change
ISS	Institute for Security Studies
LCA	Life Cycle Assessment
MCA	Minerals Council of Australia
Mt	Megatonne
MWh	Megawatt hours
P & ID	Piping and Instrumentation Diagram/Drawing
PET	Polyethylene Terephthalate
PGM	Platinum Group Metals
RWB	Rand Water Board
SAIMM	South African Institute of Mining and Metallurgy
SAPS	South African Police Service
SMI	Sustainable Minerals Institute (at the University of Queensland)
SRI/F	Sustainability Reporting Index/Framework
TSS	Total suspended solids
UDHR	Universal Declaration of Human Rights
UN	United Nations
UNEP	United Nations Environmental Programme
WAF	Water Accounting Framework
WBCSD	World Business Council for Sustainable Development
WF	Water Footprint/Water Footprinting
WHO	World Health Organization
WRC	Water Research Commission
WULCA	Water Use in Life Cycle Assessment
WWAP	World Water Assessment Programme
WWF	World Wildlife Fund
WTW	Water Treatment Works

1. INTRODUCTION

1.1 Background

Access to clean water is vital for the dignified existence of human life. According to the Universal Declaration of Human Rights (UDHR), it is an essential requirement for human well-being through the fulfilment of basic rights such as the right to shelter, food, health and sanitation. However, globally, over a billion people are unable to access a safe water supply and of these people, 28% are found on the African continent (World Health Organization, 2000).

1.2 Water Scarcity

Water scarcity is defined as the point at which the net usage of water infringes on the supply or quality of water such that the demand by all users, including the environment, cannot be met (UN, 2012). A hydrologist would normally assess water scarcity by looking at the population-water balance. For a particular area, if the water supply drops below 1000 m^3/person/year, the region is referred to as “water stressed”. Should the supply drop below 500 m^3/person/year, it is referred to as “absolute scarcity” (UN, 2012). By 2025, 1,8 billion people will reside in areas of absolute water scarcity and two-thirds of the global population could be under stressed conditions (UN, 2006).

According to Gleick (2000), there are five major influencers requiring massive increases of water resources. These are:

1. Population growth,
2. Industrial development,
3. Expansion of irrigated agriculture,
4. Massive urbanisation, and
5. Rising standards of living.

As a result, any water scarcity situation could only be worsened without intervention. Figure 1.1 illustrates regions that are currently experiencing water scarcity and those that are approaching water scarcity.

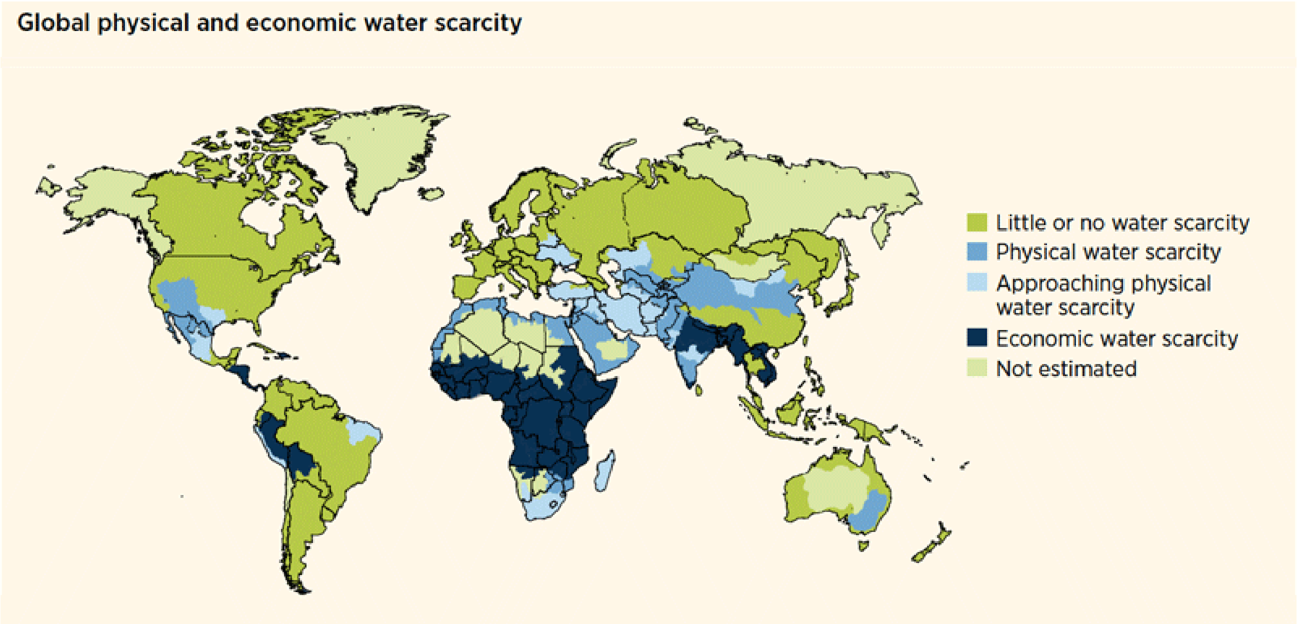

Figure 1.1 Regions that are currently experiencing water scarcity and those that are approaching water scarcity (World Water Assessment Programme, 2012)

In 2014, the World Economic Forum published a list of Top Ten Global Risks of highest concern according to level of concern, likelihood and impact posed to multi-stakeholder communities (Table 1.1) (World Economic Forum, 2014). According to the list, a water crisis was the third highest risk, followed by failure to mitigate or adapt against climate change (5) and an increase in extreme weather events (6). This demonstrates an increase in the awareness of a pending global crises resulting from inefficient usage and increased competition for water resources.

Table 1.1 Ten Global Risks of Highest Concern in 2014 (World Economic Forum, 2014)

No.	Global Risk
1	Fiscal crises in key economies
2	Structurally high unemployment/underemployment
3	Water crises
4	Severe income disparity
5	Failure of climate change mitigation and adaptation
6	Greater incidence of extreme weather events (e.g. floods, storms, fires)
7	Global governance failure
8	Food crises
9	Failure of a major financial mechanism/institution
10	Profound political and social instability

Apart from the acknowledgement of possible water crises, water shortages can have serious political implications. From as early as 2500 B.C., access to water has led to socio-political conflict. An example of this would be the Lagash-Umma Border Dispute. Urlama, the King of Lagash from 2450 to 2500 B.C. diverted water from the Lagash region to boundary canals to deprive Umma of water (Hatami and Gleick, 1994). In 1503, Machiavelli and Leonardo da Vinci planned to divert water from the Arno River away from Pisa due to conflict between Pisa and Florence (Honan, 1996). In 2007 in Burkina Faso, Ghana and Cote D'Ivoire, declining rainfall led to conflict between animal herders and famers who were competing for the same resources (UNOCHA, 2007). In 2008, protestors in Abuja, Nigeria became violent, beating water vendors while protesting over the price of water (Yakubu, 2008). Also in 2008, China launched a political clampdown in Tibet. Political tensions between China and Tibet have existed for years but Tibet has been referred to as the "world's water tower", supplying water to a quarter of the world's population (Sharife, 2008). From this, it is clear that increased competition for the scarce resource can result in geopolitical tension and potentially future "Water Wars".

The effects of increasing water scarcity, increasing demand for water resources, and the risk of political conflict combined with extremes in weather, poverty and social instability, could result in a negative impact on economic activity and development. Economic activity is of critical importance to the survival and success of any country. Failure to plan and manage water resources could have potentially catastrophic consequences. Some of the consequences that could be experienced are a shutdown or cessation of economic and industrial activities as well as the pollution of water resources. Examples of these scenarios include Coca-Cola (one of the world's biggest soft-drinks manufacturer) in Northern India, which was forced to close after local farmers accused it of using too much water (Chilkoti, 2014). Another example would be the Imiter Metallurgical Company which was forced to shut down its mining operation in Morocco in March 2012. Hundreds of villagers cut off water flow from a well supplying water to the mine. The villagers accused the mine of depleting aquifers and polluting water resources. The mine was re-opened but suffered a 40% loss in processing capacity (Ethical Consumer, 2012).

The mining industry, in particular, is a major consumer of fresh water with the copper mining industry using over 1.3 billion m^3 of water in 2006 (Gunson *et al.,* 2010). Although water usage by the mining industry accounts for a small percentage (around 2 to 4.5%) of national water usage in mining concentrated areas such as South Africa, Australia and Chile (Brown, 2003 and Bangerter *et al.,* 2010), the impact can severely affect the availability of fresh water to the local communities by increasing competition or polluting resources.

1.3 Project Scope

A refinery operating in the North West Province of South Africa was concerned about the sustainability of its operations – particularly regarding its water usage. The refinery processes ore into saleable base metal products using a hydrometallurgical process which is largely dependent on the availability of potable water. The conventional base metal process typically consists of an underground or open pit mine followed by a concentrating process. The ore is split into platinum feed and base metal feed. The platinum feed is processed to recover platinum while the base metal feed is sent to a base metal refinery to be processed into nickel, copper and cobalt products. The refinery requires water for dust control, froth flotation, dilution, reagent mixing, cooling, washing, showers and for pump gland seal water (GSW). The refinery is located in a region of physical water scarcity, as seen in Figure 1.1.

Concerned about future production interruption or a possible shut down due to water restrictions, the refinery is striving to reduce its potable water consumption and improve its water accountability to greater than 95%, that is, the refinery would like to know where at least 95% of its water is used. This way, it aims to understand and manage the resource more effectively by ultimately reducing consumption. The aim of this study was to assist the refinery in meeting their goal by verifying the water reticulation system and recommending the addition of flow measuring devices where required.

In order to report the results in a manner that can be easily compared to other sites which is transparent and conforms to global frameworks, the Minerals Council of Australia’s (MCA) Water Accounting Framework (WAF) and Hoekstra’s Water Footprinting (WF) methods were used. The aim of the WAF is to obtain a deeper understanding of water usage in the mining industry and allow sites to account for, report on and compare site water management practices. The reporting is performed in a consistent, unambiguous manner that can easily be understood by non-experts and is expressed in the form of a water balance sheet displaying inputs, outputs, water storage or accumulations and water losses (Minerals Council of Australia, 2012).

The second method used in this study to understand and compare water usage is Water Footprinting (WF). WF is the total amount of fresh and virtual water that is consumed, directly and indirectly during a production process. A full WF evaluation aims to reduce the consumption and impacts associated with production. This can be presented as units of water consumed per unit of product produced (Hoekstra *et al.,* 2011).

Water was supplied to the refinery by Rand Water Board (RWB), which is South Africa's largest supplier of potable water. In 2011, RWB supplied 4 000 000 m^3/day to Gauteng, North West, Free State and parts of Mpumalanga (Rand Water, 2012). Water supplied to the Bojanala Platinum District, the mining region of the North West province, amounted to approximately 1 400 000 m^3/day (DWA, 2011a). According to a report on water supply, the Bojanala Platinum District was considered as a high priority area for the development of a detailed water reconciliation strategy as the region is currently in a water deficit in relation to water availability (SRK Consulting, 2011).

Water scarcity and competition for resources is a serious threat to the development, growth and operation of the refinery. Understanding and better managing their water resources will help prepare the refinery to meet future challenges. This could ensure the future success of the operation and set a benchmark for similar industries.

1.4 Research Objectives

The objectives of this research are:

i. To verify the water reticulation system of the base metals refinery;
ii. To establish a monthly and yearly water balance sheet for the base metals refinery;
iii. To draw up an input-output model and operational model in accordance with the MCA's Water Accounting Framework;
iv. To calculate the water footprint of the base metals refinery; and
v. To evaluate the water usage at the refinery and identify ways in which water savings can be achieved.

1.5 Report Structure

The structure of this report is as follows:

Chapter 2 gives a literature review which discusses water scarcity and the effects of global climate change on water scarcity. It discusses water in a South African context which includes rainfall, the effects of mining on water resources as well as the impact of water shortages on industrial operations. A brief explanation of the refinery operation is provided. Various water accounting tools are discussed and examples of the tools used in this study are presented.

Chapter 3 discusses the methodology that was followed to achieve all objectives. The site water system was verified by checking all water lines and flowmeters. Thereafter a water balance was constructed and reports were generated using the WAF. The WF was calculated and contextual information regarding the study was presented.

Chapter 4 presents the results obtained from the study. The results are presented in the same order as was presented in the methodology.

Chapter 5 provides a discussion of the results obtained and compared the results to studies that were discussed in the literature review. Recommendations were also made for the site to improve the efficiency of water usage at the refinery

Chapter 6 is a conclusion of the study

Chapter 7 provides recommendations for the continuation of this research.

This work was presented at Water in Mining 2013 in Brisbane, Australia; a peer-reviewed conference (Osman *et al.,* 2013). The paper presented at the conference is given in Appendix A. A presentation of this study was also made at the South African Institute of Mining and Metallurgy's Mineral Processing conference 2012 and was chosen as one of five presentations to compete for the Outotec Sustainability Award of 2012. The study has also been presented at the 6th Wits Cross-Faculty Graduate Symposium (2014), at the Institute of Materials, Minerals and Mining Southern Africa Young Persons Lecture competition (2015) where it was awarded third place as well as the 2016 Water Institute of South Africa's biennial conference in Durban in May 2016.

2. LITERATURE REVIEW

2.1 Introduction

Water is a scarce resource and efforts should be made to ensure efficient usage. The effects of water shortages can have several negative repercussions on social, political and economic levels as discussed by Nelson Mandela at the World Summit on Sustainable Development in 2002 (Steel and Schulz, 2012).

"Among the many things that I learnt as president was the centrality of water in the social, political and economic affairs of the country, the continent and the world."
Nelson Mandela, World Summit on Sustainable Development, Johannesburg, 2002

The key to a sustainable future lies in understanding and utilising resources more efficiently. This holds especially true for industries that seek to minimise water usage through better management of resources.

In order to better understand the context of this research, this literature review begins by discussing global consensus on climate change and the effect that climate change has on water resources. The review then focuses on resulting water shortages and discusses this in a South African context. Issues such as insufficient rainfall, past impacts from mining operations including acid mine drainage, protests over shortages and water restrictions and the impact that these issues have on the ability to operate are explored.

This research is focussed at a base metals refinery and the details regarding a basic base metals refining process are included. The base metals refinery seeks to understand and minimise its potable water usage as well as report the usage using global tools and frameworks. Various international water tools are available to account for water usage onsite. The two tools used in this study are the Water Accounting Framework (WAF) and Water Footprinting (WF). The tools are discussed briefly and examples of the application of water accounting amongst different industries such as soft drinks, steel, energy, gold and platinum are presented.

2.2 Climate Change and the Effects on Water Resources

The Intergovernmental Panel on Climate Change (IPCC) is an international body formed in 1988 for the assessment of climate change. Whilst original research is not carried out, comprehensive reports are published on the state of climate change, the social and economic impacts and possible strategies for mitigation (IPCC, 2014). In 1990, the IPCC stated that the greenhouse gas emissions from human activity were increasing which could lead to global warming. By 2013, the panel had established that human influence has been the leading cause of global warming since the mid-20th century. According the IPCC's Fifth Assessment report:

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and oceans have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased …It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC, 2013)

Consensus has been reached that global warming is definitely occurring with human activity listed as one of the prime causes. As a result of global climate change, hydrological changes such as variations in precipitation and evaporation patterns will occur. This directly affects water resource levels, salt concentrations and the seasonal availability of fresh water (McDonald *et al.,* 2011 and Arnell *et al.,* 2011). According to McDonald *et al.* (2011), 150 million people globally currently live in areas with a perennial water shortage - defined as less than 100 L/person/day. As a result of climate change and the effects on water resources, water shortages will be created for an additional 100 million people and many freshwater ecosystems will experience insufficient flows to maintain adequate ecological functioning.

Charlton and Arnell (2011) state that literature on the impacts of climate change relating to water resources falls into three categories.

i. The exposure of water management systems to climate change. An example of this would be the study of Biggs *et al.* (2013) which found that improvements in management practice that were needed to meet water quality targets in the Mackay Whitsunday region in Australia would not be greatly affected by climate change in the near future (*i.e.* 2030).
ii. Methods of incorporating climate change into the management of water, using assessment techniques and management approaches - such as the study by Liersch *et al.* (2012). This study focussed on the impacts of climate change on the Inner Niger Delta and the subsequent effects on flooded surface areas, ecological cycle, livelihood and food production. A vulnerability assessment was then developed to investigate the impacts of current and future planned dams. It was concluded that climate change, together with upstream reservoir management would lead to a significant reduction in peak water discharges leading to major agricultural losses.
iii. Development and adaptation of water management strategies in practice. Bozzola *et al.* (2014) discussed policy implications of changing climate and water resources in the Po River Valley in Italy. It was concluded that farmers would need to undertake strategies to adapt to the effects of climate change by observing recent trends in precipitation and temperature. It was also concluded that in order to address the greater uncertainty of climate change, policies were required in the form of investing in institutions and infrastructure to address issues such as insufficient water storage. The roles of the public and private sector in managing water storage to prevent agricultural losses were also detailed.

This research addresses the third point as very few realistic studies have been conducted into how organisations are adapting to climate change and the resulting effects thereof (Charlton & Arnell, 2011). However, mitigation efforts to combat the effects of climate change in isolation are insufficient to avoid further negative impacts. Adaptation through effective management and the use of conceptual frameworks are necessary to avoid additional negative impacts (Meinke *et al.,* 2009).

2.3 Water in a South African Context

The African continent has been identified as particularly vulnerable to the effects of climate change (Parry *et al.,* 2007). The prevalence of existing challenges such as poverty, corrupt governance, ecosystem degradation, natural disasters and conflict, greatly decrease the adaptive capability and exacerbate the vulnerability of the continent to the effects of climate change (Parry *et al.,* 2007). Southern Africa, in particular, is highly susceptible to the possibility of droughts as a result of heightened water stresses in river basins (Parry *et al.,* 2007) and low rainfall rates. Human activities, such as mining, have also had a negative effect on South Africa’s water sources and these effects have been worsened by the expanding economy and population growth (CSIR, 2010). Some of the factors affecting water in South Africa have been discussed below.

2.3.1 Rainfall

South Africa (a semi-arid region) receives a mean annual rainfall of approximately 450 mm which is much less than the global average of 860 mm per year (CSIR, 2010).

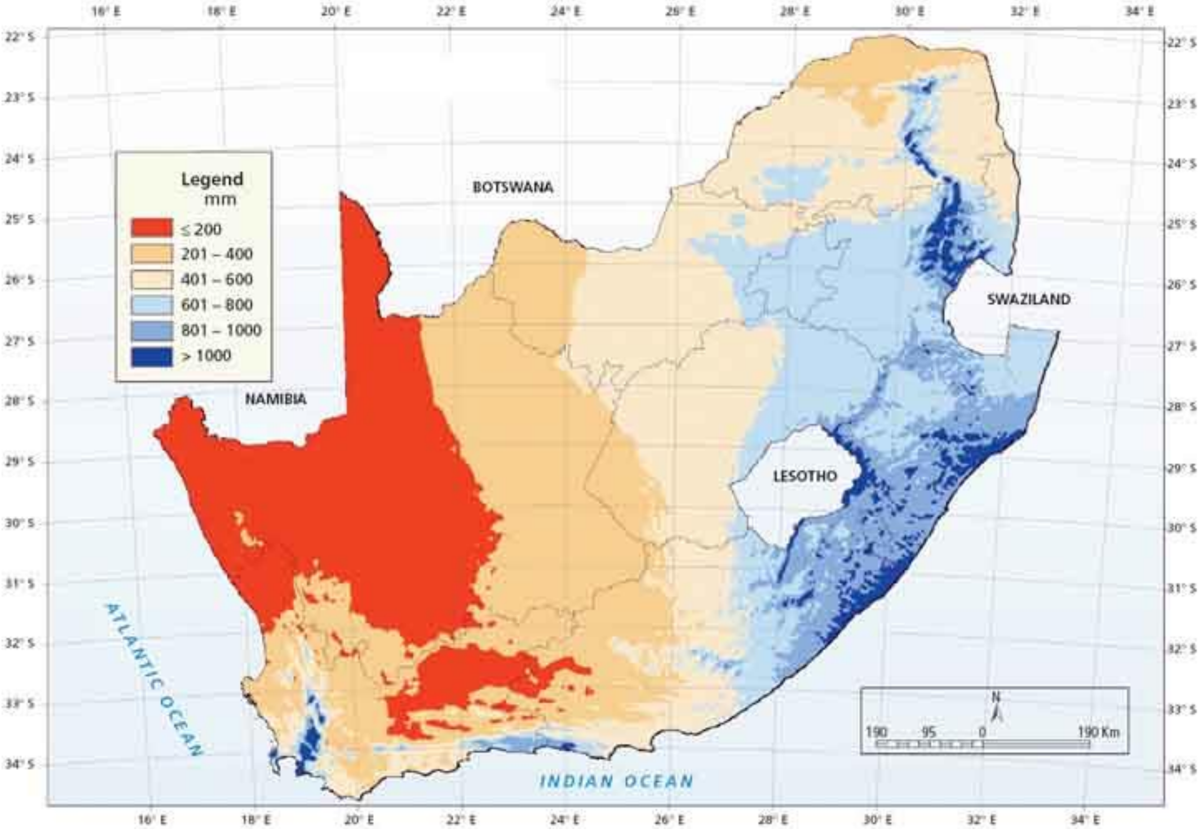

Figure 2.1 The mean annual rainfall for South Africa (FAO, 2005)

The annual rainfall throughout South Africa varies with the Richtersveldt on the Namibian border receiving less than 50 mm per annum and some of the South Western Cape Mountains receiving in excess of 3000 mm per annum. However, only 28% of the country receives more than 600 mm (Palmer and Ainslie, 2005). Figure 2.1 shows the mean annual rainfall for South Africa with areas shaded in blue the regions receiving more than 600 mm of annual rainfall. According to Oweis and Hachum (2012), 600 mm of annual rainfall is required for the safe and dependable cultivation of rain fed crops without the requirement of supplementary irrigation. Insufficient rainfall may limit the availability of fresh water, hence affecting future economic and social growth.

2.3.2 Impact from Mining Operations – Acid Mine Drainage

Acid Mine Drainage (AMD) occurs when the mineral pyrite comes into contact with water and oxygen. During the two-stage process, sulphuric acid and ferrous sulfate are formed, followed by ferric hydroxide and more sulphuric acid (McCarthy, 2011). Various chemical reactions contribute to the formation of AMD but the oxidation of pyrite is by far the greatest contributor. The reaction is shown below (Jennings *et al.,* 2008).

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) = 2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq) \qquad \text{(Reaction 1)}$$

Pyrite, which forms AMD, is commonly found in South African coal and gold deposits, especially in the Witwatersrand basin (McCarthy, 2011). During natural weathering of the rock, acid is produced very slowly so that neutralisation can occur by reacting with various minerals in soils (McCarthy, 2011). However, during mining, the rock is unevenly split and exposed surface areas increase, increasing the rate of acid production. Subsequently, the acid increases the solubility of aluminium and other heavy metals, resulting in toxic acidic water with a high heavy metal concentration (Durand, 2012). With the closure of most of the gold mines and a cessation in dewatering of the mines, underground water levels began to rise resulting in the flooding of mines and the decanting of water which was first seen in Krugersdorp and the Cradle of Humankind (McCarthy, 2011).

According to a study conducted by the Water Research Commission (WRC) in the 1980’s, mine dumps are a serious cause of pollution into water resources such as the Vaal River (Jones *et al.,* 2005). Rosner and Schalkwyk (2000) reported that topsoil layers in Johannesburg are highly acidified and contain several heavy metals such as cobalt, nickel and zinc. Traces of uranium, thorium, lead and radium have also been reported in the Witwatersrand AMD (Venter, 1995 and Coetzee *et al.,* 2006). The uranium may have originated from the uranium extraction plant which operated at West Rand Consolidated Mines Limited in 1952. The plant which was the first in the world to produce uranium commercially was strategically important to supply fuel for nuclear weapons and nuclear power stations (Durand, 2012). In the long term, the contaminants and heavy metals will be leached into groundwater.

The drainage of AMD into the Vaal River has serious consequences. Not only does the Vaal River supply water to the economic centre of South Africa (i.e. Gauteng), but it flows together with the Orange River along South Africa’s western escarpment, feeding various activities along the way, across the entire country to discharge into the Atlantic Ocean. The Vaal River currently cannot meet the demands of the regions it supplies water with and inter-basin water transfer is required (McCarthy, 2011). Water is pumped from the Tugela and Orange rivers via the Tugela Pumped Storage Scheme and the Lesotho Highlands project and supplies both the Gauteng and North West regions of South Africa. Thus, Gauteng, the centre of population mass, is already a net-importer of water.

While studies by Platinum Group Metal (PGM) mining companies state that PGM tailings have a low AMD potential, the water draining from tailings could still have a high sulfate concentration (Mudd, 2010). Active site management is required to minimise sulfate concentrations or environmental management is required to prevent impacts on water systems (Glaister and Mudd, 2010).

2.3.3 Social, Political and Economic Impacts

Water shortages are a potential consequence of poorly managed or inefficient water use by industrial operations. This could lead to social protests over access to clean water which has the potential to disrupt economic activity and result in losses by operations.

Since 1994, the South African government has been investing in infrastructure to ensure all citizens have access to water and 17 million people have been provided with access to clean water. However, an estimated 5.7 million people still lacked access to safe water in 2010 (CSIR, 2010). According to the 2009 Green Drop Report, which assessed waste water treatment facilities in South Africa, approximately R23 billion would have been needed to prevent the country's wastewater treatment facilities from failing (DWA, 2009). An assessment of 821 wastewater treatment facilities was performed in 2011 and according to the 2011 Green Drop report (DWA, 2011b);

- 14% were well managed;
- 30% performed adequately; and
- 56% did not meet acceptable standards or were in a critical state.

As a result of poorly managed wastewater treatment facilities, millions of litres of inadequately treated sewage are being discharged into water sources daily. This discharge results in further water pollution which affects clean water supply for downstream users (DWA, 2009).

On a daily basis, dissatisfaction grows against the delays in service delivery, as can be seen from the large number of protests regarding service delivery. The South African Police Service (SAPS) reported approximately 5900 protests between 2004 and 2005 (Bond, 2006). Of these, most of the protests were regarding inadequate water and sanitation services (Bond and Dougard, 2008). While many protests were of a non-violent nature, the frequency of violent protests has been increasing. According to an Incident Registration Report by the SAPS, the number of protests during the 2012/2013 period was approximately 12 399. Of these, approximately 10 517 were peaceful; implying the remaining 1822 resulted in violence (SAPS, 2013). In January 2014, four protestors were shot dead by the police as they were protesting against water shortages in Mothotlung in the North West province (ISS, 2014).

The increase in protests regarding service delivery as well as the increase in the number of violent protests has raised questions regarding the impact of protests on socio-political stability and economic activity. The impact of the 2012 Marikana protests in the North West

Province indicate that protest action can have severe economic and political consequences. The Lonmin/Marikana strike began on 10 August 2012 as 3 000 mineworkers lay down their tools and began what was referred to as “an illegal strike” demanding an increase in wages. On the 16 August 2012, after days of protesting and reports of intimidation and assault by various mineworkers, the SAPS opened fire on a crowd of mineworkers in Marikana. The shooting left 34 mineworkers dead, 78 injured and more than 250 arrested (IOL, 2012). The Marikana massacre was the biggest event of police brutality since the introduction of democracy. As a result, mine production experienced a fall of R12 billion as well as a 0.5% decline in Gross Domestic Product (GDP). This in turn increased South Africa’s current deficit and resulted in a depreciation of the national currency (Leon, 2013). According the Fraser Institute’s annual survey of mining companies, South African ranked 54 of 93 mining jurisdictions in 2011/2012. This number dropped to 64 of 96 in 2012/2013 claiming labour regulations, disruptions and general security as major areas of concern (McMahon & Cervantes, 2011 and 2012).

Shortages of water and as a result, insufficient service delivery can lead to social protests. As discussed, these can have severe repercussions on political and economic activity in South Africa.

2.4 Base Metal Refinery

The refinery in this study is located in the Bushveld Igneous Complex region of South Africa, which is known for its platinum and base metal-rich ores. More than three quarters of the world’s platinum reserves are found in South Africa (Jones, 2005). The six platinum group metals (ruthenium, rhodium, palladium, osmium, iridium, and platinum) are valuable and mined for their application in chemistry as catalysts, their corrosive resistance, aesthetic beauty, conductivity, malleability and high melting point (Crundwell *et al.,* 2011). Base metals, such as copper and nickel are extracted as a by-product during the platinum refining process. The base metals are separated from the platinum group metals and refined in a separate leaching process. According to Jollie (2010), South Africa refines 120 to 150 tonnes of platinum-group elements per year through open-pit and underground mining.

The process of extraction of PGM's and base metals begins with open-pit or underground mining to remove ore rich in PGMs and other base metals. Ore is treated using flotation to separate a concentrate rich in nickel-copper sulphides and PGMs. The product from flotation undergoes smelting to form a converter matte. The converter matte is processed using magnetic separation or leaching to produce a platinum rich feed and a base metal feed. The platinum feed is treated to recover platinum group metals while the base metal feed is processed to recover copper, nickel, cobalt and in some cases, ammonium sulfate (Crundwell *et al.,* 2011) (Figure 2.2).

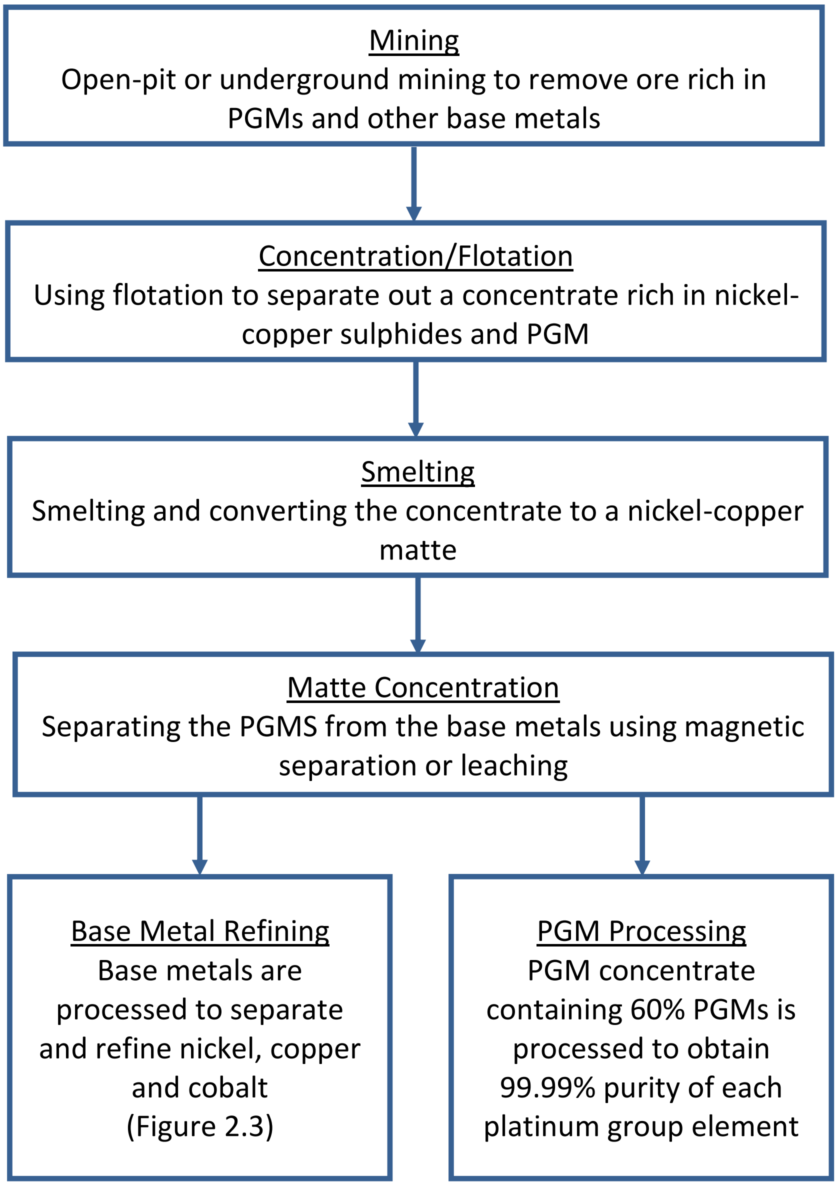

Figure 2.2 Schematic showing the extraction of base metals and PGMs from ore (adapted from (Crundwell *et al.,* 2011)

The refinery used for this study is a base metals refinery, processing feed from a concentrator to produce nickel, copper and cobalt products. The refinery uses a process of leaching, separation and various methods of refining to produce refined nickel, copper and cobalt products (Figure 2.3).

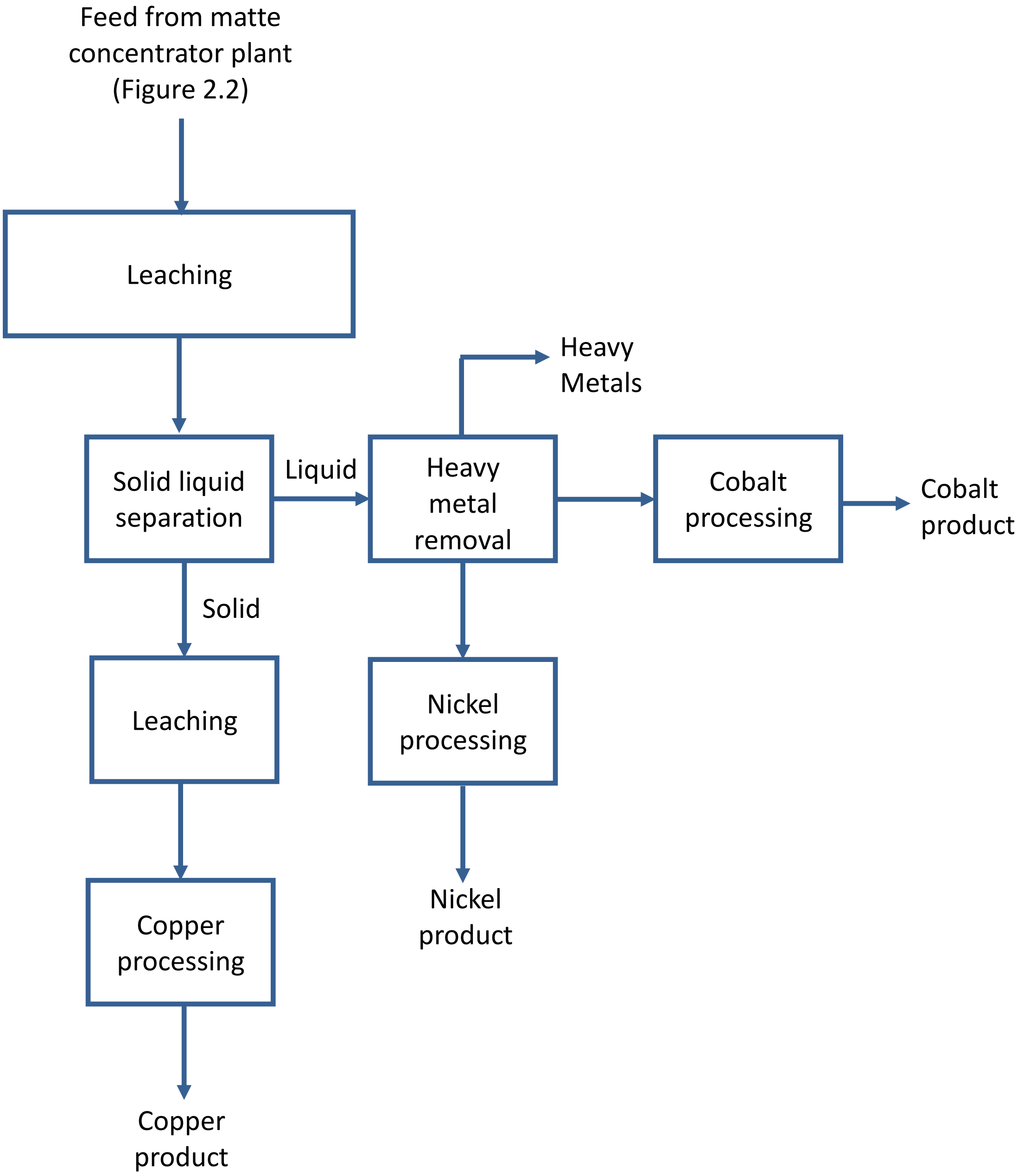

Figure 2.3 Basic base metal refining process (adapted from (Crundwell *et al.,* 2011)

During the refining process, water is used at various points for dust suppression, fire tanks, dilution, washing, flotation, reagent mixing, cooling, boilers top-up, pump gland seal water and ablution facilities. The refinery used approximately 2 280 m^3 of potable water each day. In order to reduce fresh water consumption, the refinery needed to understand where its water was being used.

2.5 Tools for Reporting Water Usage

2.5.1 Global Tools Used for Reporting Water Usage

Collecting, understanding and analysing meaningful water related data can be a difficult undertaking. As a result, several global tools have been developed to help companies in their water risk assessment and mitigation endeavours by quantifying and reporting on water usage. Some tools focus on real water usage (water balance and the WAF) whilst some use the concept of virtual water (WF, consumptive water use). Other tools focus on site water management (water balance, WAF) or cradle-to-grave analysis (WF, Life Cycle Assessment (LCA) and Water Use in LCA). Some of these tools that have been developed or used for water accounting and reporting which are briefly discussed in this section but have not used for this study are the Global Reporting Initiative's (GRI) Sustainability Reporting Framework, Life Cycle Assessment (LCA) and Water Use in LCA (WULCA), WaterMiner and the World Business Council for Sustainable Development (WBCSD) Global Water Tool.

<u>GRI Sustainability Reporting</u>

In 1997, the United Nations Environmental Programme (UNEP) in conjunction with the United States Coalition for Environmentally Responsible Economics (CERES) launched the GRI with the intention of improving the quality of sustainability reporting. The framework developed by the GRI aims to identify and report on the impacts of three focal areas: environmental, economic and social. The framework uses a hierarchical approach focusing on the three areas using performance indicators to measure the impact of focal activities. The report is presented in a universally accepted manner and measures performance toward the goal of sustainability (GRI, 2011).

In 2003, the GRI produced a report on Water Protocol to be used in conjunction with the 2002 Sustainability Reporting Guidelines which detailed six water related indicators (GRI, 2003). These six indicators clarified the environmental impacts of water use by businesses, industry, government and non-governmental organisations around the world. Two indicators were classified as core indicators which helped provide a basic understanding of an organisation’s water usage and discharge. Of the six indicators, four indicators were additional indicators which provided more information on the relative environmental impacts of the organisations water use such as the impact to regional water supply.

Life Cycle Assessment (LCA)

LCA is a tool used internationally to assess the environmental impacts of products, services and processes using a cradle-to-grave technique. It evaluates the entire life of the product or service from raw material, through different stages of processing, distribution, use, repair, maintenance and final disposal or recycling. The aim of the LCA is to compare environmental impacts of products or services by quantifying all inputs and outputs associated with the product life (ISO 2006a and 2006b). The LCA which is also standard ISO 14040 complaint, assists to identify parts of a product life cycle that have the greatest environmental impact, thus allowing companies to identify opportunities for improvement (Morrison & Schulte, 2010). The Water Use in LCA (WULCA) method focuses on assessing impacts associated with water use to provide a comprehensive WF using a life cycle perspective (WULCA, 2014).

WaterMiner

WaterMiner is an online web-based tool which follows the movement of water into and out of a mine site which was also developed by the Sustainable Minerals Institute (SMI). Using a snapshot of site water system including storage points, water sources and destinations, the tool is able to calculate how much of water a mine uses, re-uses, recycles and the volumetric changes resulting from changes in weather conditions. The tool can then be used by site management to reduce water consumption or utilise water more efficiently. The tool is used in conjunction with the WAF but was not used in this study.

WBCSD Global Water Tool

Launched in 2007, the Global Water Tool is a free, online excel-based tool to evaluate water use in the context of a particular region. It was developed to help companies assess water use, risks and opportunities relative to specific operations and supply chains (Morrison & Schulte, 2010). Companies can analyse water usage in a particular region against sanitation, population, biodiversity and stress indicators with a future outlook and thus assess water risks of a particular operation or future projects (WBCSD, 2015).

2.5.2 Tools Used in this Study

Two different tools were used for calculating and reporting water usage in this study, namely;

- Water Accounting Framework (WAF) (developed by the Minerals Council of Australia (MCA) in conjunction with the Sustainable Minerals Institute (SMI) at the University of Queensland; and
- Water Footprinting (WF).

These are discussed separately below.

Water Accounting Framework (Minerals Council of Australia, 2012).

Targeting simple and efficient reporting of water usage, and recognising the role of water in the mining industry, the MCA, in conjunction with the SMI, developed a water accounting tool or framework – the Water Accounting Framework (WAF). The aim of the framework is to obtain a deeper understanding of water use in the mining industry and allow sites to account for, report on and compare site water management practices. The reporting is performed in a consistent, unambiguous manner that can easily be understood by non-experts. The water accounting framework has been designed to align with frameworks for the GRI and Australian Water Accounting Standards (MCA, 2012).

The WAF provides:

- A consistent approach for quantifying flows into and out of a process, based on their sources and destinations;

- A consistent approach for reporting of water use by minerals processing operations that enables comparison with other mineral processing users, and relates to water planning processes;
- A consistent approach in quantifying and reporting water reuse and recycling efficiencies such that the reliance on sourced water is reduced; and
- A model for a more detailed operational water balance. This functions as guidance for businesses that currently do not have an effective operational water model.

The four outputs produced when following the WAF are the Input-output statement, a statement of operational efficiencies, an accuracy statement and contextual information.

1) The Input-Output statement

This statement describes the flows between the environment and the boundary of the site. It refers specifically to all inputs, outputs and diversions from site to the environment and vice-versa. Each water input or output has a category allocated to it from a range of 1 to 3.

- Category 1: Very close to drinking water; requiring minimal treatment (disinfection).
- Category 2: Requires treatment to remove dissolved solids and adjustment of other parameters before the water is classified as potable.
- Category 3: Unsuitable for most purposes; has a salinity of > 5 000 mg/ℓ or a pH of less than 4 or greater than 10. Water requires significant treatment before it can be classified as category 1 or 2 water.

2) The statement of operational efficiencies

The operational model describes internal site water flows of a process. Using coloured blocks to represent different points, it illustrates the movement of water onsite. The movement of water can easily be tracked from inputs to storage tanks, processes, diversions, treatment facilities. According to the framework, the following colour guideline is to be used to differentiate between different points in a process:

- Inputs are coloured green;
- Outputs are coloured red;
- Diversions are coloured yellow;

- Stores are coloured blue;
- Tasks are coloured grey; and
- Treatment plants are coloured purple.

3) Accuracy statement

The accuracy statement details whether flows used in the input-output model are measured, calculated or estimated.

4) Contextual information

Data is provided of the water resources of the surrounding regions, current infrastructure and catchments that the site is located in.

The framework uses a combination of existing data and modelled estimates to create a standardised reporting platform which can be used across different mining processes and by governments for consistency in reporting. Creating water accounts would also lead to more effective communication of water data.

Water Footprinting

The second tool used is the Water Footprinting Network's Water Footprint Method. The concept of WF builds on the idea of "virtual water" which was first introduced by Professor John Anthony Allan in the early nineties (Allan, 1993). Virtual water has been defined by Haddadin (2003) as the water "embodied" in a product in a virtual form as opposed to in a real, physical form. An example of this would be if a country exported a product containing water, e.g. an apple, to another country, water is exported not directly, but in a virtual form (Hoekstra, 2003).

The WF concept was first presented by Hoekstra in 2002 (Hoekstra, 2003) at UNESCO-IHE and later by Chapagain and Hoekstra (2004) as a method of measuring and understanding water usage in the production process. WF can be defined as the total amount of water that is consumed, directly and indirectly during a production process. WF can be used to measure water consumption in industries, businesses or commodities. A WF evaluation considers not only the water consumption and its impact, but also measures that can be implemented to reduce the consumption and impacts associated with production.

The WF is presented as units of water consumed per unit of product produced. WF is different from carbon footprinting in that the WF needs to be considered as a function of the locality in which the assessment is being performed and how different types of water are being used or wasted. Once a WF assessment has been performed, the sustainability of the operation and nearby water sources are investigated. WF also creates awareness as to where the largest consumers of water are located.

The direct WF refers to freshwater consumption and pollution used or produced directly from the consumer or producer. Indirect WF's refer to the water consumption and pollution that is associated with the production of goods and services that are used by the consumer.

One of the hallmarks of WF is to classify water into three categories:

Blue water: Fresh water resources such as surface and ground water required for the production of a product that are not returned to the same source;

$$\text{Blue WF} = \text{Blue}_{\text{water Evaporation}} + \text{Blue Water}_{\text{lost as product}} + \text{Blue Water}_{\text{lost to catchment}}$$

[Equation 2.1]

Green water: Rainwater used during the production process that does not run-off or discharge into groundwater sources that could have been stored in the soil or temporarily on top of the soil; and

$$\text{Green WF} = \text{Green}_{\text{water evaporation}} + \text{Green Water}_{\text{lost as product}}$$

[Equation 2.2]

Grey water: The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards.

$$\text{Grey WF} = \frac{L}{C_{max} - C_{nat}}$$ [Equation 2.3]

Where:

L is the pollutant load (mass/time);

C_{max} is the ambient water quality standard for the pollutant (mass/volume); and

C_{nat} is the natural concentration in the receiving water body (mass/volume).

The total WF is classified as the sum of the blue, green and grey water footprints as shown in Figure 2.4 and Equation 2.4.

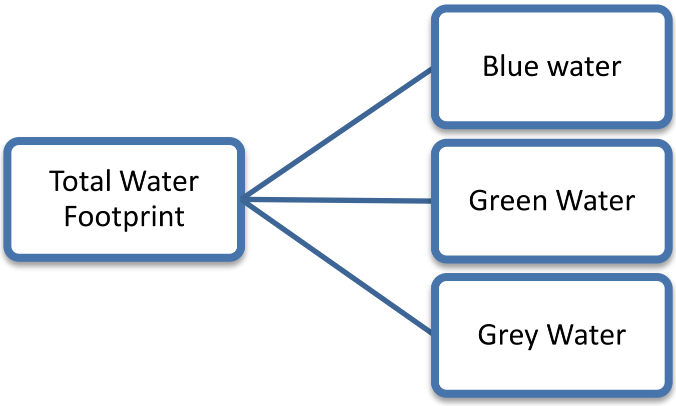

Figure 2.4 The Calculation of the Total WF

$$\text{Total Water Footprint} = \text{Blue Water} + \text{Green Water} + \text{Grey Water} \qquad \text{[Equation 2.4]}$$

Blue water evaporation refers to fresh water that has evaporated during a production process. Green water evaporation refers to rainwater which was captured, stored and has then evaporated. During green water storage, some water may evaporate and this is referred to as green water evaporation. Similarly, blue water lost as product refers to fresh water which may be incorporated into a product (for example to dilute a liquid before selling). Green water lost as product would refer to rainwater used for the same purpose.

The WF Assessment has four critical steps:

i. Setting of goals and the scope (boundaries);
ii. Calculating green, blue, and grey water footprints;
iii. Assessing sustainability and efficiency; and
iv. Adequately responding to findings of the WF calculations and sustainability assessment.

These steps are discussed in detail in the methodology.

Most mining operations, including the one that this study was performed at, operate using a zero discharge principle. As far as possible, all water is treated, recycled or stored. Water is lost mainly through evaporation. Thus no grey water footprint can be calculated for such an operation.

Some examples illustrating the use of WF and the concept of virtual water have been summarized below.

2.6 Case Studies

A few examples of WF which have been applied on different products are shown in this section. WF in the mining industry is still a novel concept and not many examples were available when this research was conducted. The different studies presented are:

a. A polyethylene terephthalate (PET) bottle of Coca-Cola drink and beet sugar required for the cola drink;
b. Beer produced in two different countries;
c. Lafarge Plasterboard;
d. Tata Steel, Tata Chemicals, Tata Motors and Tata Power;
e. Energy;
f. Gold; and
g. Platinum.

2.6.1 PET Bottle of Coca-Cola

The Coca-Cola Company, in conjunction with The Nature Conservancy (The Coca-Cola Company and The Nature Conservancy, 2010), performed WF studies on three processes in Europe:

i. Production of a 0.5 litre polyethylene terephthalate (PET) bottle;
ii. Production of beet sugar; and
iii. Manufacturing, blending and bottling of the cola drink.

A complete WF study included both direct and indirect water consumption (Figure 2.5). For direct consumption, the water consumption of the actual manufacturing process is used.

Indirect water use included water required for crop growth, transport, consumption of the product as well as disposal (Hoekstra, 2003).

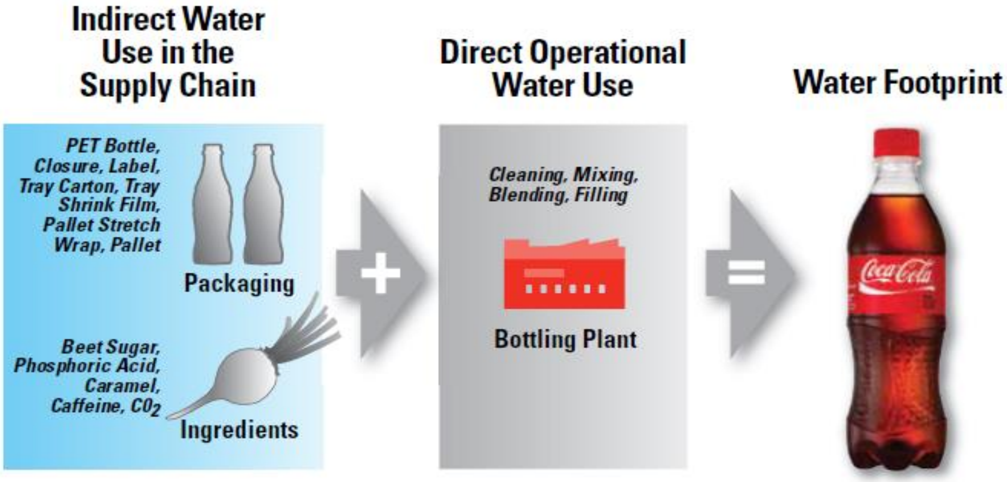

Figure 2.5 WF calculation of a bottle of Coca-Cola showing the inclusion of both direct and indirect water use (The Coca-Cola Company and The Nature Conservancy, 2010)

Indirect water use included the water required to produce the PET bottle and beet sugar while direct water use referred to water used during the blending and bottling process.

The total green water footprint to produce a 0.5 L bottle of Coca-Cola was calculated to be 15 L, the blue water footprint as 8 L, and the grey water footprint was 12 L. Most of the blue and green water footprints were associated with the sugar beet production. The most noticeable consumption of grey water occurred with nitrogen fertiliser use for beet production and the cooling water required for PET bottling (Hastings and Pegram, 2012).

The water footprint of sugar beet was performed on a number of different source locations. The average blue water footprint obtained was 54 L/kg sugar. The average green and grey water footprints were 375 and 128 L/kg sugar respectively. Figure 2.6 shows the different water footprints of sugar beet across different countries. It is seen that Greece has the highest water footprint with a total of almost 1200 L/kg of beet, while France has the lowest with just under 400 Ls/kg of sugar (The Coca-Cola Company and The Nature Conservancy, 2010).

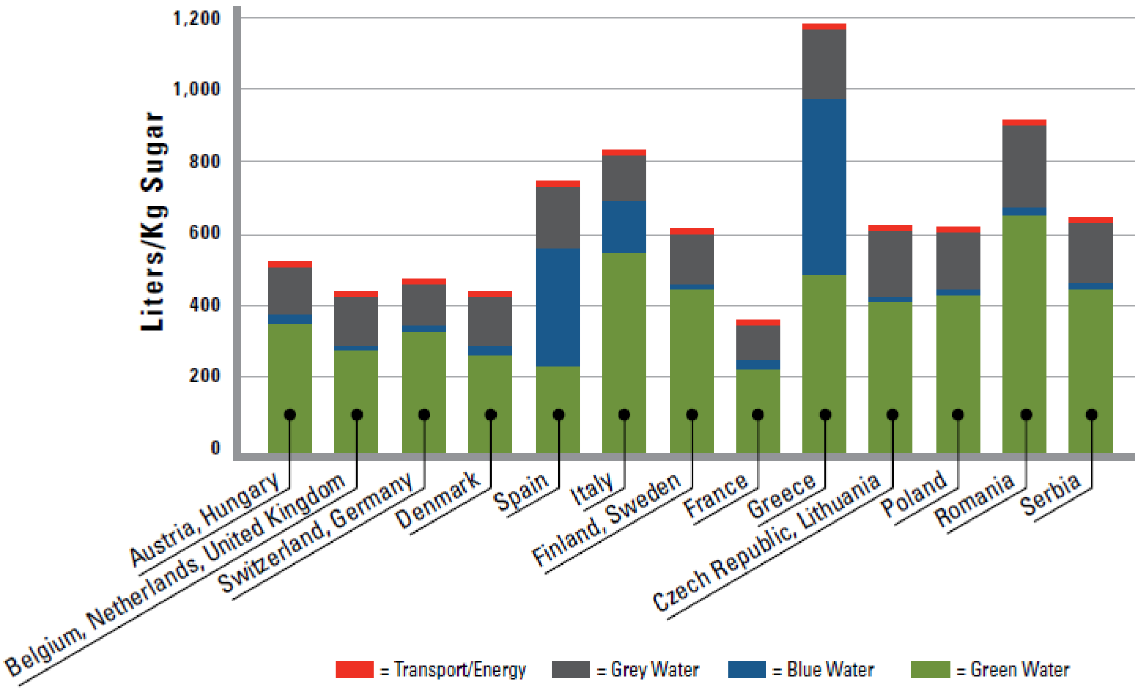

Figure 2.6 Water footprints of sugar beet for different countries (The Coca-Cola Company and The Nature Conservancy, 2010)

The following important points were observed from the study:

- More than two-thirds of the total water footprint of the 0.5 L PET bottle of Coca-Cola arises from blue and green water used in the supply chain to grow sugar beets;
- Greece had the highest WF per kg of sugar produced; and
- One third of the total water footprint is grey water associated with the supply chain (The Coca-Cola Company and The Nature Conservancy, 2010).

The results of the study indicated that the WF of the sugar produced from sugar beet as well as other (substitution) sweeteners used in Coca-Cola production were to be investigated in order to understand the water use associated with these products. It is important to source sustainably produced sugar (The Coca-Cola Company and The Nature Conservancy, 2010).

2.6.2 WF of Beer Produced by SABMiller

The World Wildlife Fund (WWF) in conjunction with SABMiller performed a WF study on the production of beer in South Africa and the Czech Republic. The objective of this was to understand and compare the amount of water used, specifically during the agricultural phase. This would help the organization make future decisions based on water risks (Hastings and Pegram, 2012, SABMiller and WWF-UK, 2009).

The WF study was performed for a litre of beer produced in South Africa and the Czech Republic. During the study, crop cultivation, crop processing, brewing, transport, consumer use and disposal were studied (Figure 2.7).

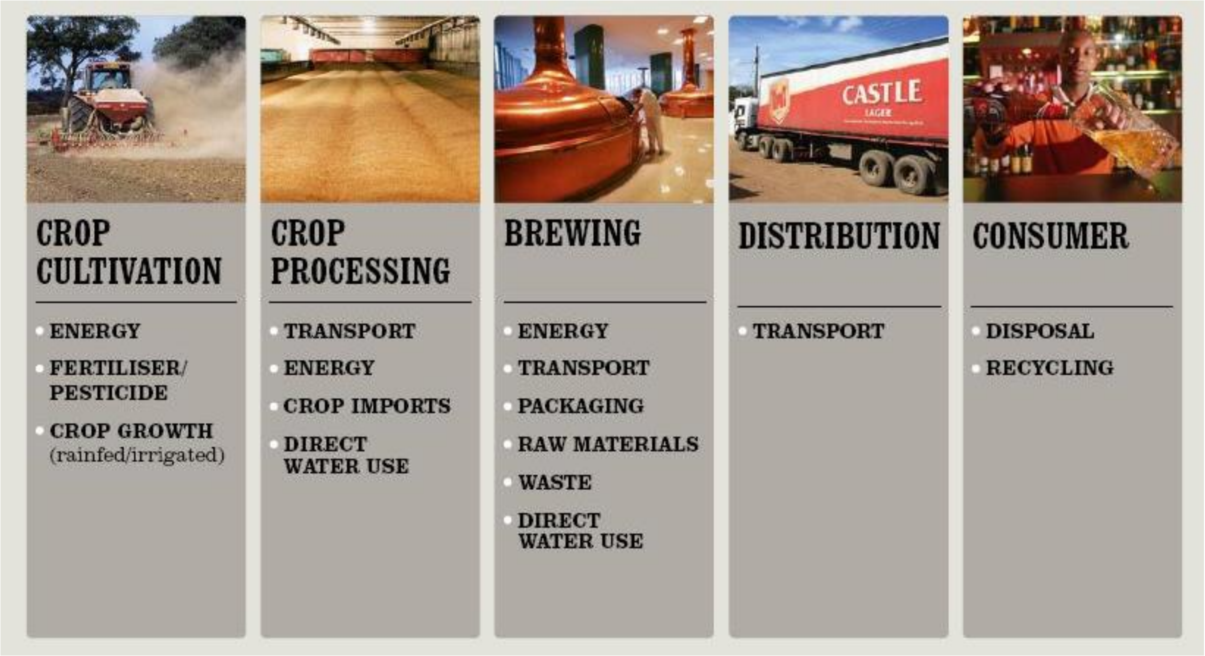

Figure 2.7 The value chain showing direct and indirect water usage in the calculation of the WF of beer (SABMiller and WWF-UK, 2009)

In both South Africa and the Czech Republic, agricultural cultivation accounted for more than 90% of the overall WF; this showed the significance of accounting for indirect usage in the WF study. It was found that South Africa had a WF of 155 L of water/L of beer while the Czech Republic had a WF of 45 L of water/L of beer (SABMiller and WWF-UK, 2009). South Africa, as a semi-arid country, had a larger WF than that of the Czech Republic. South African evaporation rates are quite high and resulted in a much larger fresh water demand for crop growth. This led to a higher blue WF (as more fresh water was required for crop cultivation) and as a result a higher overall WF. A comparison of the blue, green and grey WFs for both countries can be seen in Figure 2.8.

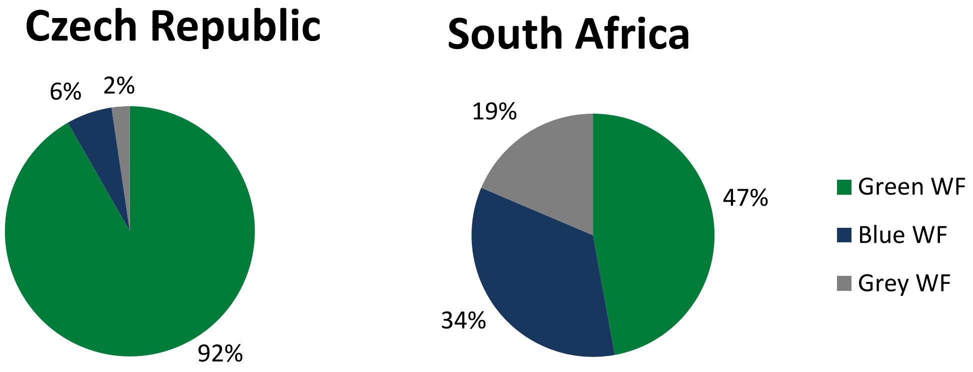

Figure 2.8 A comparison of the blue, green and grey WF for the production of beer in South Africa and the Czech Republic (adapted from SABMiller and WWF-UK, 2009)

Although the one WF is larger than the other, the degree of impact cannot be determined as this requires a full study of the local impact. In this context, the WF of different locations should be used more for benchmarking as opposed to assessing impacts (Hastings and Pegram, 2012).

2.6.3 Lafarge Plasterboard

Lafarge is a company specialising in the production of plasterboard, cement and construction materials. Lafarge aimed to calculate the WF of its operations in order to assess and understand freshwater requirements with the goal of reducing water usage. A study performed by Lafarge UK found that the plasterboard facility had a WF of 6.6 L of water per square metre of plasterboard produced. This WF was mostly a result of freshwater use during operations and the disposal of wastewater. This differs from the previous food and beverage studies discussed as the WF of food and beverages relied greatly on indirect agricultural water usage (Hastings and Pegram, 2012).

2.6.4 Tata Group

Tata Steel, Tata Chemicals, Tata Power and Tata Motors are four companies which form part of the international Tata Group. These companies, in collaboration with the International Financial Corporation (IFC), undertook a WF study across twelve Tata plants in India (Unger *et al.,* 2013).

The aim of the study was to:

i. Calculate the WF of the twelve plants in India;
ii. Understand the water efficiency of the plants;
iii. Understand the impact on local water sources;
iv. Formulate strategies to reduce the WF and minimise water pollution; and
v. Take on a leading role in corporate water stewardship.

The results were reported for each of the four individual companies of the Tata Group.

Tata Steel Ltd.

It was found that the Tata Steel Jamshedpur facility had a high blue water footprint, requiring 24.9 million m^3 of water per year. Most of this water (81%) was required for direct operations such as steel and iron making. The facility did not have a direct green WF but did have a green WF associated with onsite horticulture. The green WF was approximated to be 122 500 m^3 per year for 18 hectares of greenery. The WF of Tata Steel Ltd. established an international benchmark and assisted in identifying possible points of inefficient water usage. The total grey WF was 15.2 million m^3 per year due to the high volume of total suspended solids (TSS) that required dilution by TATA prior to discharge. The blue water footprint of the end product was 4.21 m^3 per ton of steel produced (Unger *et al.,* 2013).

Tata Chemicals Ltd.

Studies were performed to calculate the WF at three different Tata Chemicals facilities;

i. Mithapur;
ii. Babrala; and
iii. Haldia.

Tata Chemicals Mithapur manufactures soda ash, caustic and salt. Babrala makes urea and Haldia produces di-ammonium phosphate (DAP), nitrogen phosphorus potassium (NPK) fertiliser (3:8), NPK 10:26 and sulphuric acid. The blue WF (in m^3 per megatonne (Mt)) for the period 2010 to 2012 can be seen in Figure 2.9. The blue WF resulting from direct manufacturing, raw materials, energy required and packaging were included (Unger *et al.,* 2013).

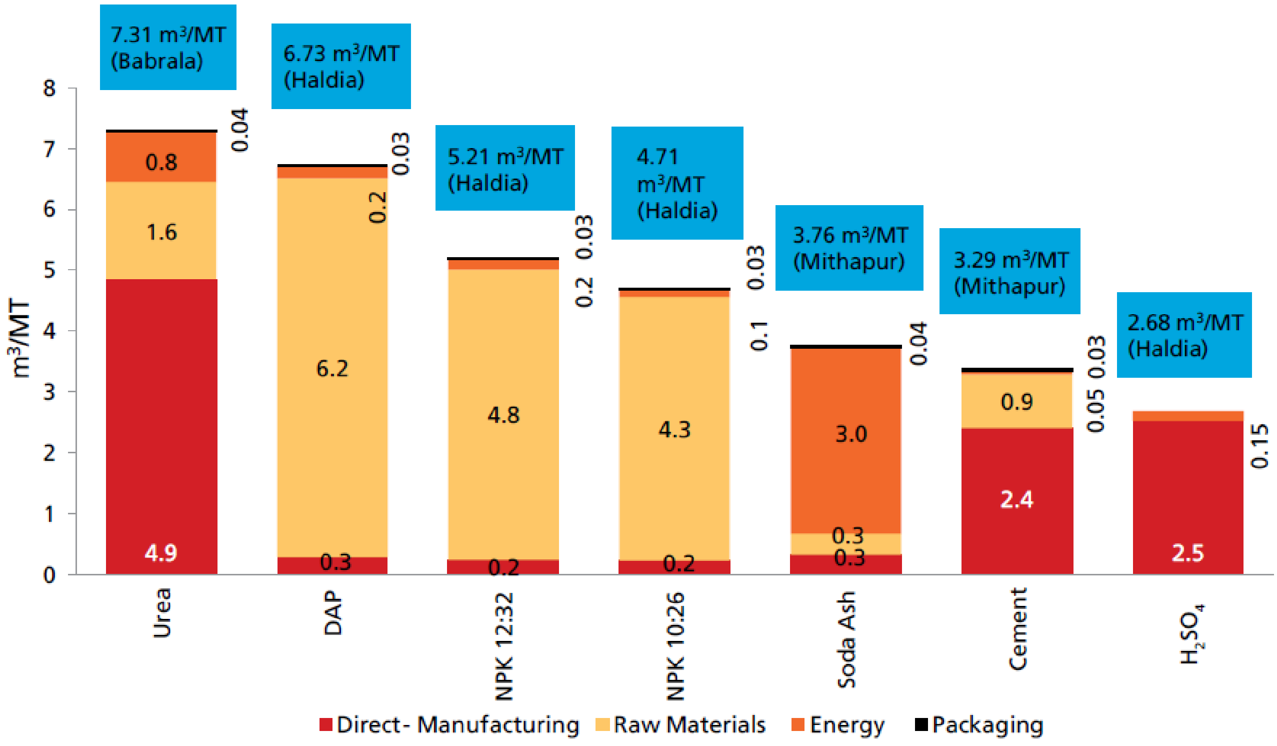

Figure 2.9 The blue WF (direct water only) of three different Tata Chemicals production facilities (Babrala, Haldia and Mithapur) for the period 2010 to 2012 (Unger *et al.,* 2013)

The blue WF of Babrala was the highest at 7.31 m^3 water/Mt urea produced. Babrala uses groundwater as its major source of water. The water is used as boiler feed, for cooling and various other processes. The Babrala facility also supplies freshwater to the nearby villages and the homes of its employees. Groundwater is also used to maintain gardens, the canteen and offices. The study showed that cooling was the most water intensive process, accounting for almost 70% of water use (Unger *et al.,* 2013).

Tata Chemicals Haldia operations used fresh water, primarily for cooling, demineralisation and other processes to manufacture phosphoric acid, sulphuric acid and NPK fertilizers. The freshwater is supplied by a local water facility and is also used for gardening and domestic water supplies. The WF assessment showed freshwater used for cooling accounted for 43% of water usage. Demineralisation was the second largest user accounting for 22% of the freshwater use. The production of sulphuric acid is not water intensive and hence a low blue WF was calculated (2.68 m^3 water per megatonne of acid produced) (Unger *et al.,* 2013).

The Mithapur facility manufactured soda ash and cement. Mostly seawater was used and thus the facility had comparatively low blue WFs (3.76 m^3 for soda ash and 3.29 m^3 for cement per megaton versus the 7.31 m^3 per megatonne of Babrala) (Unger *et al.,* 2013).

The indirect water usage of the three Tata Chemical facilities was also calculated. Babrala had an indirect blue WF of 3.09 million m^3 for the 2012 period. Most of this was as result of the WF associated with the production of the natural gas and naphta which was used during production of urea. Haldia had an indirect blue WF of 3.11 million m^3 of water for the same period while Mithapur had an indirect blue WF of 3.63 million m^3. Most of the indirect blue WF was associated with fuel sourcing (Unger *et al.,* 2013).

All three sites had small green WFs as water was only used for gardening and horticultural purposes (Unger *et al.,* 2013). Domestic effluent accounts for nearly 93% of Babrala's grey WF. The remaining 7% is as a result of the production process. Demineralisation and cooling processes used at the Haldia facility accounted for almost two-thirds of the grey WF. Mithapur does not have a grey WF as effluent is discharged into the sea (Unger *et al.,* 2013).

Of the total WF calculated for the 2012 period, the blue, green and grey WFs for Tata Chemicals Ltd. were 85%, 7% and 8 % respectively (Unger *et al.,* 2013).

Tata Power Ltd.

Assessments were performed at two different Tata Power plants – Trombay and Jojobera. Trombay had a blue WF of 3 m^3 per million megawatt hours (MWh) while Jojobera had a blue WF of 4.3 m^3 per million MWh. The extensive use of seawater resulted in a lower WF for the Trombay operation. Seawater is not accounted for in blue or grey water and thus resulted in a much lower WF for the Trombray operation. From the study it was also seen that choice of fuel can drastically affect the WF with oil having a much higher blue WF than coal and gas. No grey WF was calculated as the Trombay operation discharges effluent into the ocean whilst Jojobera has a high quality effluent treatment plant (Unger *et al.,* 2013).

Tata Motors Ltd.

The direct blue WF of the different Tata Motors operations varied from 1.69 m^3 of water per vehicle to 5.46 m^3 per vehicle. The resulting difference is as a result of different vehicles being produced at different facilities. One facility may produce fewer medium and heavy commercial vehicles whilst another may produce lighter passenger vehicles. During the assessment, painting and forging were found to be the most water intensive processes (Unger *et al.,* 2013).

A summary of these WF studies is shown in Table 2.1. References are shown as a footnote to the table.

2.6.5 WF for the Energy Industry

Virtual water studies have also been performed over a number of different energy sources. A study was conducted by Gleick (1994) and Gerbens-Leenes *et al.* (2008) to compare the different sources of energy and to express the water footprint as the amount of water consumed per unit of energy produced. Fossil fuels, uranium, natural gas, coal and crude oil were examined. In the category of renewable energy, wind energy, solar thermal energy, hydropower and biomass were investigated.

The most common non-renewable energy resources are crude oil, followed by coal, natural gas and uranium (Gerbens-Leenes *et al.,* 2008). In the renewable fuel category, the water requirement of wind power, solar power, hydropower and biomass was investigated.

Crude oil

Crude oil is produced by drilling oil wells and pumping out the oil (Gerbens-Leenes *et al.,* 2008). In a study performed by Gleick in 1994, it was estimated that approximately 1.06 m^3 of water was required per gigajoule (GJ) to drill, pump out the oil and treat the crude oil. When crude oil volumes pumped out decreased, a process of thermal steam injection was used which increased the water requirement by approximately 2250%.

Table 2.1 A summary of selected water footprint studies

Location	Product	Observations	Green/Blue/Grey WF
Europe	0.5 L bottle of Coca-Cola (packaging, drink and bottling)[1]	Most of the blue and green water footprints were associated with the sugar beet production	Per 0.5 L cola: Green: 15 L Blue: 8 L Grey: 12 L
South Africa	SAB Miller Beer Production[2]	Agricultural water usage accounted for >90% of overall WF	155 L per litre of beer
Czech Republic	SAB Miller Beer Production[2]	Agricultural Water usage accounted for >90% of overall WF	45 L per litre of beer
United Kingdom	Lafarge Plasterboard[3]	WF calculated was mostly as a result of mostly freshwater use during operations and the disposal of wastewater	6.6 L of water per m^2 of plasterboard
India	Tata Steel[4]	A large amount of freshwater was required for direct operations such as steel and iron making	Blue WF: 4.21 m^3 per ton of steel
	Tata Chemicals[4]	Sites using seawater had a lower WF than those using freshwater Boilers and cooling processes were the largest consumers of freshwater	2.68 - 7.31 m^3 water per Mt of chemical product
	Tata Power[4]	Use of seawater resulted in a lower WF for Trombay No grey WF was calculated as the Trombay operation discharged effluent into the ocean whilst Jojobera had a high quality effluent treatment plant	Trombay: 3 m^3 per million MWh Jojobera: 4.3 m^3 per million MWh
	Tata Motors[4]	Variation in WF is as a result of the production of light or heavy motor vehicles at different facilities	1.69 m^3 to 5.46 m^3 of water per vehicle

References:
1) Coca-Cola Company and Nature Conservancy, 2010
2) SAB and WWF Fund, 2009
3) SAB and WWF Fund, 2009
4) Unger *et al.,* 2013

Coal

Coal is the most important fuel source in South Africa, providing 75% of the fossil fuel demand and 91% of energy generation (Mwakasonda, 2007). Coal was extracted through various mining activities. Open pit mining required approximately 0.16 m^3 water/GJ of energy produced. Underground mining required up to ten times more water since a large amount of contaminated water was produced during operation (Gleick, 1994).

Natural gas

Natural gas is the third most commonly used non-renewable energy source across the world and is recovered by drilling wells into the ground. Crude oil and natural gas are often found together in porous reservoir rocks (Gerbens-Leenes *et al.,* 2008). Gleick estimated that 0.11 m^3 water/GJ is required to extract the natural gas.

Uranium

Uranium is found in regions of the earth's crust and is extracted by open-pit and underground mining of uranium oxide (U_3O_8) containing ore. During mining, water is used for dust control and beneficiation of the ore. The WF of uranium mining was 0.09 m^3 water/GJ of energy produced (Gleick, 1994 and Gerbens-Leenes *et al.,* 2008).

Wind and Solar power

Wind power had the smallest WF of 0 m^3 water/GJ as wind energy uses kinetic energy in the air to generate electricity. Solar energy also had a small WF with a footprint of 0.27 m^3 water/GJ of energy produced. This footprint increases when steam is used to generate power through turbines.

Hydropower

Hydropower is generated when the movement of water is used to generate energy. The water requirement is mainly as a result of water lost through seepage and evaporation and was calculated to be 22 m^3 water/GJ of thermal energy produced.

Biomass

Biomass had the largest WF of all the renewable energy forms. This was due to the large agricultural water requirement and resulted in a WF of 70 m^3 water/GJ. However this figure can vary from 10 to 250 m^3 of water depending on the type of fuel burnt (Gleick, 1994 and Gerbens-Leenes *et al.,* 2008).

The results and observations of the WF of the various energy sources are summarised in Table 2.2.

Table 2.2 Examples of the water footprints of different energy sources (adapted from Gleick, 1994 and Gerbens-Leenes *et al.,* 2008)

Energy Type	Energy Source	Observations	WF (m^3/GJ)
Non-renewable	Natural gas	Water is often withdrawn with extracted gas	0.11
	Coal	WF of deep mining coal is high due to a large amount of contaminated water production	0.16
	Crude oil	Thermal steam injection increases the WF by almost 2250%	1.06
	Uranium	WF of underground uranium mining is negligible, but can increase if turbines are used.	0.09
Renewable	Wind energy	Smallest WF of renewable energy types	0
	Solar thermal energy	WF increases when steam is used to generate power through turbines.	0.27
	Hydropower	Largest WF of renewable non-biomass energy types	22
	Biomass energy	Largest WF of renewable energy types	70 (range: 10-250)

2.6.6 WF of Gold Production

In 2007, Mudd published a report on the sustainability of gold mining as well as the impact of decreasing ore grades on resource consumption (Mudd, 2007a). The study focussed on gold mines listed in the annual world gold production reports: United States, Australia, South Africa and Brazil. Data was collected from annual sustainability or technical reports. Combining the data from the years 1991 to 2006, an average of 691 m^3 of water was required to process one kilogram of gold (Mudd, 2007b). According to Mudd (2007b), gold mines that have higher ore grades (>6 g/t gold) use less water for processing than mines with lower ore grades (<2 g/t gold), i.e. as ore grades decrease, water usage increases.

The WF (calculated as the volumetric water requirement per unit of gold produced) could also depend on the method of processing, with heap leaching possibly proving to be the more water efficient process when compared to tank leaching. Examples to illustrate this would be the Eldorado Gold mining and processing operations in Turkey and China. The Kişladağ and Efemçukuru mines operate in Turkey while the Jinfeng and Tanjianshan mines operate in China. Of the four operations, only the Kişladağ mine operated using heap leaching and used 121.5 m^3 of water to process one kilogram of gold. Water usage for the three tank leaching operations varied from 143 to 407.5 m^3/kg gold produced. Water usage per kilogram of gold is summarized in Table 2.3 for the four gold processing operations (Eldorado Gold Corp, 2012).

Table 2.3 Water usage at various Eldorado Gold mining and processing operations (Eldorado Gold Corp, 2012).

Mine	**Location**	**Process**	**Water usage (m^3/kg)**	**Detail**
Kişladağ	Turkey	Heap	121.5	Low-grade open pit operation using heap leaching
Efemçukuru	Turkey	Tank	143	Gravity circuits followed by flotation to produce a flotation concentrate and a gravity concentrate
Tanjianshan	China	Tank	228.7	Ore is processed using a flotation circuit followed by roasting and finished with carbon in leach methods
Jinfeng	China	Tank	407.4	BIOX technology and a conventional carbon in leach circuit to produce gold doré

2.6.7 WF of Platinum Production

The critical process steps in a platinum refining process are mining, concentrating, smelting, base metal recovery and precious metal recovery. Haggard *et al.* (2013), published a study investigating the water usage at a precious metal concentrator plant and the associated tailings facility. The concentrating process utilised crushing, milling and flotation to separate precious metals from other materials. Figure 2.10 shows a simplified flow diagram of the process indicating points where water enters and exits the process.

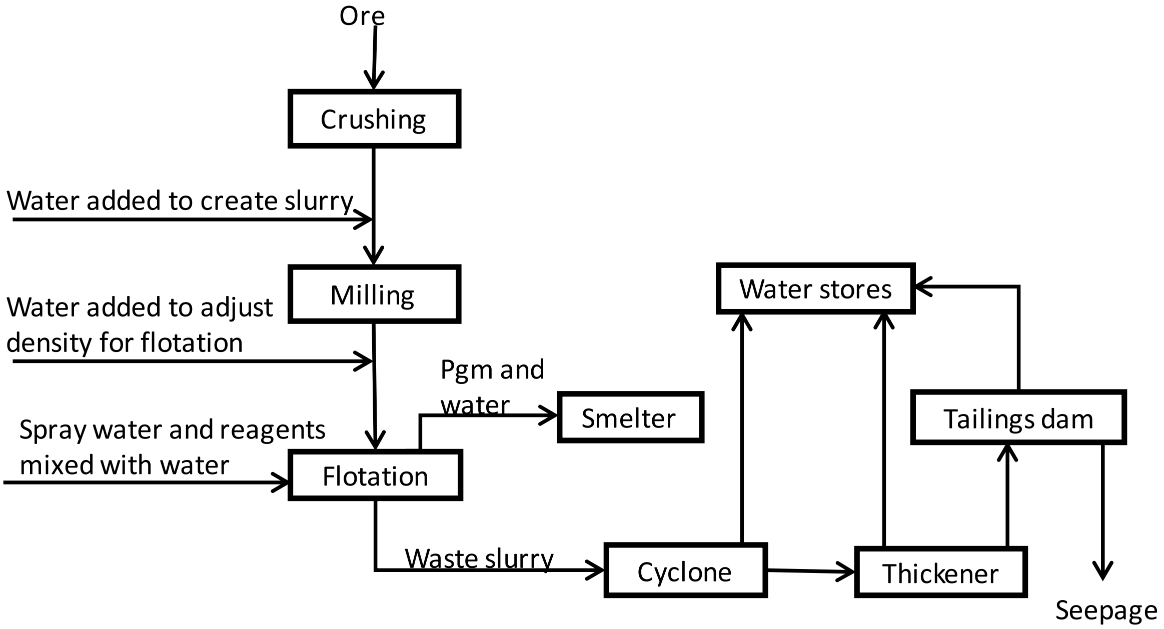

Figure 2.10 Simplified water flow sheet for the concentrator plant and tailings dam of a platinum processing plant (Haggard *et al.,* 2013)

As can be seen from Figure 2.10, water was used to create slurries, for density adjustment during flotation and for general dilution of reagents. Water left the process through seepage from the tailings facility, evaporation or is sent to the smelter. The WFs obtained from the study are summarised in Table 2.4.

From Table 2.4, it is seen that the grey WF contributed the more significantly to the overall WF than the blue or green WF. This was a result of the seepage of water from the tailings dam into underground aquifers. By covering water storage tanks that are open to the atmosphere to prevent loss of water through evaporation, the potential exists to reduce the

WF of the concentrators and tailings facility to 11 173 ML/a. The product WF was calculated to be 201 m^3/kg PGM produced (Haggard *et al.,* 2015).

Table 2.4 Blue, Green and Grey WF obtained for a South African Platinum Mine

Description	WF calculated (ML/a)
Blue	5 537
Grey	5 929
Green	344
Total	11 811

A similar study was performed by Ranchod *et al.* (2015) to investigate the blue WF of a South African platinum mining operation. It was seen that the largest loss of water during the platinum production process was from evaporation from the mineral processing plant and from the tailings facility. It was recommended to use floating covers to reduce the evaporative losses. According to Northey *et al,* (2014), the tailings storage facility at most mine sites provided the largest source of reusable water and thus potential to reduce water usage.

2.6.8 WF of Copper

In 2013, Peña and Huijbregts completed a study on the extraction and production of high-grade copper from both a copper sulphide and copper oxide ore in the Atacama Desert in northern Chile. It was seen that the blue WF of refining the sulphide ore (96 m^3 water/t copper) was 2.4 times higher than that of the oxide ore refining process (40 m^3 water/t copper) (Peña and Huijbregts, 2013). Seepage, accumulation and evaporation at the concentrator plant were the largest contributors toward the blue WF of the sulphide ore refining process. Heap leaching followed by crushing/agglomeration and electrowinning of the oxide ores were the largest users of water during the oxide refining process. The greatest water losses during the oxide process were as a result of evaporation. Preventative measures that could reduce the consumption of water included the use of more sophisticated equipment during irrigation of heap leach pads for the oxide process and improving water recovery during the sulphide process. Using seawater during the production process could reduce the blue WF by up to 62% (Peña and Huijbregts, 2013).

In 2013, Northey *et al.* assessed the WF of various copper producing mines, operations and companies in Australia, Papua New Guinea, South Africa, Turkey, Finland, the USA and Canada. The study was performed by collecting data from the sustainability reports that had been published by copper operations from 1996 to 2010. It was seen that more water was lost through evaporation at operations that were located in arid regions that experienced higher temperatures. Evaporation reduced the amount of water that was available for recovery and thus increased the external water required. The water required for dust suppression was also increased as the amount of moisture in the soil decreased. The WF calculated varied from several m^3 to 350 m^3/t copper, averaging around 74 m^3/t copper produced (Northey *et al.,*2013).

2.6.9 WF of Base Metals

To the best of the author's knowledge, neither WF nor the WAF studies have been conducted on refinery producing copper, nickel and cobalt simultaneously. This study would assist industry in providing the first benchmark of this kind.

3. METHODOLOGY

The main objective of this research was to report water usage of the refinery using global reporting tools such as the WAF and WF. In order to accomplish this, four stages were followed. This is shown in Figure 3.1 and explained in detail thereafter.

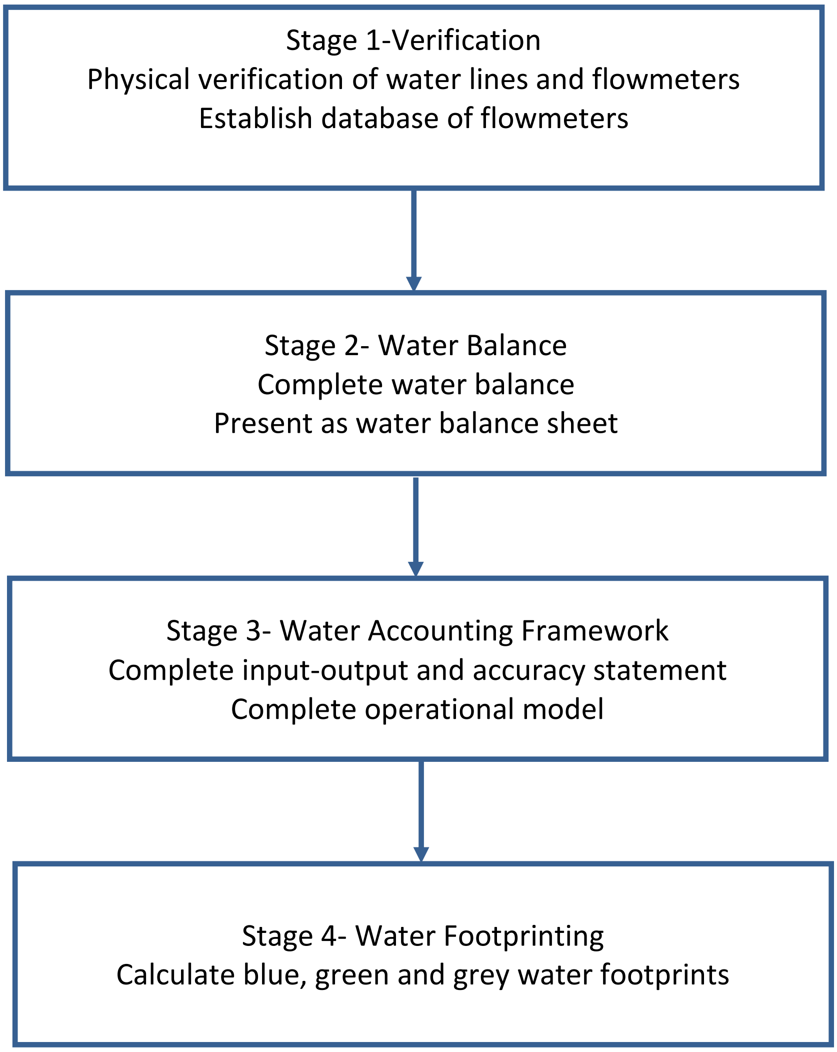

Figure 3.1 The sequence of work that was followed in completing the research

3.1 Stage 1: Verification and Updating of Water System

The first objective of this work was to analyse and update the current water reticulation system. This was achieved by:

- Physically verifying the flowmeters and pipelines of potable water, steam, process and rainwater (dam) lines and establishing a database of existing flowmeters; and
- Constructing water reticulation diagrams.

3.1.1 Physical Verification and Flowmeter Database

There were two aspects to the physical verification. The first concerned the piping layout, and the second the identification of the installed flowmeters. The water reticulation system was to be verified by physically tracking all the water lines from source to usage or final end-point. The flowmeters were identified, photographed and recorded into a database. All water lines were tracked from start to end point and verified against the existing piping and instrumentation diagrams. A database of flowmeters was drawn up once the water lines and flowmeters had been verified. The database contained:

- The tag/equipment numbers;
- A brief description;
- Flowmeter type;
- A photograph of the flowmeter; and
- The flowmeter numbers as would be displayed on reticulation diagrams.

3.1.2 Reticulation Diagram

The information from the physical verification and various plant diagrams was used to construct water reticulation diagrams detailing usage from entrance into the system to final usage. The reticulation diagrams were split into six diagrams to represent the different sections of the plant. Water enters the system from the main potable water line as supplied by the local municipality. This line splits to provide water to the following sections:

- Effluent and sulfate (E&S);
- The main refinery area;
- Storage water for fire usage; and
- Boilers and utilities.

Rain water is collected in storage dams and is pumped to fill the recycled water tank (also known as the rainwater tank) which provides additional water for use onsite. Water from operations that is not fit for re-use is also pumped to the storage dams. Thus, the storage dams contain water that has been contaminated from leaking equipment. This water can still be re-used onsite for washing of floors and to clean up spills. In the event of insufficient water available in the storage dams to fill the recycled tank or if pumping issues occur, water is pumped from the fire tank to the recycled water tank. This implies that potable water is also used indirectly to feed the recycled water storage tank.

The different sections of the plant can be seen in Figure 3.2. The blue blocks show the different sections that split from the main water line. The recycled water (rainwater) tank represents water storage and is also shown. Evaporation is the only form of water loss from site and occurs from all tanks, dams and spillages. During a period of rainfall, all run-off onsite is collected and diverted to the storage dams. No water is allowed to leave the site.

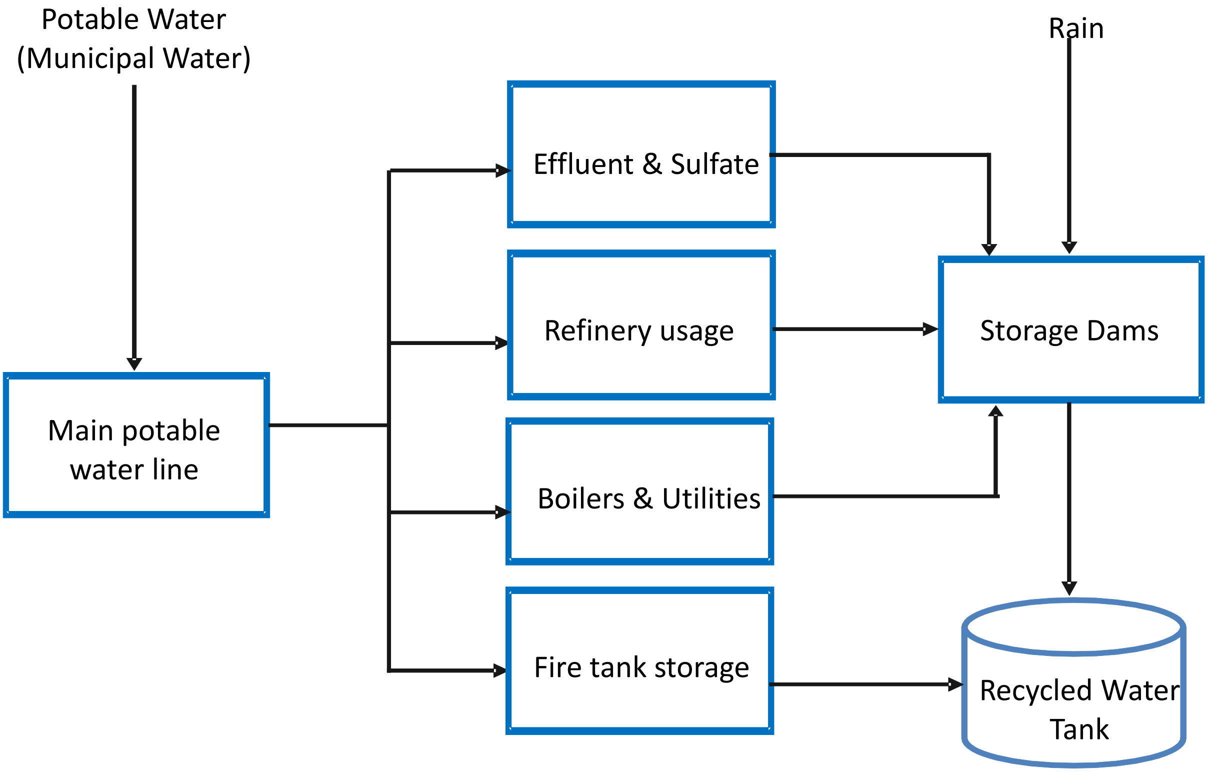

Figure 3.2 The water reticulation circuit of the refinery is split into six diagrams

The blocks in Figure 3.2 show the six diagrams and their connection to the main potable (municipal) water line. The flow of water to the recycled water tank is also shown.

The water reticulation diagrams display three critical pieces of information:

- The water flowrates through flowmeters,
- The percentage of water that is drawn from the previous (parent) stream, and
- The accountability of the stream.

Water accountability refers to the amount of water whose end points are exactly known, i.e. the water usage can be tracked during processing to its final end point. The method of calculating accountability has been illustrated in the following example as shown in Figure 3.3. The flowrate through flowmeter 1 is 50 m^3/day. Of that 50 m^3/day, 5 m^3/day flows through flowmeter 2 and 10 m^3/day flows through flowmeter 3. As a result, only 15 m^3 of the total 50 m^3 flow through flowmeter 1 per day is known to its end point. The accountability on flowmeter 1 is thus 30%.

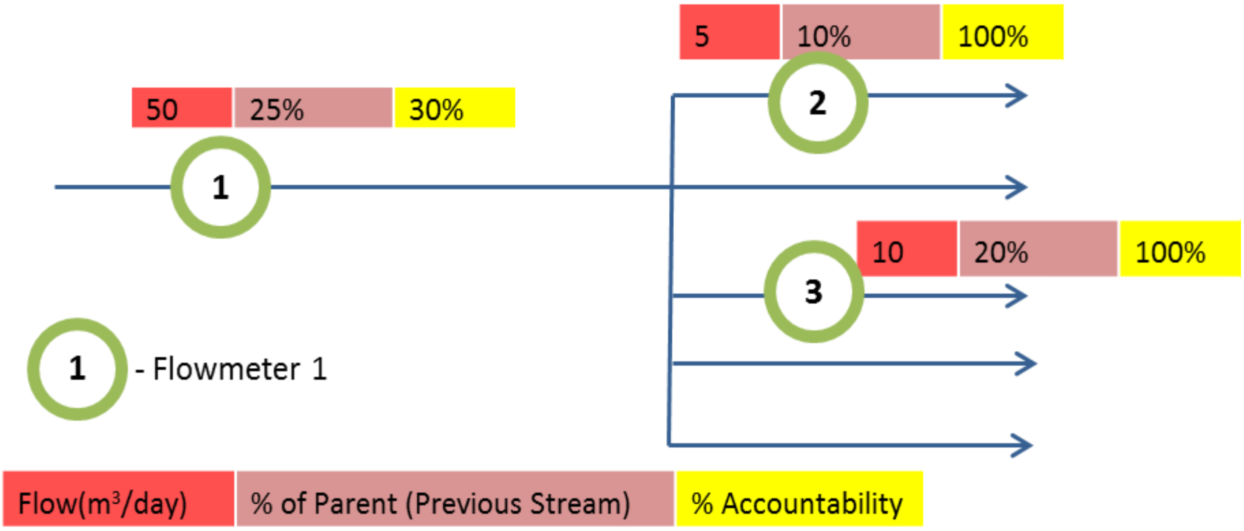

Figure 3.3 Accountability example

The percentage of parent refers to the amount of water in the original stream that ends up at a particular point. For example, the percentage of parent stream for the stream containing flowmeter 2 is 10% of stream/flowmeter 1 and is shown in the centre pink block.

Flowrates from flowmeters are summed every 24 hours and reported to staff onsite in the form of a daily totalizer report. The flowrates for the reticulation diagrams are updated on a daily basis from these totalizer reports and can be emailed on a daily basis to the refinery staff.

3.2 Stage 2: Water Balance

Data from the flowmeter totalizer recordings were used to calculate a site water balance. The balance was performed so that the refinery was able to record all water entering and leaving site and was presented in the form of a water balance sheet. Values from the water balance were also used to assist in completing the WAF and calculating the WF. The water balance was constructed in Microsoft Excel. Values are either calculated (rainfall, evaporation, sewage) or totalled from daily flowmeter readings (totalizer reports). Monthly water balances were summed to provide a yearly water balance.

Flows into the plant are:

- Potable water – obtained from totalled flows from the main potable water flowmeter;
- Rainfall runoff collected – calculated based on monthly rainfall data provided by the refinery's environmental division as well as the refinery surface area;
- Site 3 steam return – totalled flows from the flowmeter measuring steam flows;
- Water entering with reagents – calculated based on the moisture content and mass of reagents required; and
- Rainfall into dams – calculated based on monthly rainfall data provided by the refinery's environmental division. Changes in rainwater dam levels were used to calculate monthly inventory changes (accumulation/decrease in levels) on the rainwater dams.

Flows out of the plant are:

- Evaporation – calculated based on monthly evaporation data provided by the refinery's environmental division. Evaporation was calculated for all dams, tanks and open water sources;
- Water leaving with products formed – calculated based on the moisture content and mass of products leaving site;
- Water leaving from ablutions to sewerage facilities – assumed based on the number of people onsite and an average value of 200 l per person per day (Swistock and Sharpe (2005)); and
- Steam to site 3 – flows from the flowmeter measuring steam flows.

3.3 Stage 3: Water Accounting Framework

The first report generated using the MCA's WAF is the Input-Output model. It refers specifically to all inputs, outputs and diversions from site to the environment and vice-versa. The accuracy statement was combined with the input-output model to report whether flows had been calculated, estimated or measured. The second report is the Operational Model which describes internal site water flows during a process. The operational model includes water flows between storage facilities onsite to tasks and treatment points.

3.3.1 Input-output Model with Accuracy Statement

The Input-Output model provides a report of inputs and outputs to the process that are supported by volumetric flows and information that adds context to the volumetric flows presented. Information is provided regarding inflows and outflows and their interaction with the environment and community. The model also provides a consistent report for detailing flows entering and flowing out of a process. Volumetric flows are reported based on their sources and final end points.

Inputs are defined as volumes of water received by the operation and can be categorised as:

- Surface water: water extracted from natural bodies such as lakes and rivers as well as rainfall runoff or precipitation that is collected by the facility;
- Groundwater: water below the earth's surface or is entrained in ore;
- Sea water: water from oceans or estuaries; or
- Water supplied by a third party- water supplied by external facilities

Diversions of water refer to water that is diverted away from the operation and is not used for any tasks. These diversions can flow to creeks, rivers or underground aquifers.

Outputs are classified as volumes of water that are removed from the operation and can be classified according to the point of receipt outside the facility. Outputs are categorised as:

- Surface water: water open to the atmosphere excluding oceans and estuaries;
- Groundwater: water below the earth's surface that could form aquifers or seepage from water stores and tailings;
- Sea water: water to oceans or estuaries;

- Water supplied to a third party: water supplied to external facilities;
- Evaporation-water released to the atmosphere during operations;
- Entrainment: water lost from the operation in the form of a product or waste stream; or
- Other: destinations that are not identified or that cannot be accounted for or measured.

Data obtained during the physical verification was used to draw up the input-output and operational model. Each water input or output has a quality category allocated to it from a range of 1 to 3 as defined in section 2.5.2.

The values used in the input-output model are the annual volumetric water flows, measured in m^3/year. The accuracy statement provides detail as to whether flows were measured, calculated or estimated. Confidence levels indicate whether there was a high, medium or low level of confidence in the values obtained. This information has been coupled with the Input-Output model to provide information as to how flows were obtained.

3.3.2 Operational Model

The Operational Model provides guidance for companies for water processes within their operations. This is of more value to businesses which currently do not have an effective operational water model or see an opportunity in developing this new approach.

For the operational model, the following definitions have been used:

- Raw water is received at an input and has not been used;
- Worked water has been through equipment or a process; and
- Treated water has been treated to provide water suitable for a particular task, e.g., demineralised water for steam turbines.

In order to represent inputs, outputs and operational water in accordance with the framework, the following guideline is to be used.

- Inputs are coloured green

- Outputs are coloured red
- Diversions are coloured yellow
- Stores are coloured blue
- Tasks are coloured grey
- Treatment plants are coloured purple

Flowrates used in completing the operational model were obtained from the refinery flowmeter readings. The total monthly flowrate for March 2011 was used to obtain an average daily flowrate for March 2011. The average daily flowrates were measured in m^3/day.

3.4 Stage 4: Water Footprints

WF can be defined as the total amount of fresh water that is consumed, directly and indirectly during a production process. A full WF evaluation considers not only the water consumption and its impact, but also measures that could be taken to reduce the consumption and impacts associated with production (Hoekstra et al. 2011). The Water Footprint Assessment Manual outlines four steps or phases to be followed in completing a WF study. The four steps are:

- Setting of goals and scope;
- WF accounting;
- WF sustainability assessment; and
- Response formulation.

3.4.1 Setting Goals and Scope

The first step is to identify objectives that are to be achieved from the WF assessment. Does the main objective focus on a particular step or is the assessment focussed on all four phases? The scope of the study also needs to be defined. This is done by specifying the system boundaries and time frame of the study. Considerations such as which footprints are of importance and whether supply chain footprints are to be included are decided during this step.

3.4.2 WF Accounting

This step entails the collection of data and the calculation of the WF. The total water footprint is classified as the sum of the blue, green and grey water footprints as shown in Figure 3.4 below and Equation 2.4 from the literature review.

Figure 3.4 The total water footprint shown as the sum of the blue, green and grey WFs

One of the tools of WF is to classify water into three categories. The three types of water are discussed below.

<u>Blue water</u>

Blue water represents fresh water resources such as surface and ground water that are not returned to the same source. Seawater is not included as a blue water source. The blue WF refers to the amount of fresh water that has evaporated, been incorporated into a product or returned to a different location as opposed to its source. The equation representing the calculation of the blue WF is shown in Equation 2.1 in the literature review.

<u>Green water</u>

Green water refers to rainwater used during the production process that could have been stored in the soil or temporarily on top of the soil. It can also be described as the amount of rainwater incorporated into the product or lost through evaporation which is shown as Equation 2.2 in the literature review.

<u>Grey water</u>

The grey WF refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards. This is shown in equation 2.3 in the literature review.

The refinery operates using a zero discharge principle. Wastewater is stored onsite and thus no grey WF could be calculated.

In addition, the WF can also be calculated for a particular product.

WF of a product

The WF of a product is the total volume of fresh water that is used directly or indirectly in the production process. Values for consumption and pollution for the product WF are often estimated and all steps of the production chain are considered. The product WF can be calculated using either the chain summation approach or the stepwise accumulative method. The chain summation approach is used when only one product or output is produced. The stepwise accumulation method is used when more than one product or output is produced.

For the chain-summation approach, the WF of a product, p, is equal to the sum of the relevant WF divided by the production of the product. The equation for to calculate the WF of a product using the chain-summation method is shown as Equation 3.1 (Hoekstra et al. 2011).

$$\mathrm{WF}_{\mathrm{prod,[p]}} = \left(\frac{\sum_{s=1}^{k} \mathrm{WF}_{\mathrm{proc,\,[s]}}}{\mathrm{P}_{[\mathrm{p}]}}\right) \qquad \text{[Equation 3.1]}$$

Where:

$\mathrm{WF}_{\mathrm{prod,[p]}}$ is the WF (volume/mass) of output or product p;

$\mathrm{WF}_{\mathrm{proc,[p]}}$ is the process WF of the process steps (volume/time); and

$\mathrm{P}_{[\mathrm{p}]}$ is the production quantity of the product p (mass/time).

3.4.3 WF Sustainability Assessment

The sustainability assessment is performed to determine the impact of operations on the local environment and society. The impact assessment also looks at water use of the plant as compared to local water availability.

3.4.4 WF Response Formulation

In this step, recommendations are made on how to reduce the impact that the operation has on the local environment. Response formulations can include strategies, targets or policies.

The sustainability assessment and response formulation have been included in the discussion and conclusion sections of this research.

3.4.5 Time Frame and Boundaries of the Study

The time frame that the study was conducted over was from November 2010 to October 2011. Onsite analysis (work performed at the refinery) was completed from September 2011 to March 2012. System boundaries were restricted to the refinery and excluded nearby operations such as smelters or concentrators. As such, the system boundary was the physical fence surrounding the refinery. Water entering or leaving the site across this boundary was regarded as water into and out of the site.

4. RESULTS

4.1 Verification of the water system

The first stage of the study was to verify the water reticulation system of the refinery. This was done in two steps. The first step was to track all water lines and flowmeters. The second step was to update the water reticulation diagrams at the refinery.

4.1.1 Physical Verification and Construction of a Flowmeter Database

All water lines were tracked from start to end point and verified against piping and instrumentation diagrams/drawings (P&ID). A database of existing flowmeters was drawn up once the water lines and flowmeters had been verified. The database contains:

(i) the flowmeter numbers as displayed on reticulation diagrams;
(ii) the tag numbers;
(iii) a brief description;
(iv) flowmeter type; and
(v) a photograph of the flowmeter.

A flowmeter list was also compiled as a reference for the database. An excerpt of the flowmeter list is shown in Table 4.1. An example from the database is shown in Figure 4.1. The complete flowmeter list and database are not shown in this report as they contain confidential information regarding the refinery.

Table 4.1 List of Flowmeters on Water Lines

Number	Tag Number	Description	Type
1	T851_FI_007-PV	Main potable water flowmeter	Magnetic
2	T851_FI_003-PV	Potable water to E&S	Magnetic
3	T851_FI_008-PV	Potable water to Leaching & Utilities	Magnetic
4	PL855_FIT_005-PV	Potable water to Fire Tank 1	Magnetic
5	T851_FI_004-PV	Potable water to Utilities	Magnetic

Figure 4.1 Example of a photograph from the flowmeter database

4.1.2 Reticulation Diagrams

The water reticulation circuit is divided into six diagrams as shown in Figure 4.2 on which the main flows between subsections is shown. All minor water connections are not shown in Figure 4.2 but in subsequent figures (Figures 4.5 to 4.9).

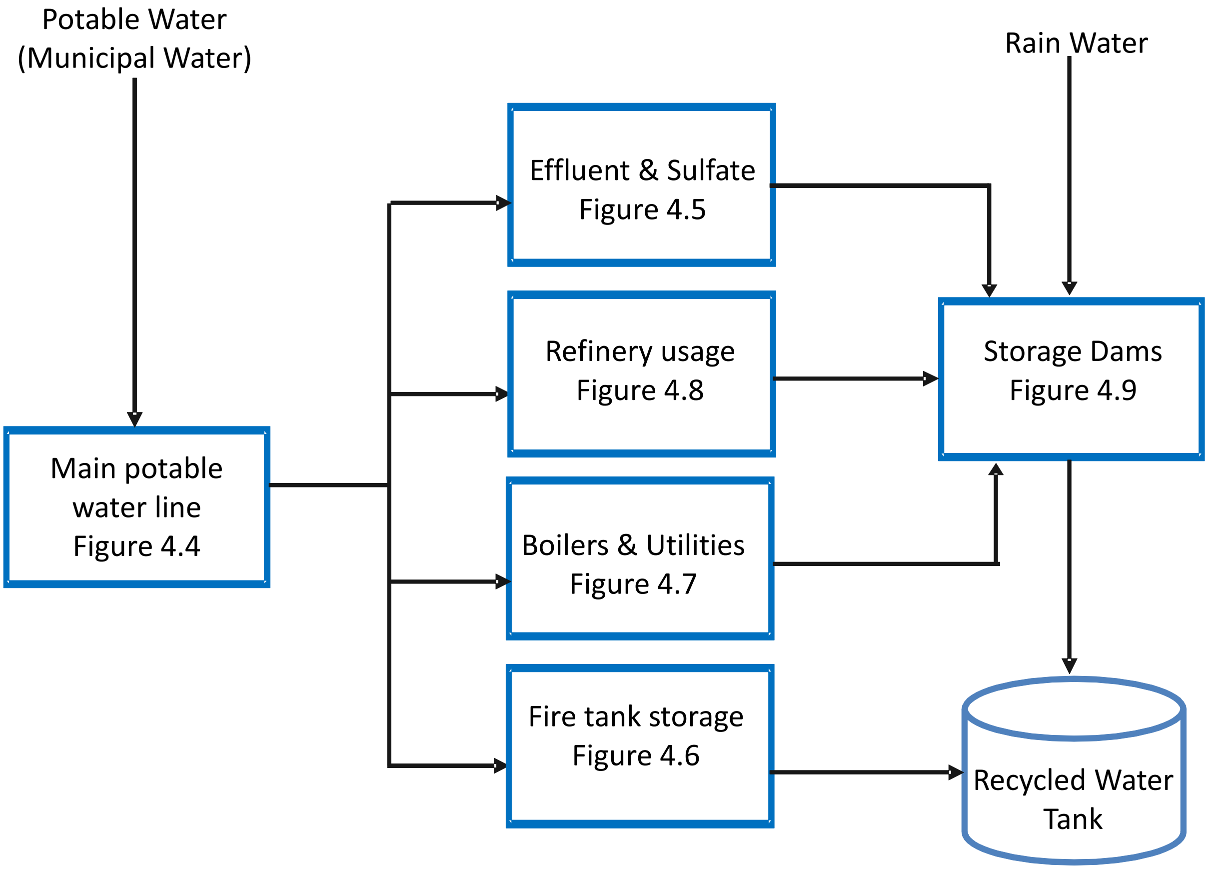

Figure 4.2 The splitting of the water reticulation circuit of the refinery into smaller sub-sections

The water distribution chart for the main potable line is given in Figure 4.3 and the reticulation diagram for the main potable water line is shown in Figure 4.4.

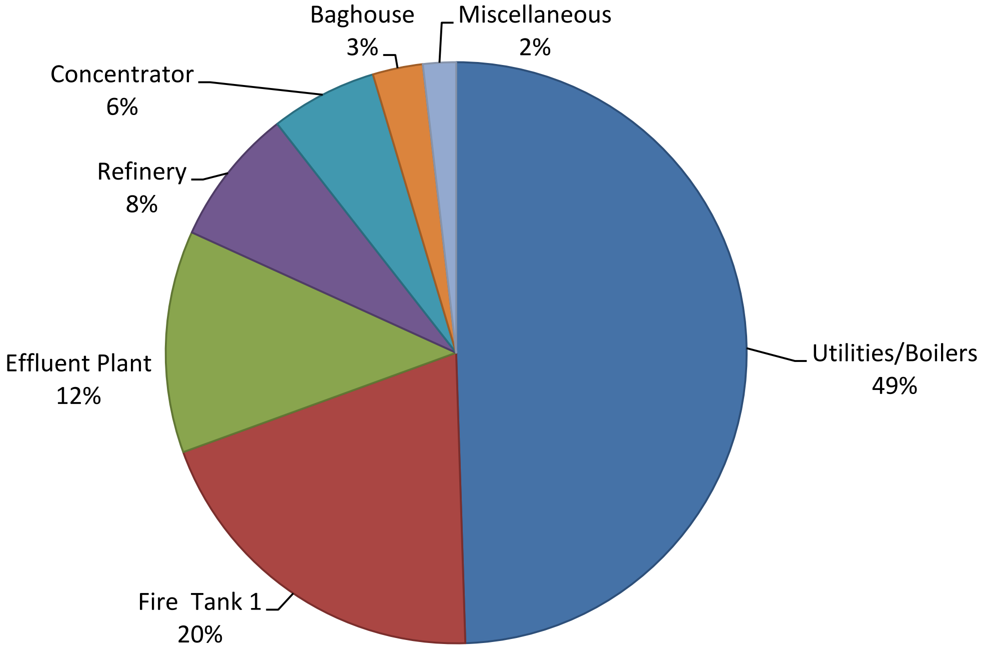

Figure 4.3 The distribution of water from the main potable water distribution line

Accountability for Figure 4.4 was 100% with the site able to identify where 100% of the water was distributed. Water flows from figure 4.4 to other sub-sections has been shown with the use of a block around the sub-section as well as the corresponding figure number. The potable water flow was seen to be 2 291 m^3/day with almost half of that (49%) flowing to the Utilities and Boilers section as seen in Figures 4.3 and 4.4. Approximately 20% of the potable water to the site was used to top up the fire tanks and to supply the refinery and concentrator sections where it was used for processes such as leaching. Water flow to the bagging plant was not monitored but approximately 64 m^3 (3%) of water per day supplies the bagging plant, emergency showers and toilets from the main water line. This value was calculated from Figure 4.4 by subtracting known flows from the main water flow into the refinery.

The first reticulation diagram shown in Figure 4.4 describes the distribution of potable water from the main potable water to the different parts of the site. Flowmeter readings have been taken from daily totalized reports.

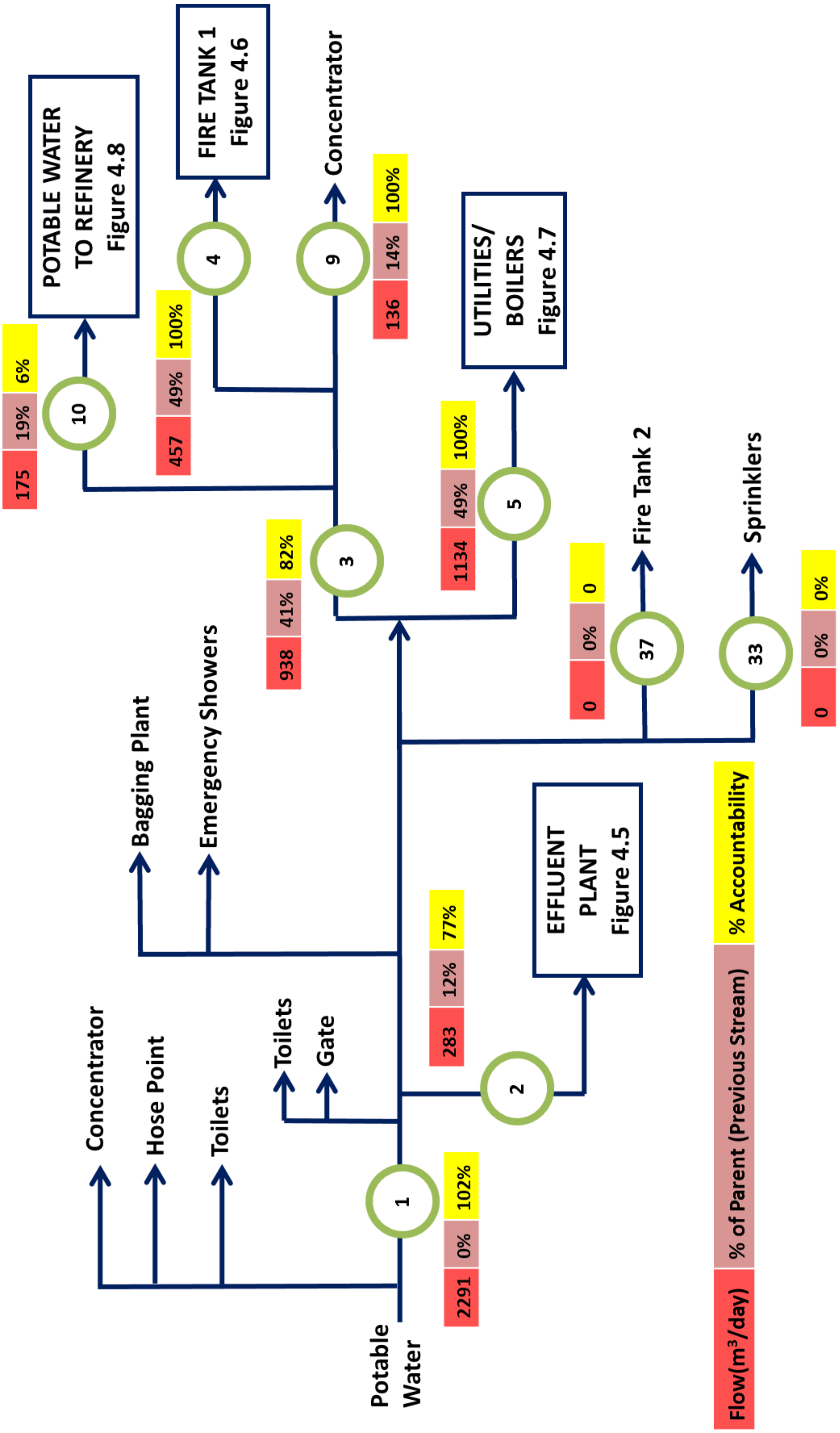

Figure 4.4 Main Potable Water Reticulation Diagram showing water lines to Effluent Plant, Fire tanks, Refinery sections, Concentrator plant and Utilities/Boilers

The water distribution diagram for the Effluent Plant is shown in Figure 4.5. Water to the Nickel plant and Effluent Cooling Towers was supplied from this line. Accountability for the water reticulation of this section was 77% as flowrates to the labs are not measured. Approximately 36 m^3 of water per day was used for the Effluent Plant Cooling tower and 23 m^3/day was used for the Crystalliser section. These usages together account for 2.5% of the total daily potable water consumption which was measured by Flowmeter 1 as in Figure 4.4. The water to the nickel plant and ablutions was measured to be 69 m^3/day which accounted for 3% of the daily potable water consumption.

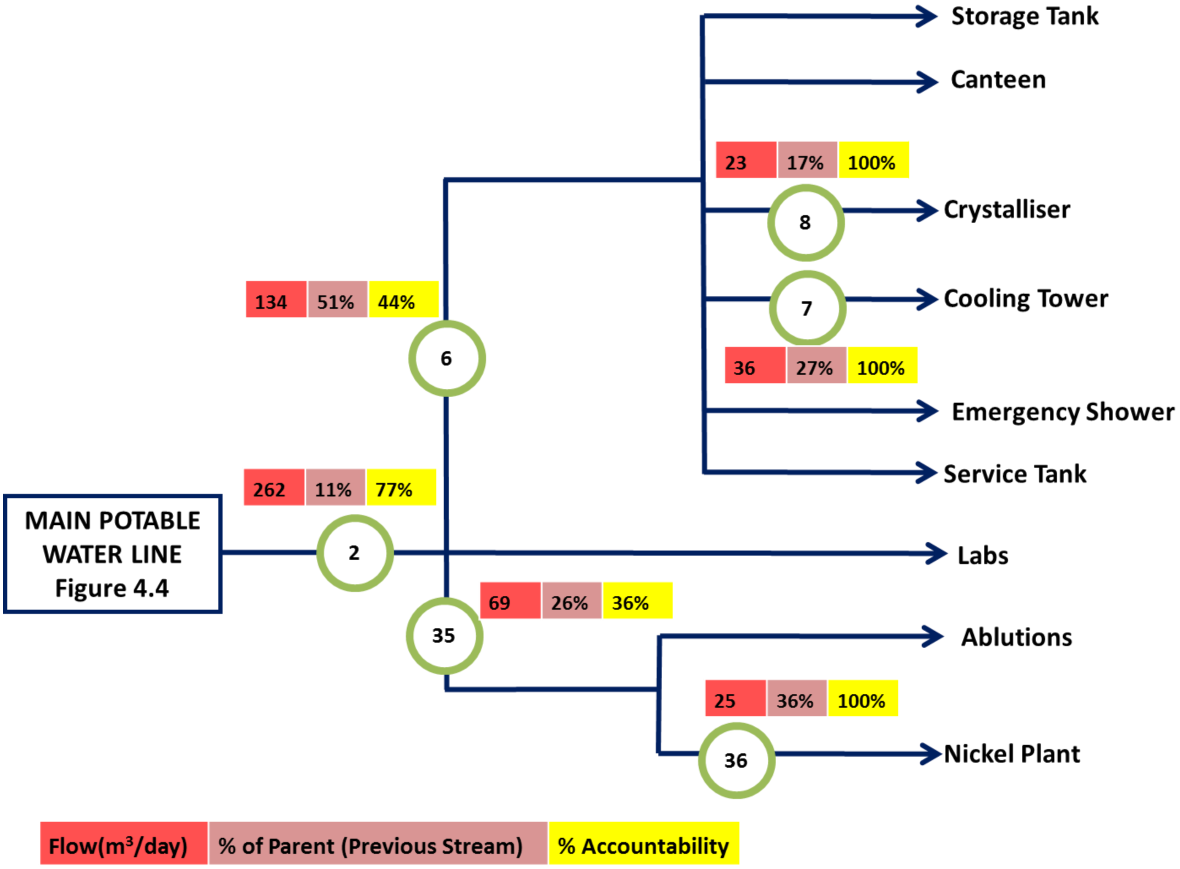

Figure 4.5 Potable water to Effluent Plant

Figure 4.6 shows the main water flows into and out of Fire Tank 1. This tank stores water that could be re-used onsite. Water from Fire Tank 1 supplied the recycled (rainwater) water tank, evaporators, refinery tanks and processes as well as the concentrator plant. The fire systems of both the Refinery and Concentrator plant were fed with water from the fire tank. Water flow to Fire Tank 1 from the main potable water line was 457 m^3/day. This accounted for 20% of the daily total potable water consumption. Recycled water from the Concentrator Plant and returning steam condensate from the Effluent Section, evaporators and various heat exchangers were returned to the tank. Condensate that was returned from Site 2 was sent initially to a blend tank and later to Fire Tank 1. Potable water was pumped into the tank as a top up in order to prevent the water level from dropping below a set minimum. This top up stream flowed from the main potable water line as shown in Figure 4.4 and was measured.

Water distribution to the Utilities section is shown in Figure 4.7. The potable water line to the utilities section splits to supply the compressor cooling towers, plant cooling towers, emergency showers, blend tank and the hot water feed tank. The water from the feed tank could be sent via a direct line to the hotwells or via hot water softeners to the hotwells and later to the boilers. Before the water was pumped to the hot water softeners, the conductivity (salt content) was measured. The water was sent to the firebreak tank, dams or the hot water softeners depending on the quality of the water. If the water had a low conductivity, it was sent to the hotwells to be reused in the boilers. Water from the Hot Water Feed Tank could be re-directed to Fire Tank 1 if the water had been slightly contaminated. This water would be to be recycled for plant use. If the water from the Hot Water Feed Tank had a very high conductivity, it would be pumped to the storage dams. There were two hot water softeners that fed the hotwells. Steam returning from various sections of the plant was also pumped to the hotwells. Water from the hotwells was sent for de-aeration. The water was then sent to the boilers for steam generation.

Water to two sets of cooling towers was also supplied from flowmeter 4. The water to the cooling towers amounted to 235 m^3/day and accounted for 10% of daily potable water usage. Water to the hotwells and later boilers was 698 m^3/day. This accounted for 31% of the daily potable water usage.

Water balances over pipelines that were not measured were not completed and displayed on the reticulation diagrams. This was due to uncertainties in flowrates and non-disclosure agreements regarding the publication of flowrates that could be confirmed.

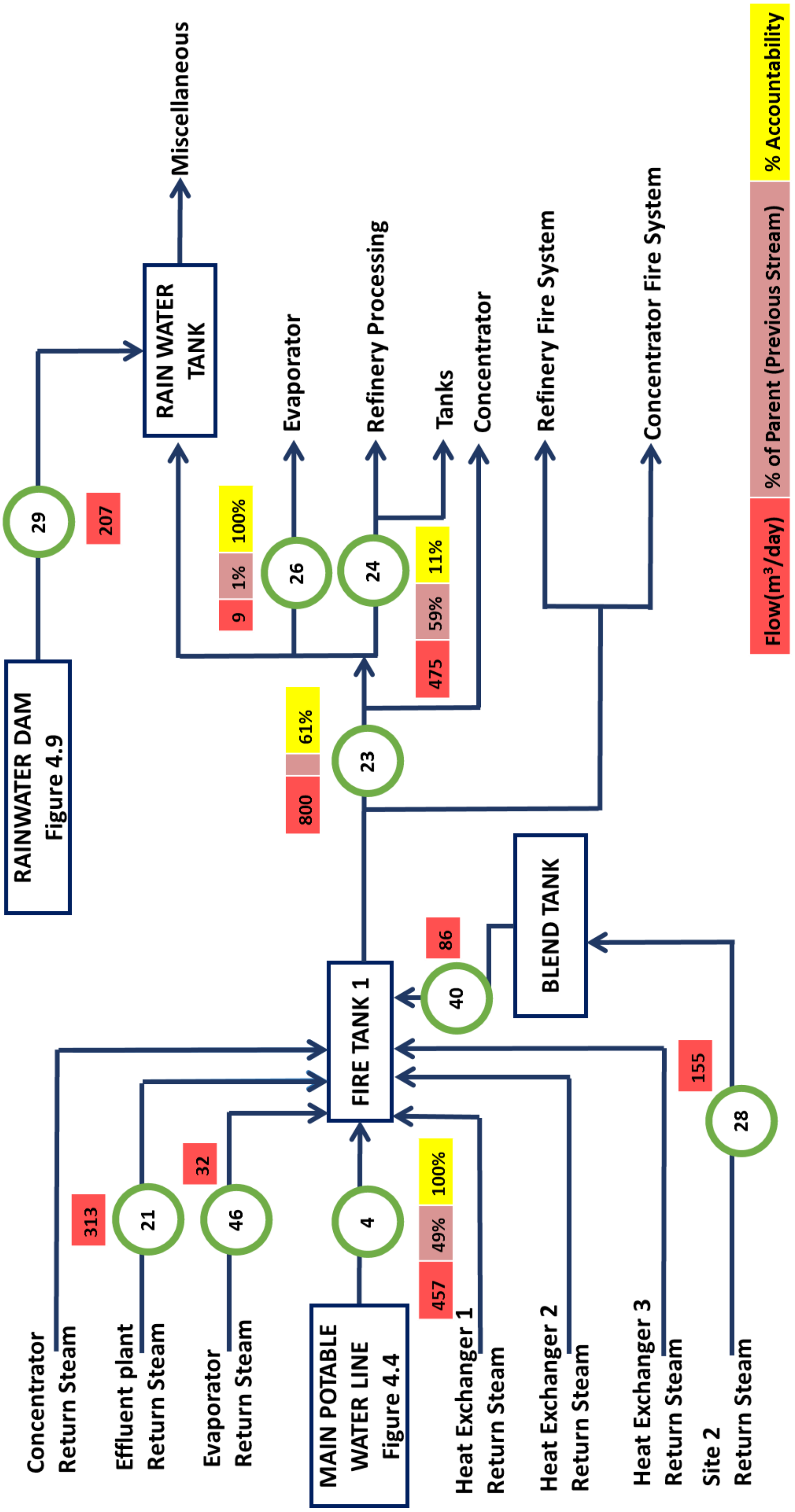

Figure 4.6 Water flows into and out of Fire Tank 1

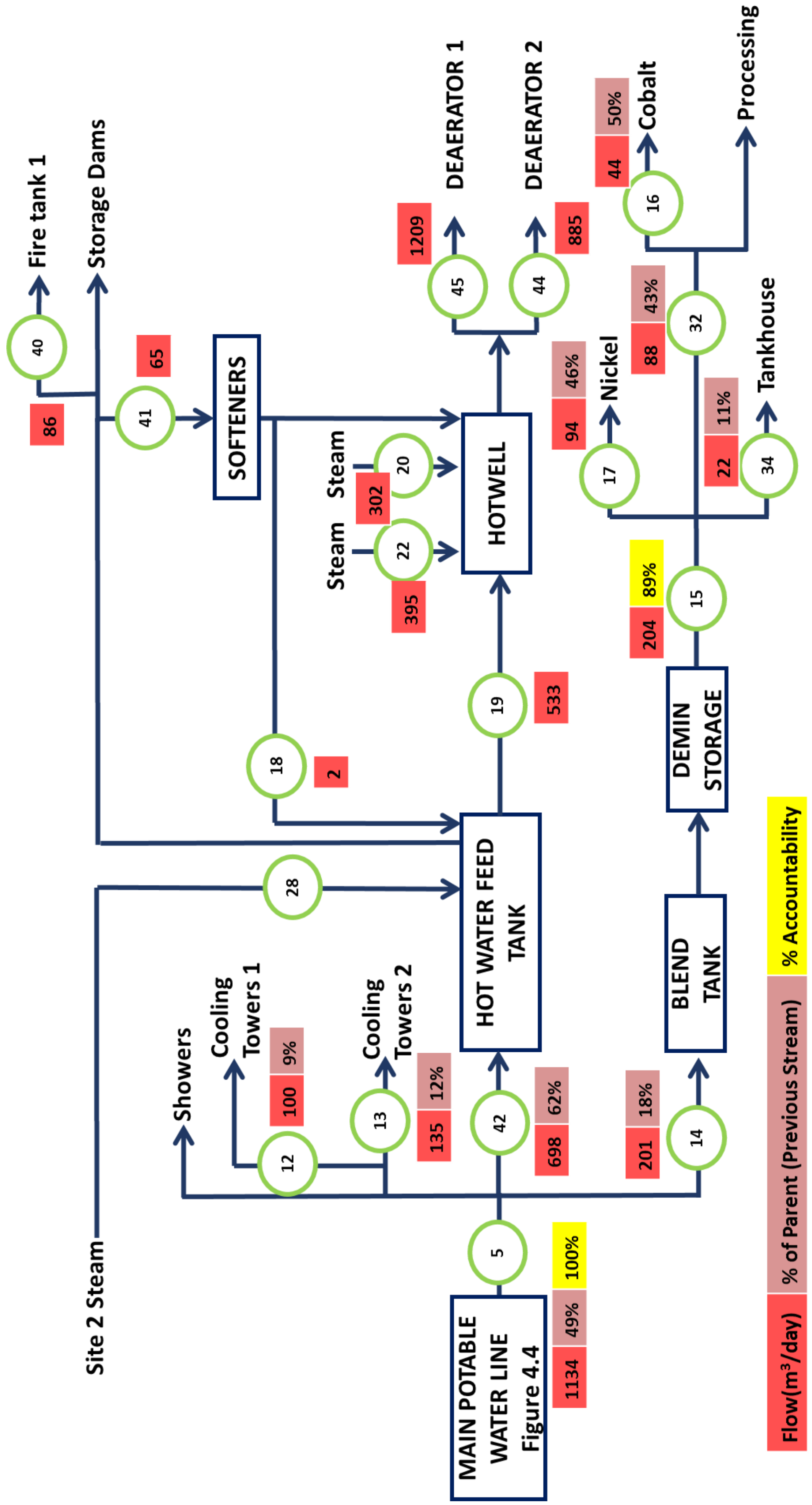

Figure 4.7 Water flow from the main potable water line (Figure 4.4) to Utilities/Boilers

Potable water from Figure 4.4 to the refinery leaching section is displayed in Figure 4.8 and was split into three sub-lines. The first sub-line supplied copper agitators and emergency showers. The second sub-line supplied the changehouse, cooling towers, tanks and more emergency showers. The last line supplied the cobalt plant, geysers, various toilets and emergency showers. Potable water with a flowrate of 175 m^3/day flowed to this section from Figure 4.4 through flowmeter 10. Of the 175 m^3/day, 11 m^3/day was accounted for and flowed to the cobalt plant. The accountability of the refinery potable water usage was 6%, as it was only known where 6% of the water flowed to.

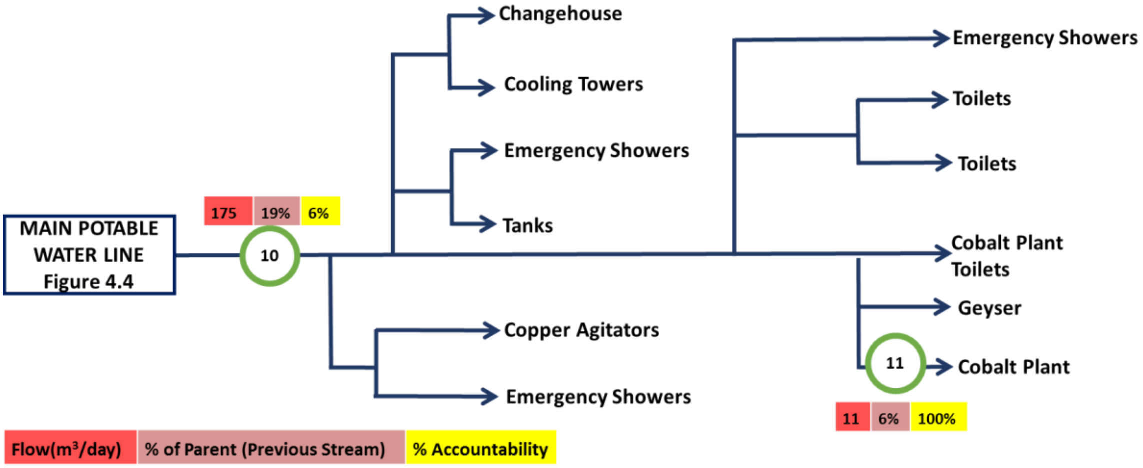

Figure 4.8 Potable water distribution for the refinery leaching section showed an accountability of 6%

Figure 4.9 shows the flow of dam (rain) water into the refinery. Rain water from site ran off into the dams. Water from the dams was pumped to various units such as the scrubbers, rain water tank, fire tank 2 and site 3. Fire tank 2 was not in use at that time.

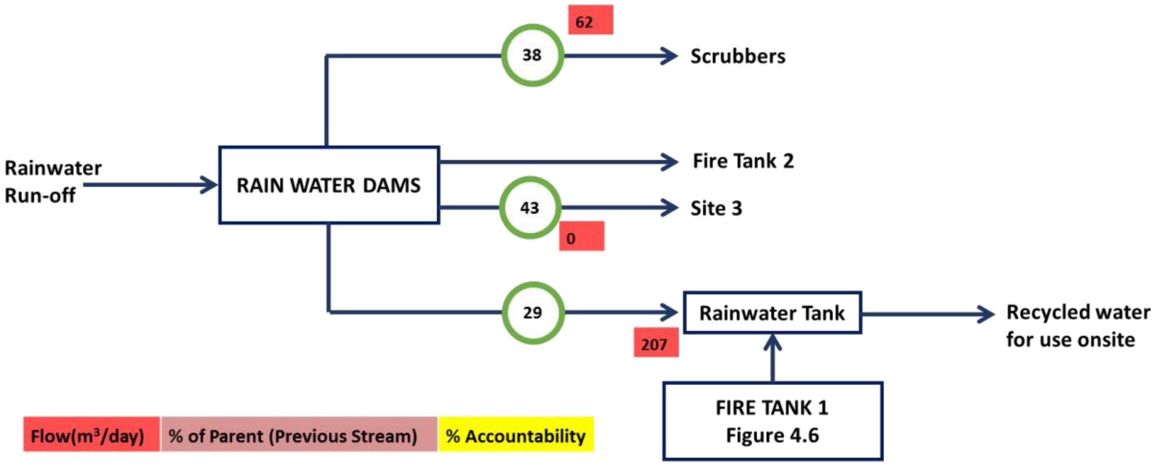

Figure 4.9 Rainwater distribution to the rainwater storage dams and refinery

The accountability over subsequent sections (Figures 4.5 to 4.9) after the main potable water line (Figure 4.4) varied from 6% to 100%. Looking at Figure 4.8, the accountability over the leaching section was 6% and the flowrate to this section was 175 m^3/day. This flowrate accounted for less than 8% of the daily potable water supplied to the refinery leaching section. The flowrate to the Utilities section as shown in Figure 4.7 was 1 134 m^3/day and the accountability is 100%. This accounted for almost 50% of the daily potable water consumption. It is better to have higher accountability over a section that uses 50% of the daily water intake as opposed to a section that uses 8%.

4.2 Water Balance

4.2.1 Water Balance Results

An annual water balance for the period November 2010 to October 2011 is given in Table 4.2. Details of the assumptions used in the balance are given after the table.

The difference between the inputs and outputs for the annual balance was 16 183 m^3 which is less than 2% of the potable water which is used by the refinery. This equated to about 44 m^3 per day (approximately 1.9% of the daily fresh water intake). As can be seen in Table 4.2, the utilities water consumption was 401 800 m^3 for the year. This value was high because it supplied the plant and compressor cooling towers, the blend tank and the hot water feed tank and ultimately the boilers. Water that has been contaminated during processing is unfit to be used in the boilers and cannot be recycled.

As can be seen from the balance shown in Table 4.2, the major inflows into the plant were potable water (832 363 m^3) and rainfall (261 970 m^3). The major consumers of potable water were the utilities section (401 800 m^3) and process water (179 720 m^3). The major outputs of water from the site were evaporation (937 058 m^3) and accumulation in dams (119 830 m^3). These inputs and outputs may be seen graphically in Figures 4.10, 4.11 and 4.12 shown after Table 4.2 and the notes to the table.

Table 4.2 Annual Water Balance from Nov 2010 to Oct 2011

Nov 2010-Oct 2011

Inflows	**Notes**	**m^3**	**m^3**
Potable Water to Plant			**832 363**
Refinery	1	59 077	
Utilities/Boilers	2	401 800	
Fire Tank 1	3	179 720	
Effluent plant	4	94 066	
Concentrator	5	52 839	
Bagging Plant, Ablutions, Airlock	6	44 860	
Rainwater (catchment)			**261 970**
Rainfall	7	261 970	
Return flows			**25 501**
Site 2 Condensate Return	8	25 501	
Reagents			**14 513**
Reagents Required	9	14 513	
Production			**0**
Water produced during reactions	10	0	
Rainwater Dam decrease			**150 830**
Level decrease in Dams	11	150 830	
Difference			**16 183**
Difference in water balance	12	16 183	
Total Inflows			**1 301 358**

Outflows	**Notes**	**m^3**	**m^3**
Evaporation	13		**937 058**
Tank/Process evaporation		757 617	
Dam evaporation		179 441	
Product			**11 274**
Filter Cake and Ash Residue	14	11 274	
Sewage			**87 600**
Water for Ablutions	15	87 600	
Site 3 Steam			**49 425**
Steam Sent	16	49 425	
Water Used in Reactions			**0**
Water Reacted during Production	17	0	
Rainwater to Site 3			**96 172**
Water from dam 3B to site	18	96 172	
Rainwater Dam Accumulation			**119 830**
Accumulation in Dam 3A and 3B	19	119 830	
Total Outflows			**1 301 358**

4.2.2 Data, Assumptions and Limitations

1. Refinery Potable water: Values for the refinery total potable water usage are obtained from the summed flowrates of Flowmeter 10 as shown in Figures 4.4 and 4.8.

2. Utilities Potable water: Utilities water usage is obtained from Flowmeter 5 as shown in Figures 4.4 and 4.7.

3. Potable water to Fire Tank 1: Values for process water were obtained from the total daily readings as measured by flowmeter 4 as shown in Figures 4.4 and 4.6.

4. Potable water to Effluent Plant: Values are based on flowmeter readings from flowmeter 2 Figures 4.4 and 4.6.

5. Potable water to Concentrator: Values are based on flowmeter readings from flowmeter 9 Figure 4.4.

6. Potable water to bagging plant and ablutions: Values for the baghouse and ablutions value is taken as the difference between the main potable water flowmeter 1 and the sum of the potable water to the refinery(flowmeter 3), utilities (flowmeter 5), Fire Tank 1 (flowmeter 4), effluent plant (flowmeter 2) and the concentrator (flowmeter 9)

7. Rainfall: Data recorded by the site of the yearly rainfall for 2011 was used in the water balance. Rainfall capture was calculated by assuming that 70% of rainfall is directed to the rainwater dams, while the other 30% would run off site. The Refinery stormwater system is connected to a valve present near the Concentrator Plant. This valve controls when water is sent to the rainwater dams to prevent flooding of other site dams during rainy season. It is used for emergencies and as a pollution control measure and has been designed for a 1:50 event as per legal regulations. When this valve is open, water is diverted to the river. When the valve is closed, water is directed to the rainwater dams. Water from the Effluent Dam is pumped to the rainwater dams using this system. Record is not kept of when the valve is open or closed.

8. Site 2 Condensate: Condensate return values were taken from site flowmeter readings of Flowmeter 28 as shown in Figure 4.6.

9. Reagents: Water enters with sodium hydroxide which has a 50% dilution rate. Site purchase values were used to calculate the mass of sodium hydroxide and water purchased and utilised for the required time frame.

10. Water produced during reactions;: It was found that the water produced and reacted were almost identical. Thus these values were omitted.

11. Changes in Dam level: Monthly volume changes were calculated using dam levels at the beginning and end of each month together with the dam surface area.

12. Difference: The difference between the inputs and outputs is 16 183 m^3/yr with the outputs greater than the inputs. This equates to 44 m^3 per day.

13. Evaporation: Site evaporation is calculated in detail for the water balance of 2006. These calculations were modified and used together with an evaporation rates obtained from the refinery. Evaporation was calculated per tank and per dam using surface areas. The values obtained are displayed in the balance. Values used for rainfall and evaporation cannot be shown in this report due to a NDA.

14. Products: Filter cake and ash residue values were obtained from metal accountants at the refinery. Water is added to the ash to prevent ash dispersion or flyaway.

15. Sewage: An average value of 10m^3/h was assumed as ablution/sewage.

16. Site 2 steam: Values for steam sent to Site 2 were used for the site balance.

17. Water used in reactions: It was found that the water produced and reacted were almost identical. Thus these values were omitted.

18. Water to Site 3: Water is infrequently pumped to Site 3 prior to or during the rainy season to prevent dams from overflowing. These values were taken from the totalised flowrates of Flowmeter 43 as shown in Figure 4.9.

19. Rainwater Dam accumulation: Monthly volume changes were calculated using dam levels at the beginning and end of each month together with the dam surface area. This was done for the rainwater dams.

4.2.3 Water Balance Analysis

The monthly inputs and outputs may be seen graphically in Figures 4.10 and 4.11. The net difference of the monthly inputs and outputs is shown in Figure 4.12. From these figures, it was seen that the most significant flows of water into the plant were potable water and rainwater. The most significant flow of water out of the plant was through evaporation. Rainfall and Evaporation Rates for Nov 2010 to Oct 2011 are shown in Figure 4.13.

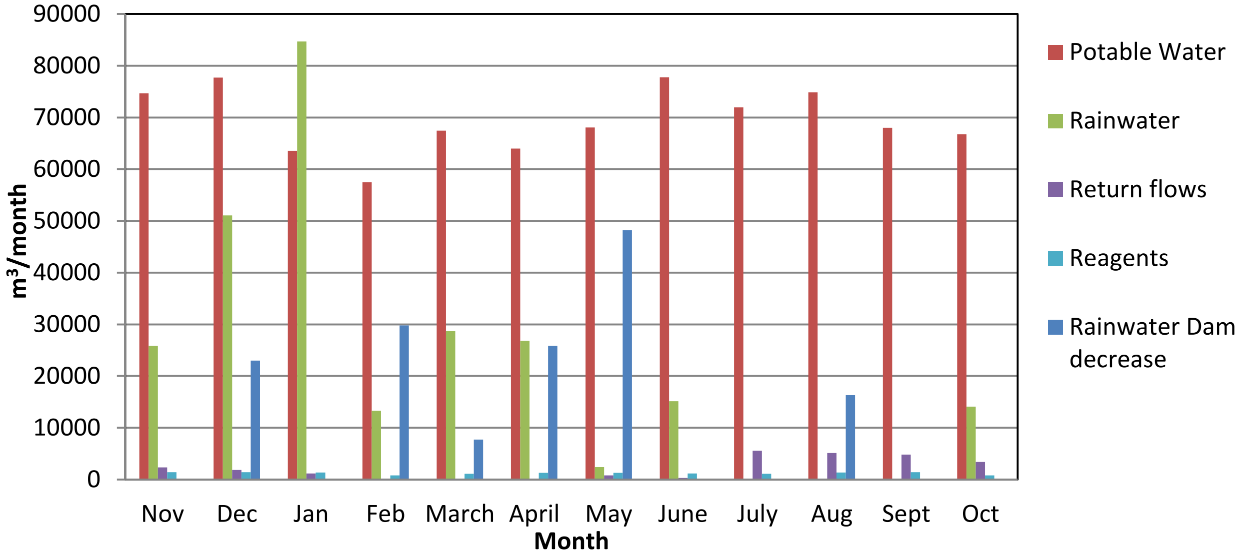

Figure 4.10 Monthly Inputs for Nov 2010 to Oct 2011

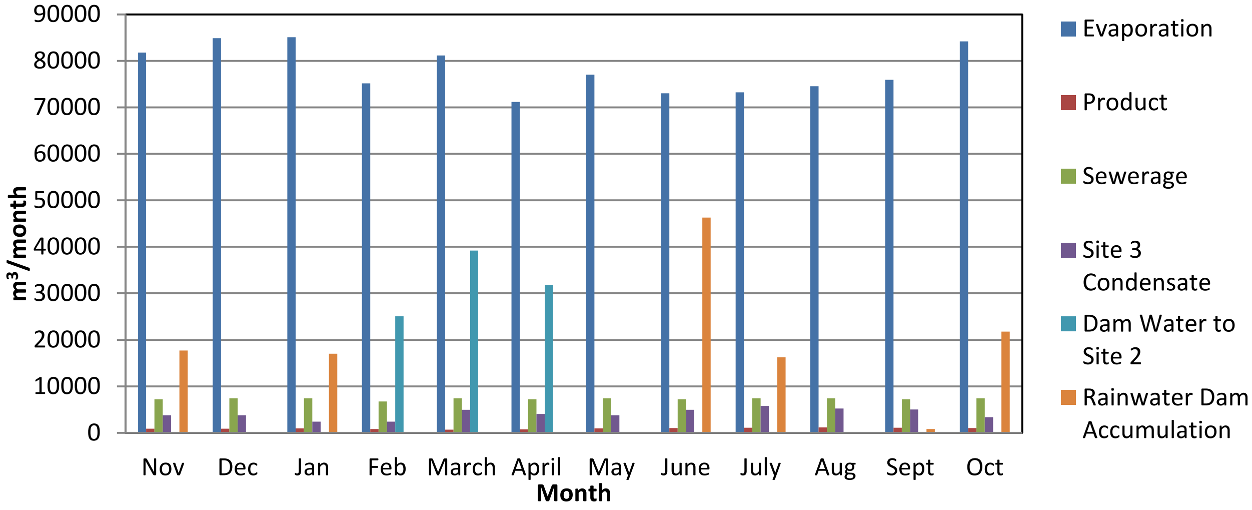

Figure 4.11 Monthly Outputs for Nov 2010 to Oct 2011

During the month of May, the level of water in the rainwater dams noticeably decreased as seen in Figure 4.10. This was possibly due to an increase in the amount of recycled water that was required by the refinery. Recycled water was pumped out of the dams to be used by the refinery and thus the dam levels decreased. Very little rainfall is experienced in May, as seen in Figure 4.13. As a result, the level of water in the dam decreased. During the following month, June, the level of water in the dam increased as seen in Figure 4.11. Water was pumped from the Effluent Dam and other site storage dams to increase the amount of water in the Rainwater Dam to maintain water levels.

While the monthly difference varied from 8 207 m^3/month in June to 54 842 m^3/month in January, the water balance for the year evened out these differences to 44 m^3/day. The difference of 44 m^3/day could be attributed to inaccuracies in flowmeter measurements or discrepancies in the amount of rainfall captured or the calculated water that had evaporated.

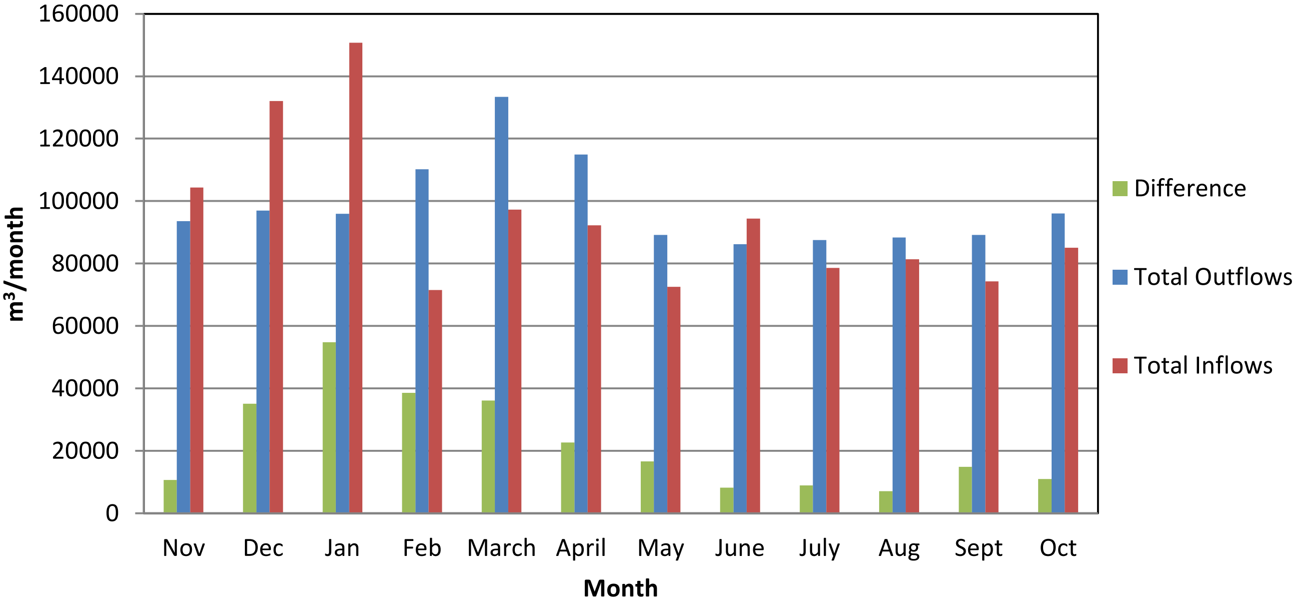

Figure 4.12 Difference between the inflow and outflows of water to the refinery

The rainfall and evaporation rates used for the balance are shown in Figure 4.13. These values were obtained from the refinery’s environmental department.

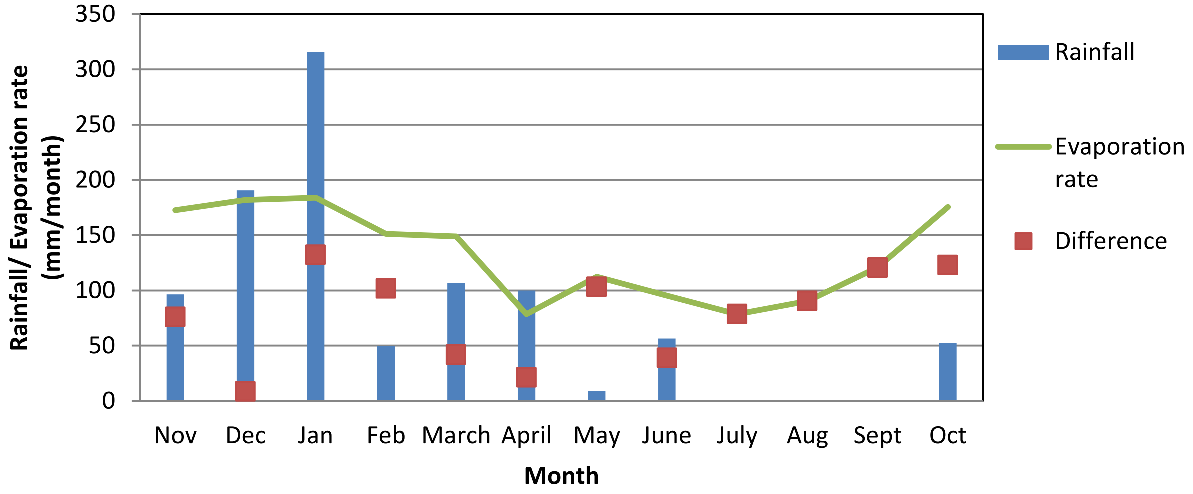

Figure 4.13 Rainfall and Evaporation Rates for Nov 2010 to Oct 2011

4.3 Water Accounting Framework

The first report generated using the MCA's Water Accounting framework is the Input-Output model. The second report is on the Operational Model which describes internal site water flows during a process.

4.3.1 Input-Output Model with Accuracy Statement

Data obtained during the physical verification was used to draw up the input-output and operational model. The input-output model is shown in Table 4.3.

The input-output model details information regarding all inflows and outflows to and from the site. The flows are classified according to where they originate from and what type of water they contain. Values for the input-output report were obtained from the site water balance.

Inflows to the site were municipal/potable water and rainfall. Municipal water has been classified as Category 1 water as it required no treatment before human consumption. Rainwater run-off was collected in rainwater dams. This water required filtration or mild treatment before consumption and has been classified as Category 2. The accuracy statement has been included with the input-output model and details how flows were obtained as well as confidence levels in the values are also given.

Outflows from the site were evaporation, water transferred to Site 2 and sewage. Evaporation has been classified as Category 1 water because if it were condensed and collected, it would be suitable for drinking purposes. Sewage and untreated recycled water which sent to Site 2 would have required significant treatment before the water would be fit for drinking water and has thus been classified as Category 3 water.

In the water balance as shown in Table 4.2, water entering with reagents or leaving with products, changes in dam levels and water flows between sites have been shown as inflows and outflows from the site. These values are not accommodated for in the Input-output model of the WAF.

Table 4.3 Input-output model describing total yearly flows in and out of the refinery site measured in m^3/y

Reporting period Nov 2010 to Oct 2011							
Input/Output	**Element**	**Sub-element**	**Water Quality**			**How were the flows obtained?**	**Confidence Level**
			Category 1	**Category 2**	**Category 3**		
Inputs	Third Party Water	Municipal/Potable	832 363	0	0	Measured	High
	Surface Water	Rainfall Run-off		261 970	0	Estimated	Medium
		TOTAL INPUTS	**832 363**	**261 970**	**0**		
Outputs	Third Party Water	Sewerage	0	0	87 600	Estimated	Medium
	Surface Water	Water to Site 2	0	0	96 172	Measured	High
	Other	Evaporation	937 058	0	0	Calculated	Medium
		TOTAL OUTPUTS	**937 058**	**0**	**183 772**		

4.3.2 Operational Model

The operational model is shown in Figure 4.14. In order to represent inputs, outputs and operational water in accordance with the framework, the following guideline was to be used as described in section 3.3.2:

- Inputs are coloured green;
- Outputs are coloured red;
- Diversions are coloured yellow;
- Stores are coloured blue;
- Tasks are coloured grey; and
- Treatment plants are coloured purple.

Flowrates used in completing the operational model were obtained from the refinery flowmeter readings and the water balance. The average daily flowrates for March 2011 are shown in Figure 4.14 and are measured in m^3/day.

The operational model provided an indication of onsite water usage during a process. It also showed the complexity of onsite water movement. Water recycling could be seen from the diagram as well as wasteful water flows. An example of a wasteful water flow would have been the use of potable water to top up fire tanks, which in turn provided water to a raw/rain water tank. The raw/rain water tank needed to source its water from the dams to provide recycled water for onsite use. This flow of potable water to the fire tank and later the raw water tank was undesirable, as clean water was then being used to provide water for tasks that were able to use secondary/ recycled water.

Flowrates were obtained from daily flowmeter readings as shown in the water balance in Table 4.2 and Figures 4.4 to 4.9. These flows are shown in black on the operational model. All flowrates measured, including those showing a zero flowrate are shown.

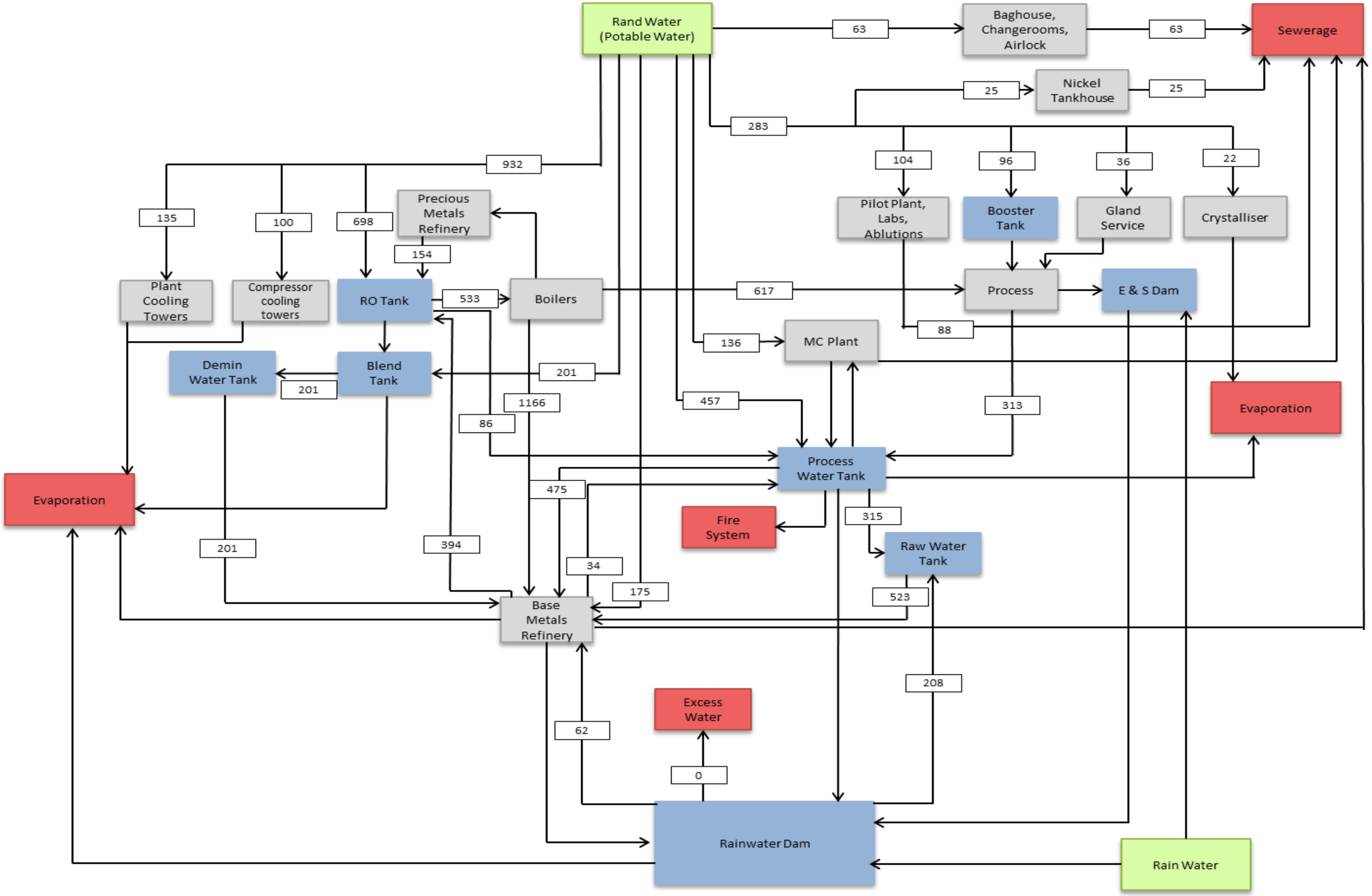

Figure 4.14 Operational model describing internal water flows during processing

4.4 Water Footprint

4.4.1 Setting of Goals and Scope for the Refinery

One of the goals of this study was to calculate the WF's for the refinery. In doing so, the refinery was made more aware of the freshwater consumption and the water required in producing one tonne of base metals. The footprints of the refinery that were calculated were the blue, green and product WF. Supply chain WF's were not included in this study. The refinery does not discharge any waste water so no dilution water (i.e. grey WF) is required.

The main products produced by the refinery were nickel and copper and these formed 98% of the base metal product. Cobalt was produced in minimal quantities. The WF's were calculated for the base metals (nickel, copper and cobalt) only as these were the key products produced by the refinery. The chain summation approach was used to calculate the WF of producing one tonne of a base metal as the base metals were regarded as one product together. All the products of the refinery were produced simultaneously and it was not possible to separate the water required to produce individual base metals. The WF of input products was also not known.

4.4.2 WF Accounting

The water footprint was calculated for the base metals, nickel, copper and cobalt as these were the key products produced by the refinery.

Blue WF

Due to a mixture of blue and green water sources, it was not possible to separate evaporation values for the individual footprints. The blue and green water footprints were thus calculated based on consumption or usage only.

The Blue WF of the refinery was calculated to be 832 363 m^3/y.

Green WF

The green water footprint was calculated based on the amount of rainfall that is captured onsite and used during processing or stored.

The Green WF of the Refinery was calculated to be 261 790 m^3/y.

Grey WF

Grey water is the amount of water required to assimilate or dilute pollutants before discharge. The Refinery did not discharge any waste water so no dilution water was required. The grey water footprint corresponding to this was 0 m^3/y.

Product WF

To calculate the WF of the refinery products, the chain-summation formula was used as shown in Equation 3.1 of the methodology section. The total amount of base metal produced per year was required to calculate the product WF. Table 4.4 shows the production values of the base metals for the period Nov 2010 to Oct 2011 as obtained from the refinery.

Table 4.4 Base metal production values for Nov 2010 to Oct 2011

Base Metal	**Mass (tons/y)**
Nickel	16 247
Copper	8 180
Cobalt	489
Total	**24 916**

The product WF of the refinery was calculated to be 43.9 m^3 of water required to produce one tonne of base metal. The blue WF (76%) contributed more significantly to the product WF than the green WF (24%). The product WF was calculated using Equation 3.1 and is shown on the following page.

Calculation of the product WF:

$$\mathrm{WF_{prod}[p]} = \left(\frac{\sum_{s=1}^{k} \mathrm{WF_{proc}[s]}}{\mathrm{P[p]}}\right)$$

$$\mathrm{WF_{prod}[p]} = \left(\frac{\mathrm{WF_{Blue}} + \mathrm{WF_{Green}}}{\mathrm{P[p]}}\right)$$

$$\mathrm{WF_{prod}[p]} = \left(\frac{832\ 363 + 261\ 970\ \mathrm{m^3/yr}}{24\ 916\ \mathrm{t/y}}\right)$$

$$\mathrm{WF_{prod}[p]} = 43.9\ \mathrm{m^3/t}$$

5. DISCUSSION

5.1 Verification of the Water System

The first objective of this research was to verify the water reticulation system of the refinery. This was done by tracking water lines, generating reticulation diagrams and a list of functional flowmeters.

Recommendations were made to the refinery to install flowmeters on water lines to improve accountability to 95%. However, flowmeters are expensive and it would be costly to install flowmeters on water lines experiencing lower water flowrates (like those in Figure 4.8). Thus it was recommended to first measure the flowrates in these unmeasured water pipelines to determine the water flowrates and install flowmeters based on the measured flowrates. Water lines with suspected large water flows or those which experience large increases in water usage should be given preference when installing the new flowmeters. An example of a water line with a significant water flow would be the water pipeline to the bagging plant as shown in Figure 5.3 which was not being measured. As mentioned, it is too costly to install flowmeters on every unmeasured water line, thus accountability may not be increased to greater than 95% but water use on site will be more easily monitored and understood.

It was seen that most of the potable water (49% entering the plant) was used for the utilities section. This water was sent to the boilers which produced the steam required for heating equipment. It was also seen that not all the steam, once condensed, returned to the hotwells and boilers. This was as a result of leaks in heating equipment contaminating the steam streams. Once the condensed steam had been contaminated, it was sent to the fire tank to be used as process water. Thus additional potable water was required by the boilers to meet their steam production requirement. To decrease potable water usage, leaks in heating equipment should be repaired to avoid contamination.

Verifying the water reticulation system also resulted in a higher level of confidence in the values that were used for the water balance, WAF and WF studies that were performed.

5.2 Water Balance

A water balance was performed for the refinery in order to better understand the water consumed by the plant and was shown in Table 4.2.

As can be seen from the water balance, the utilities water consumption was 401 800 m^3 for the year. This value was high as it included water supplied the plant and compressor cooling towers, the blend tank and the hot water feed tank which feeds water to the hotwells and boilers.

The outputs for the water balance were 16 183 m^3 per year greater than the inputs (approximately 1.2% of the total for the balance). This equated to about 44 m^3 per day and could be attributed to either inaccuracies in flowmeter measurements or discrepancies in the amount of rainfall captured or calculated water that had evaporated. Monthly variations between the inflows and outflows varied from 8 207 m^3/month in June to 54 842 m^3/month in January. The larger difference in the water balance for January was as a result of the higher amount of rainfall experienced during the month of January (316 mm/month) as compared to June (57 mm/month).

The refinery is located in a region of physical water scarcity as discussed in section 1.3 and shown in Figure 1.1. The refinery attempted to collect and store all rainwater that fell onto the site in order to prevent polluted water running off site to the surrounding environment. The refinery collected large volumes of water during the rainy season and due to the zero-discharge principle, the refinery experienced difficulty in storing all the collected water. The water was pumped around the site between different dams to prevent overflows. Water flows between dams could be monitored so that rainfall run-off can be properly accounted for. Monitoring water flows between dams would also allow for tracking of changes in water inventories (accumulations or decreases in stored water).

Water was supplied to the refinery via Rand Water Board. Water supplied to the Bojanala Platinum District, the mining region of the North West province, amounted to approximately 1 400 000 m^3/day (DWA, 2011a). The refinery water requirement

(832 363 m^3/y or 2 280 m^3/day) accounted for 0.16% of the water supplied by RWB to the Bojanala Platinum District. While this may seem small, according to the SRK report on water supply, the Bojanala Platinum District was considered as a high priority area for the development of a detailed water reconciliation strategy as the region is currently in a water deficit in relation to water availability (SRK Consulting, 2011). The refinery therefore needs to decrease the amount of potable water used to ensure successful future operations.

5.3 Water Accounting Framework

An input-output model was constructed in accordance with the MCA's WAF. From the model, it was seen that evaporation was 937 058 m^3/y and accounted the largest loss of water from the refinery. The evaporative losses per year are 104 696 m^3/y larger than the potable water (832 363 m^3/y) supplied to the refinery from RWB.

An advantage of the input-output model over other frameworks was the classification of water entering and leaving the site. Water was classified according to quality and source and not simply as an input or discharge from the site. The model also made allowance for confidence levels and mentioned whether the flows were measured or calculated. As a result, assumed flowrates were easily identifiable. Of the water flowing into the site, 24% was of a medium confidence level as the rainfall to site was estimated. The remaining 76% was of a high confidence level as the value was measured using flowmeters. Of the water flowing out of the site, 91% was of a medium confidence level as the values of evaporation and sewage were calculated and estimated respectively. The remaining 9% was of a high confidence level as the value of water pumped between sites is measured using a flowmeter.

An operational model was drawn up in accordance with the MCA WAF. The operational model described internal site water flows during a process. The operational model included water flows between storage facilities onsite to tasks and treatment facilities. The operational model was an indicator of the complexity of onsite water flows. Unwanted recycles or misuse of water were identifiable when the model was studied. One such movement of water was the filling of the rainwater tank from Fire Tank 1. The rainwater tank (water used for washing of floors and cleaning of spills) was to be filled from dam water but was often filled with process water from Fire Tank 1. Fire Tank 1 was topped with potable water when required. Thus potable water was then indirectly being used instead of water from the dams.

5.4 Water Footprint

The blue and green WF's of the refinery were calculated to be 832 363 m^3/y and 261 970 m^3/y respectively. The grey WF was calculated to be zero as no pollutants or water was discharged from the refinery. According to Haggard *et al.* (2013), the blue WF of a Platinum Mine was 5 537 000 m^3/y, the green WF was 344 000 m^3/y and the grey WF was 5 929 000 m^3/y. In their study, the grey WF was high as a significant amount of water was lost through seepage from the tailings dam into underground aquifers. The green WFs of both sites were reasonably comparable (344 000 m^3/y for the platinum mine and 261 970 m^3/y for the refinery). Both sites are located in the North West province of South Africa but the green WF would depend on size of the site and on how much rain water was collected. The platinum mine operated using crushing, milling, smelting and had a tailings storage facility. The refinery used for this study did not use these processes or facilities as the refinery received treated ore specifically for base metal refining into saleable products.

The product WF was calculated to be 43.9 m^3/t of base metal from a sulphide ore feed. Peña and Huijbregts (2013) found that the blue WF of refining sulphide ore was 96 m^3 water/t copper for the copper refining process in Chile. The blue WF of the oxide ore refining process was 40 m^3 water/t copper (Peña and Huijbregts, 2013). The WF of the refinery in South Africa uses less water to produce one tonne of base metal from sulphide ores as compared to the copper refining operation in Chile. This may be due to the Chilean operation including the process of crushing and agglomeration whereas the refinery in South Africa receives a crushed, separated feed. For both the refinery in South Africa and the refinery in Chile, evaporation was a major element of loss.

According to Mudd (2007b), an average of 691 m^3 of water was required to process one kilogram of gold. Eldorado Gold Corp use between 143 and 407.5 m^3 water/kg gold produced. The product WF of a platinum processing plant was calculated to be 201 m^3/kg PGM produced (Haggard *et al.,* 2015). These values are significantly higher than the water required to produce one tonne of a base metal. However, gold and PGM's are economically more valuable than copper, nickel or cobalt.

An advantage of the WF method was the classification of blue versus green water. Blue water relied on potable or surface water whilst green water accounted for water from rainfall. It would be a good idea to attempt to reduce the blue WF while increasing the green WF to reduce the amount of potable and surface water used. This is especially important for the refinery which is operating in a water scarce region.

While the blue, green and product WF provided a good indication of the water usage required by the plant, the grey WF provided no indication of the polluted water that was produced by the process. The reason for this was that the refinery stored the water onsite and did not discharge it. However, the zero discharge practice means that the grey WF cannot be calculated. Therefore this method has a significant limitation at this type of site. Allowance should be made in the grey WF for polluted water which is stored and not discharged. Another option would be to create another WF to accommodate for polluted water created by a process, irrespective as to whether it is stored, diluted or discharged.

5.5 Recommendations for the Refinery to Achieve Savings in Fresh Water Usage

There are four ways in which savings to water might be made. These are:

i. Increasing return of steam condensate and gland seal steam to hotwells;
ii. Use of dam water as top-up to rainwater tanks;
iii. Water treatment of process condensate; and
iv. Detailed water studies for individual refinery sections.

5.5.1 Increasing Return of Steam Condensate and Gland Seal Steam to Hotwells

Live steam fed to the process cannot be recovered as condensate; however, steam condensate used for heating in heat exchangers and glands seals could have a 100% recovery. Contamination occurs with inefficiency or leaks in equipment. Leaks in heating equipment leak salt content into the heating steam stream from the boilers causing contaminating of the steam. The condensed contaminated steam is not returned to the boilers. Potable water is then used in the boilers for subsequent steam generation.

5.5.2 Use of Dam Water as Top-Up to Rainwater Tanks

Water from the rainwater dams is pumped to the rainwater tank. The rainwater tank is topped up with water from the fire tanks which is in turn topped up with potable water. The pumping of water from dams to the rainwater tank should be increased so that a process water top up is not required.

5.5.3 Treatment of Process Condensate

Condensed steam returning from heat exchangers and other equipment onsite which has been contaminated cannot be reused in the boilers. The water resulting from the condensed steam is often sent to the Fire Tank to be used as recycled water. Water treatment methods such as reverse osmosis or desalination could be investigated to treat the water and reduce the salt concentration so that the water can be reused in the boilers for steam generation. Reusing the condensed steam could reduce the potable water consumption of the refinery.

5.5.4 Detailed Water Studies for Individual Refinery Sections

Detailed water studies should be performed to calculate the required amount of water for each section. These studies would assist in understanding precisely where additional water is used and would also provide accurate water requirement figures per section. Water requirements may then be used to monitor and minimize fresh water usage.

6. CONCLUSIONS

6.1 Verification of the Water System

The mining industry is moving towards operating in a more sustainable manner and needs to be more efficient in their water usage to achieve this. This research assisted a refinery in the North West Province accomplish this by analysing and updating records of the water reticulation system. The physical verification of water pipelines and flowmeters ensured that values and reports generated for further analysis were reliable and could be reported with confidence.

6.2 Water Balance

A water balance was drawn up detailing water usage by various process operations. It was seen that the biggest consumer of water was the boilers and utilities section and the biggest loss of water was through evaporation. The refinery water requirement (832 363 m^3/y) amounted to 0.16% of the water use for the Bojanala Platinum District and Rustenburg Local Municipality. The region was considered as a high priority area for the development of a detailed water reconciliation strategy as the region is currently in a water deficit in relation to water availability. The refinery would need to decrease the amount of potable water used to ensure successful future operations.

The generation of a water balance displayed the largest consumers of water in the refinery and showed where water was used and discharged. Completion of a water balance resulted in the easier completion of the WAF and WF methods as values from the water balance feed into the WAF and WF reports.

6.3 Water Accounting Framework

Four reports (outputs) were generated using the WAF. The four reports generated provide a good indication of the movement of water into, out of and during a process. Of the water flowing into the site, 24% was of a medium confidence level 76% was of a high confidence level. Of the water flowing out of the site, 91% was of a medium confidence level and 9%

was of a high confidence level. The operational model provided an indication of the complexity of onsite water flows and wasteful water flows were identified.

6.4 Water Footprinting

WFs were calculated for the process. The blue WF was calculated to be 832 363 m^3/y and the green WF was calculated to be 261 970 m^3/y. The product WF was 43.9 m^3/t of base metal produced. There was no grey WF as the site did not discharge polluted water. These values were compared to the water usage at other refineries and processing plants and were found to be less than the WF's found in literature. The WF method provided a good indication of the surface, potable and rainwater usage by a particular process. Allowance could be made for polluted water that is produced as a result of the operation. This could be done by the creation of an additional WF.

The WAF and WF are not related and do not necessarily feed into each other. They merely report water usage or consumption in different ways. The aim of the study was to report the water usage in a manner that could be globally compared across sites and to set a benchmark for the industry. Using global tools such as the WAF and WF method assisted in reporting site water usage in a manner that can now be compared to the water usage at other base metal refineries

This research provided an opportunity for the refinery to improve its water efficiency on site as well as improve reporting standards. Water usage was reported using global reporting tools to set a comparative benchmark for the base metals industry.

6.5 Recommendations for the Refinery to Achieve Water Savings

The four ways in which savings to water might be made are:

i. Increasing return of steam condensate and gland seal steam to hotwells;
ii. Use of dam water as top-up to rainwater tanks;
iii. Water treatment of process condensate; and
iv. Detailed water studies for individual refinery sections.

7. RECOMMENDATIONS FOR THE CONTINUATION OF THIS RESEARCH

Further water minimisation studies should be performed at base metal refineries, both in South Africa and globally. Reporting water usage using the WAF and WF method will ensure easier comparison of reports generated and WF's calculated.

A new WF should be developed or the grey WF should be amended for the allowance of polluted water that has been created as a result of the process. The WF could account for polluted water generated as a result of the process/unit of base metal produced.

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9. APPENDIX A—Water in Mining 2013 Peer Reviewed Paper

This study was presented at Water in Mining 2013 in Brisbane, Australia; a peer-reviewed conference (Osman *et al.,* 2013). The peer reviewed conference paper is presented with myself as the lead author. I carried out the work required for the study and wrote the paper under the supervision of the co-authors.

Water Accountability and Efficiency at a Base Metals Refinery

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ABSTRACT

Most mineral processing plants have high water requirements for their operational activities. These plants often function in an environment where water is becoming increasingly scarce. An increase in population will result in an increased demand for water; potentially beyond the limits of supply and hence increased competition for the resource. In South Africa, Gauteng and the North West Province are likely to be first to experience a shortage of potable water.

In order to avoid a water crisis, efforts must be made to ensure the effective management of water resources and the minimisation of wastage. Hydrometallurgical plants have a responsibility to society and the environment to operate in a sustainable manner – reducing their water requirements will certainly assist towards developing a sustainable footprint.

This project improved site water management by:

- surveying the potable water and storm water systems with a view to assessing the current water accountability and determining methods to improve accountability
- determining the monthly and yearly water balance for the site and presenting it in the form of a water balance sheet
- drawing up an input–output and operational model in accordance with the Minerals Council of Australia's 'Water Accounting Framework for the Minerals Industry'
- calculating the water footprints of the refinery
- identifying ways in which water savings could be achieved
- recommending management systems for water usage monitoring.

This work was conducted in South Africa. The value of this work lies in that it established the current baseline and assisted in developing management systems that can reduce water usage sustainably.

INTRODUCTION

Access to safe water is a basic human need. However, globally, over a billion people are unable to access a safe water supply and of these people, 28 per cent are found on the African continent (World Health Organization, 2000). By 2015, it is forecasted that most of the world's population will be suffering severe water shortages due to population growth experienced and mismanagement of water resources. In South Africa, Gauteng and the North West Province will be the first to experience the shortage of potable water. In order to avoid a possible water crisis in the near future, efforts must be made to ensure the effective management of water resources and the minimisation of water wastage.

Most mineral processing and hydrometallurgical operations have large water requirements. These plants often function in an environment where access to water is becoming increasingly competitive. Hydrometallurgical plants have a responsibility to society and the environment to operate in a sustainable manner and consequently they seek to minimise their potable water consumption. Implementing water accounting and other best practice guidelines can assist in this aim.

Recognising the important role of water in the mining industry, the Minerals Council of Australia (MCA) developed a water accounting framework. The framework allows sites to account for, report on and compare site water management practises in a consistent manner. It is expressed in the form of a water balance displaying inputs, outputs, water storage or accumulations and water losses (MCA, 2012).

An alternative method of representing water usage is water footprinting (WF) (Hoekstra *et al*, 2011). WF is the total amount of fresh water that is consumed, directly and

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